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Australian-Developed Lightning Detector Pathfinder Mission

Pre-Phase A Study

Australian National Concurrent Design Facility

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Australian-Developed Lightning Detector Pathfinder Mission

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Cover image | Australian outback landscape with heavy thunderstorm and lightning on the horizon. By photodigitaal.nl/stock.adobe.com.

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Australian National
Concurrent Design Facility

Pre-Phase A Study

Australian-Developed Lightning Detector Mission for the Bureau of Meteorology

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Executive Brief

This work reports on the **Lightning Detector** Pre-Phase A study and subsequent work completed at the Australian National Concurrent Design Facility (ANCDF) by UNSW Canberra Space on the 17-21 October 2022 in Canberra, Australia.

The Lightning Detector concept was first explored in a 2021 exploratory study on candidate satellite missions for the Bureau of Meteorology conducted by UNSW Canberra Space[1]. The current study involved the UNSW Canberra Space team, members of the Bureau of Meteorology and CSIRO, as well as Australian industry experts from FrontierSI and mission and payload experts from Aerospace Corporation and The University of Alabama in Huntsville.

Operational satellite lightning sensors have been taking measurements since the mid-1990s, with the first global measurements being provided by low earth-orbit missions from 1998 onwards. The first geostationary instrument was the Global Lightning Mapper (GLM) launched in 2016 by NOAA. In December 2022 EUMETSAT launched the first European geostationary instrument aboard the Meteosat Third Generation Imaging satellite (MTG-I1).

Developing a sovereign Australian space lightning detector capability would result in new and extended scientific datasets that would benefit the Australian public, regional partners and the global scientific and meteorological community through improved severe weather forecasts.

This study assesses that meeting the Bureau's requirements for a lightning detector mission as well as the broader Australian government policy objectives of the 2021 Earth Observation Roadmap[2], the following should be considered.

- The development of any space-based Australian Lightning Detector sensor should be aimed at achieving a geostationary (GEO) capability.
- A geostationary capability may be too high-cost and high-risk as a first mission development in this field, so a smaller, cheaper, lower-risk option of a low-earth orbit (LEO) pathfinder mission could be considered initially to build up Australian industry capability and allow risk mitigation towards the development of an eventual geostationary capability.
- A geostationary mission could be developed by Australia but will be challenging. It could be considered in partnership with other agencies or countries, or as an Australian payload to be hosted aboard a third-party geostationary satellite. The benefits and risks of these various options are assessed in this report.
- This study has also identified further opportunities for collaboration with international partners.
- An Australian lightning sensor contribution to the WMO meteorological measurement ecosystem would fill an identified observational gap for the Australian and Asia-Pacific hemisphere, and would go some way towards the sharing of the global responsibility for space-based meteorological measurements.

[1] Australian Bureau of Meteorology Pre-Phase A Mission Study Report (2021). Available at: https://www.unsw.adfa.edu.au/our-research/facilities/ancdf

[2] Earth observation from space roadmap 2021-2030, Australian Space Agency, 26 November 2021, https://www.industry.gov.au/publications/earth-observation-space-roadmap-2021-2030

The study also provides guidelines towards design, cost and schedule related to development of the LEO and GEO options under consideration:

- LEO pathfinder mission estimates:
  - Cost estimate: AUD$ 19M
  - Schedule: 2-3 years design and development, up to 1 year for launch and in-orbit commissioning, with 2-3 years operational lifetime (depending on design choices).
- GEO mission estimates:
  - Cost (order of magnitude only): AUD$ 103M (GEO satellite); AUD$ 30-40M (shared payload for a third party satellite)
  - Schedule: 5 years design and development, up to 1 year for launch and in-orbit commissioning, with 2-5 years operational lifetime (depending on design choices).
- Potential collaboration opportunities with international partners (requires further investigation and discussion):
  - Cost: unknown.
  - Schedule: unknown.

Document revision status

Date	Revision	Author	Status	Comments
10/02/2023	01	UNSW Canberra Space	Draft	For Bureau Review.
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Study sponsors

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Above-the-line advice

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AEROSPACE

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CSIRO	Craig Ingram	Domain expertise
University of Alabama Huntsville	Hugh Christian	Lightning payload expertise

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Reference Documents

1. ECSS-E-HB-10-03A Space Engineering Testing Guidelines (31 May 2022)
2. ECSS-Q-ST-10-09C-Rev. 1 Space Engineering NCR Process (1 March 2018)
3. ECSS-Q-ST-30-02C Space Engineering Failure Modes Effects and Analysis (6 March 2009)
4. ECSS-E-ST-10-06C Space Engineering Technical Requirements Specifications (6 March 2009)
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7. ECSS-Q-HB-30-01A Space Engineering Worst Case Analysis (14 January 2011)
8. ECSS-E-ST-10-24C Space Engineering Interface Management (1 June 2015)
9. ECSS-E-ST-10-03-Rev.1 Space Engineering Testing (31 May 2022)
10. Bureau Of Meteorology – Draft Satellite Lightning Sensor Mission description and requirements document (14 October 2022)
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1 Introduction

1.1 Background

In the 2021 Earth Observation Roadmap[3] developed by the Australian Space Agency (ASA), the Bureau articulated an ambition for Australian operational meteorological satellite sensing capabilities in the 2030s. As a first step towards achieving this ambition, the Bureau commissioned UNSW Canberra in 2021 to undertake a preliminary investigation into satellite mission pathfinders to build towards this capability. The resulting Pre-Phase A Mission Study Report[4] identified three missions for further exploration that can support meteorological forecasting and disaster monitoring and mitigation:

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

To further analyse potential mission implementations to meet Bureau requirements, the Australian National Concurrent Design Facility (ANCDF), located at the University of New South Wales (UNSW) Canberra, was engaged in 2022 to conduct three studies in relation to these proposed missions.

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

The Bureau has been a substantial user of Earth observations from space for several decades, and this usage 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 the Bureau's commitments for safety and security.

Over the next decade, the volumes of data used by the Bureau are expected to increase significantly with the development of next-generation meteorological sensors that more thoroughly measure phenomena in the atmosphere, on land and at the sea surface. Observations from satellites have a large impact on forecast accuracy, particularly in the Southern Hemisphere, where the number of observations from surface stations and radiosondes is much reduced and unevenly distributed. Added to this is the fact that gaps exist in certain satellite observation types in the southern hemisphere and Australian regions of interest, which could be addressed by Australian EO missions.

[3] Earth observation from space roadmap 2021-2030, Australian Space Agency, 26 November 2021, https://www.industry.gov.au/publications/earth-observation-space-roadmap-2021-2030

[4] Australian Bureau of Meteorology Pre-Phase A Mission Study Report (2021). Available at: https://www.unsw.adfa.edu.au/our-research/facilities/ancdf

1.2 Document Purpose and Scope

This document reports on the Lightning Detector Pre-Phase A study and subsequent work completed at the Australian National Concurrent Design Facility (ANCDF) by UNSW Canberra Space on the 17-21 October 2022 in Canberra, Australia. The information and analysis presented in Section 2 was prepared ahead of the ANCDF study and results partly in analyses conducted in previous related studies as well as a preliminary mission requirements document received from the Bureau.

Section 1 (this section) provides a description of the ANCDF, the National Space Missions, previous study work, and a survey of previous missions related to lightning detection. Provides background information on the Lightning Detector mission, its requirement sources and the ANCDF.

Section 2 details the programmatic, mission and user requirements of the mission. This information builds on customer-supplied requirements and on the end-user requirements outlined in earlier ANCDF study reports.

Section 3 gives an overview and background for general space mission design concepts.

Section 4 gives an overview of considerations related to developing an Australian lightning detector mission, including possible pathways towards a GEO spacecraft mission and potential benefits in developing a LEO pathfinder mission.

Section 5 gives an overview of a LEO pathfinder spacecraft mission option and its concept of operations and provides design details and drivers for deriving technical requirements and preliminary subsystem sizing work.

Section 6 gives an overview of a GEO spacecraft mission development, including payload, platform, orbit and other design considerations. A detailed design for a GEO mission is outside the scope of this report and would require a dedicated study.

Section 7 gives an overview of the space segment mission implementation of the potential LEO and GEO missions discussed in the previous sections, including some discussion of Australian industry capabilities.

Section 8 gives an overview of Assembly, Integration and Testing (AIT) considerations related to GEO and LEO mission development.

Section 9 gives an overview of Calibration and Validation (Cal/Val) considerations related to GEO and LEO mission development.

Section 10 gives an overview of launch services considerations related to GEO and LEO mission development.

Section 11 gives an overview of the ground segment options to support both the LEO pathfinder and GEO missions, including design drivers for deriving technical requirements and preliminary system sizing.

Section 12 provides an introduction to mission risk assessment issues related to GEO and LEO space mission development.

Section 13 provides costing and schedule breakdowns for the GEO and LEO mission options.

Section 14 concludes the report with recommendations for future work and open points.

Appendices present technical details and derivations.

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[5]).

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 of the mission requirements and objectives, cost, and schedule constraints, as well as design options and trade-offs. This allows mission implementation options to be assessed and adjusted to better meet customer needs.

The typical final product of the CDF process is a comprehensive study report (such as this one) that provides details on 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 to date, including with Airbus, the French Space Agency CNES, the Office of National Intelligence, the Australian Space Agency, Geoscience Australia, CSIRO and the Bureau of Meteorology.

Figure 1: The Australian National Concurrent Design Facility.

[5] See 3.0 NASA Program/Project Life Cycle | NASA for NASA's definition of typical mission phases. Accessed 02/12/2022.

1.4 Survey of Related Lightning Detector Missions

Operational satellite lightning sensors have been taking measurements since the mid-1990s (see Figure 2 below). These instruments all measure lightning events in the near infrared, specifically in a narrow oxygen emission line located at 777.4 nm.

The first global measurements were provided by the polar orbiting Optical Transient Detector (OTD) detector on Orbview-1 followed by the Lightning Imaging Sensor (LIS) detector on TRMM operating in an inclined tropical orbit. In 2017 a spare LIS instrument was allocated for use on the International Space Station (ISS) to provide additional lightning observations from LEO, but this is planned to be decommissioned in 2024. Figure 2 presents a graphical summary of all relevant lightning detector missions.

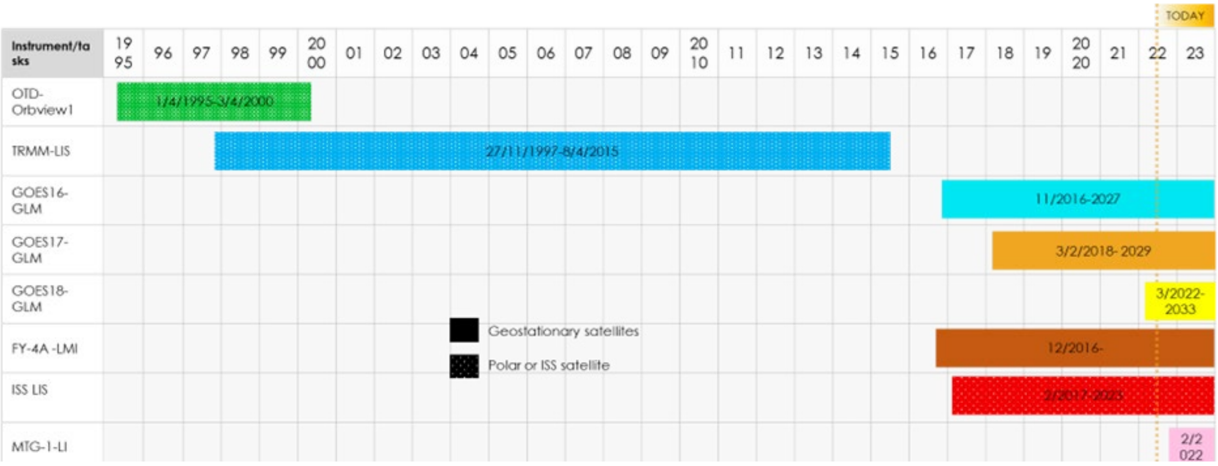

Figure 2: Timeline of past and current satellite lightning sensors.

It was not until late 2016 that the first geostationary instrument was launched, the Global Lightning Mapper (GLM) on-board the first of the GOES-R series platforms (GOES-16) which covers North and South America. Since then, two further satellites in the series (GOES-17 and GOES-18) have been launched hosting the GLM instrument as well as other advanced atmospheric imagery and atmospheric measurement sensors.

NOAA's Geostationary Extended Observations (GeoXO) satellite system will expand the observations of Earth that the GOES-R Series currently provides from geostationary orbit. NOAA expects that GeoXO will begin operating in the early 2030s as the GOES-R Series nears the end of its operational lifetime and extend until the early 2050s. A lightning mapper (LMX) with improved temporal and spatial resolution is planned as part of this future program.[6]

In 2020 the GOES-13 satellite, launched in 2006 and retired in 2018, was repurposed by the US Department of Defence for collecting weather imagery over the Indian Ocean region. This activity provides an important precedent for the repurposing of NOAA GEO assets for use by other agencies

[6] https://www.nesdis.noaa.gov/next-generation/geostationary-extended-observations-geoxo

and could lead to at least an initial GEO implementation for Australia (discussed further in section 3 of this report).

EUMETSAT launched the first of four geostationary Meteosat Third Generation Lightning Imager (MTG-LI) instruments in December 2022. Lightning mappers on MTG platforms are planned until the early 2040s.

For reference, detailed instrument performance specifications for LIS, GLM and MTG-LI are provided in Appendix G to this report.

1.4.1 Geostationary Lightning Mapper (GLM) on NOAA GOES-R Satellites

The GLM conceptually is a high-speed event detector operating in the near infrared. Because of the transient nature of lightning, its spectral characteristics, and the difficulty of daytime detection of lightning against the brightly lit cloud background, actual data handling and processing is much different from that of a simple imager. A wide field-of-view (FOV) lens combined with a narrow-band interference filter is focused on a high-speed charge-coupled device (CCD) focal plane. Signals are read out in parallel from the focal plane into real-time event processors for event detection and data compression. The resulting event detections are formatted, queued, and sent to the satellite's Local Area Network (LAN). The GLM CCD focal plane stares continuously at storms from the GOES-E (75° W) and GEOS-W (137° W) position. Its resolution at nadir is 8 km and degrades slightly to ~14 km at the edge of the FOV. The near-uniform spatial resolution across the GLM FOV is accomplished by a novel variable pixel pitch focal plane design that has larger pixels near the centre and smaller pixels towards the outer edges of the CCD.

A combination of spatial, temporal, and spectral filtering is used to achieve the high detection efficiency. A solar blocking filter at the front aperture of the instrument works in combination with a solar rejection filter to limit out-of-band light from entering the instrument. The 1-nm narrow-band interference filter ensures the 777.4 nm oxygen triplet is passed to the detector.

GLM's detection efficiency is specified to 70% during the day and 90% at night. It is very much dependent on the payload-data downlink rate which determines the threshold setting to detect weak lightning optical pulses and enable optimal ground processing that will filter out the non-lightning events. The telemetry downlink is sized to also accommodate the background data, to aid in navigation and registration. Because GLM is an operational instrument, minimal latency (< 1 min) is important.

The instrument design for GLM is shown in Figure 3 below.

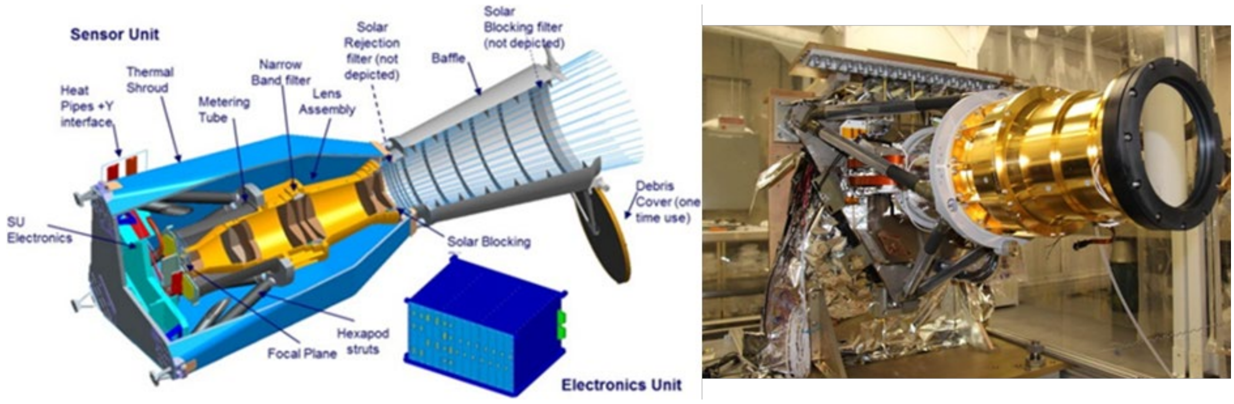

Figure 3: GLM instrument hosted on the GOES-R series satellites.

1.4.2 EUMETSAT Meteosat Third Generation Imager Satellites

The Meteosat Third Generation (MTG) mission will be a constellation of one sounding (MTG-S) and two imaging (MTG-I) satellites. The MTG-LI instrument hosted on the MTG-I satellites uses many of the same principles developed for GLM but has chosen a design that has four optical heads (see Figure 4 below) which each have detector arrays of more than 1.2 million pixels. These arrays are sampled every millisecond to measure the energy emitted in their respective fields of view. The EUMETSAT MTG-LI instruments will cover Europe and Africa as shown in Figure 4 below.

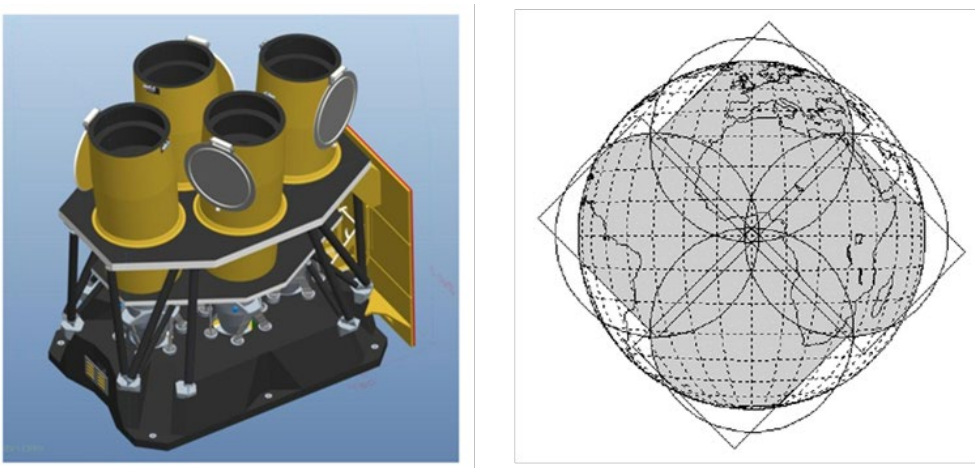

Figure 4: MTG-LI lightning optical head consists of four identical channels (left) to enable global coverage (right).

For each of the more than 4.8 million pixels, these signals are then compared to a reference image of Earth to determine if a lightning event has occurred. With this number of pixels and a sampling rate of 1 kHz the raw data rate of the instrument is significant, at several Gbit/s. This is then reduced by over a factor of 250 through logic in the front-end electronics followed by advanced signal processing in the state-of-the-art, single-board computer. The net result is an output from the instrument of around 30 Mbit/s, so that a filtered data set with more relevant data (false events need to be excluded) are transmitted to the ground segment for further analysis.

The MTG-LI's detectors are so sensitive that relatively weak lightning events can be detected, even in full daylight.[7] Despite a relatively simple instrument architecture, with no moving parts, the complexity of the Lightning Imager is in the narrowband filters, resolution[8] and speed of the detectors, and the subsequent image processing of the data on board, which automatically rejects most data that is not related to lightning. Additional filtering of data is also performed at the ground segment level. High detection efficiencies require that the false event rate is minimised, and that true events are not mistakenly removed by the on-board event processor.

1.4.3 Lightning Event Products

The standard level 2 gridded products are total lightning density, Flash Extent Density (FED), average flash area and total energy. The FED products are proving the most popular product with forecasters. Figure 5 shows examples of GLM Level 2 products.

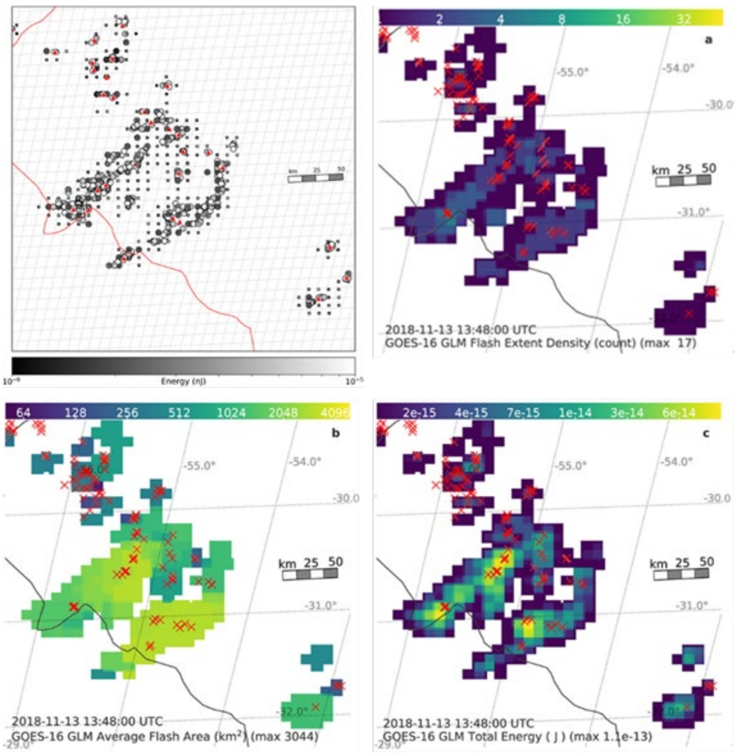

Figure 5: GLM Level 2 product example from the 13 November 2018 near the border of Uruguay and Brazil.

1.5 Scientific Applications

Geostationary lightning products are relatively new, and the applications are emerging and rapidly evolving. Five years of GLM data have highlighted many applications which are relevant to Australian

[7] https://www.eoportal.org/satellite-missions/meteosat-third-generation#mtg-spacewire-architecture

[8] C. Montcalm, A. Badeen, D. Burbidge, R. Bruce, G. Carlow, J. Dane, N. Firdawsi, G. E. Laframboise, A. M. Miles, J.-P. Noel, R. Rinfret, B. T. Sullivan, R. Bardazzi, S. Lorenzini, L. Giunti, "Solar rejection window and narrow band pass filters for the Meteosat third generation lighting imager," Proc. SPIE 11180, International Conference on Space Optics - ICSO 2018, 111804Z (12 July 2019); https://doi.org/10.1117/12.2536098

users. The main Australian applications are briefly described below (taken from Reference Document 10, the Bureau of Meteorology Draft Satellite Lightning Sensor Mission description and requirements document, dated 14 October 2022).

1. **Improving public safety and infrastructure,** through the provision of consistent, gridded, timely, and free public data. Information on lightning is useful for many industries from mining and energy companies to event organisers.
2. **Severe convection:** Integrating lightning data enables detecting, tracking, and monitoring of storm intensification leading to better prioritisation, earlier warnings and fewer false alarms. The data is particularly useful in regions with radar outages and areas with poor radar coverage.
3. **Improved aviation forecasting:** By observing the complete spatial footprint of total lightning flashes, GLM helps better characterize the lightning risk and increase confidence/certainty for airline flight and airport ramp operations, leading to enhanced safety and improved efficiency for commercial, military, and private aircraft. The information is particularly valuable over oceanic regions where observations of thunderstorm intensity are scarce. The Bureau already uses the GOES West GLM data in aviation hazard forecasting over the Pacific Ocean east of New Zealand.
4. **Calibration of models:** The satellite data can be used to verify forecasts and in the calibration of atmospheric and thunderstorm models.
5. **Fire weather monitoring:** Satellite data provides an additional lightning strike detection capability. Fire applications (such as the probabilistic detection of strikes with continuing current are enhanced when combined with ground-based lightning measurements and NWP. The information can be used for better characterisation of pyro cumulous events and post fire forensics.
6. **Lightning data assimilation for Numerical Weather Prediction (NWP)** is new however early results relating lightning to model state variables or column-maximum vertical updraft, have shown promising results, particularly for short range forecasts of radar reflectivity, accumulated precipitation, and lightning threat in convection-allowing models. Alternative methods have used convolutional neural networks (CNN) to create pseudo radar reflectivity from satellite data to assimilate. Data assimilation is particularly effective in radar sparse regions.
7. **Tropical Cyclone (TC) monitoring:** Satellite lightning mappers may help identify convective tendencies below cloud top in TCs which helps better diagnose TC structure and evolution and aids forecasts of TC intensity change including rapid intensification.
8. **Climate monitoring:** Lightning is correlated strongly with convection, trends in lightning can be used to track storm frequency and severity changes under climate change. Lightning discharges can affect climate by producing nitrogen oxides (strong greenhouse gas) in the upper atmosphere which are now a variable in WMO global climate change.
9. Additional application areas include bolide detection, volcanic eruptions, lightning chemistry, and lightning sensor calibration.

1.6 Complementarity with Ground Lightning Networks

Measurements of lightning, location and type (cloud to ground or intra cloud) from ground-based radiofrequency arrays are already a critical part of the Bureau's observation system. The satellite observations (total lightning) complement the ground-based observations by:

- Additional information on the duration of lightning, useful to identify lightning with continuing current, i.e., lightning more likely to ignite fires.
- Additional information on spatial extent, and energy of lightning flashes.
- Increased sensitivity to inter cloud lightning, which is often a precursor to cloud to ground lightning particularly in lightning ground network sparse regions and over the ocean.
- Consistent sensitivity of measurements over the observation area which enables simpler data assimilation.
- Providing an alternative measurement, no measurement system is perfect, satellite measurements are particularly valuable in radar sparse regions over land and over the ocean. The satellite data can provide information over regions where the commercial ground data is inaccessible or non-existent.
- Free and open data to enable increased academic collaboration and novel spinoffs.

There are already several applications, many of which are machine learning-based, such as Probsevere (NOAA)[9], that combine satellite lightning data, satellite imagery, ground-based lightning measurements, NWP, and other environmental data sets for applications such as early identification of severe storms, automated bushfire detection algorithms, lightning jumps, and prediction of hail, tornados or flash floods.

1.7 Meteorological Satellite Coverage Gaps

The Coordination Group on Meteorological Satellites[10] recommends the advancement of a new generation of geostationary satellites, including those with advanced lightning mapping.

The WMO Integrated Global Observing System identifies[11] "lightning imagers" alongside "high-resolution multi-spectral Vis/IR imagers" and "IR hyperspectral sounders" in their recommended "backbone" of the Geostationary Ring, and notes:

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[9] https://cimss.ssec.wisc.edu/severe_conv/pltg.html#:~:text=The%20ProbSevere%20LightningCast%20model%20uses,in%20the%20next%2060%20minutes

[10] C. Secretariat, CGMS_Secretariat, C. Secretariat, and CGMS_Secretariat, "CGMS HIGH LEVEL PRIORITY PLAN (HLPP) 2021 - 2025." CGMS, 2021. [Online]. Available: https://www.cgms-info.org/wp-content/uploads/2021/10/CGMS_HIGH_LEVEL_PRIORITY_PLAN.pdf

[11] WMO, "Vision for the WMO Integrated Global Observing System in 2040." WMO, 2019. [Online]. Available: https://library.wmo.int/doc_num.php?explnum_id=10278

"The global observing system for climate: implementation needs GCOS-200." World Meteorological Organization, 2016. [Online]. Available: https://library.wmo.int/doc_num.php?explnum_id=3417

There is no current geostationary lightning sensor planned for the Australian region, a significant gap in the global meteorological ecosystem.

Australia is currently 100% reliant on other nations for its meteorological satellite data. The Bureau depends very heavily on space-based meteorological intelligence to predict the weather, which in turn supports decision making, particularly during extreme weather events. A lightning sensor contribution to this measurement ecosystem would fill an identified gap for the Australian region and beyond, and would go some way towards the sharing of the global effort for space-based meteorological measurements.

2 Bureau Lightning Detector Mission Requirements

This section presents the programmatic, mission and user requirements of the Lightning Detector mission.

2.1 Mission Objective

Lightning is a factor in most severe weather events ranging from fires, flash floods, severe thunderstorms, tropical cyclones, and volcanic eruptions. Lightning, which can occur from cloud-to-cloud or cloud-to-ground, is a key sign of turbulence in the atmosphere, and can be used by forecasters and in numerical weather prediction to provide an early indicator of the development of severe weather events. The earlier lightning events can be detected, the sooner mitigative action can take place. The space-based lightning detector is particularly useful in radar-sparse regions and over the ocean.

Lightning is the predominant natural source of fire ignition, and lightning is difficult to predict. Identifying a fire early is key to prioritising fire resources and decreasing the response time to tackle the fire.

The lightning detector mission aims to provide high-quality observations of lightning to support the growing need for improved forecasting of severe weather events. Key Australian application areas for this mission are:

- Primary Application areas:
    - Severe Convection forecasting
    - Aviation hazard avoidance
    - Numerical Weather Prediction
    - Fire weather
    - Climate Monitoring
- Secondary Application areas:
    - Volcanic Ash Advisory Centre (VAAC)
    - Tropical Cyclone
    - Bolide detection
    - Atmospheric Chemistry.

A suitably located lightning detector satellite over the Australian region would complement ground lightning networks, as well as fill a current meteorological observational gap for lightning data in the region.

2.2 Programmatic requirements

Programmatic requirements are requirements that are not technical in nature. They relate to broader strategic and program-level constraints. Table 1 presents the Lightning Detector mission programmatic requirements as supplied by the customer.

Table 1: Bureau Lightning Detector Programmatic Requirements.

ID	Requirement
PRG-1	The mission shall deliver capability into the Australian space industry.
PRG-2	The mission shall store all data from the mission in Australia.
PRG-3	The mission shall consider the possibility of locating the Mission Operations Centre (MOC) and its staff in Australia or sharing MOC with an international partner.
PRG-4	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.
PRG-5	The mission imagery, products and services shall be made freely available.
PRG-6	The mission shall leverage existing National Space Program and Sub-Program governance, procurement strategy and ground segment wherever viable.
PRG-7	The costings should include design, build, and launch and commissioning of the payload.
PRG-8	The mission shall align with the Bureau strategy.
PRG-9	The mission shall undergo space segment Assembly, Integration and Testing in Australia as much as possible.
PRG-10	The mission shall consider ground segment requirements. The CDF should consider using an external provider to operate the ground segment component. The CDF report should include a costing of a commercial solution to the Ground Segment, including an option for 24/7 monitoring, if this is required.

2.3 Mission requirements

Mission requirements are understood in this report as the highest level of technical requirements. These requirements lay the basis of functional and performance requirements and inform the requirement derivation work conducted in later sections. Table 2 presents the Lightning Detector mission requirements as supplied by the customer. Unless specified the requirements are for the geostationary mission.

Table 2: Bureau Lightning Detector Mission Requirements.

ID	Requirement
MIS-1	The mission will add complementary information to the existing ground lightning detection systems.
MIS-2	The mission shall strengthen key partnerships with international satellite data providers, to ensure ongoing access to critical satellite data streams.
MIS-3	The mission shall archive and make freely available L0 to L2 data.
MIS-4	The mission shall provide data in Near Real time L2 products in less than 20 seconds.
MIS-5	The mission shall generate data and products which are commensurate with the measurements from existing geostationary lightning images.
MIS-6	Each space segment shall have an in-orbit operational life of no less than 5 years following commissioning.
MIS-7	Should a pathfinder pathway be appropriate the pathfinder space segment shall complete in-orbit commissioning within 4 years of the kick-off of the implementation phase.
MIS-8	The first geostationary space segment shall complete in-orbit commissioning within 8-12 years of the kick-off of the implementation phase.
MIS-9	The mission shall contribute to global efforts in mapping and monitoring lightning.
MIS-10	The mission shall have the capability to be programmed to change data acquisition depending on the filtering required to maximise the detection efficiency and minimise the false alarm rate.

2.4 End-user requirements

End-user requirements are understood in this report as the performance levels required for the mission to meet the end-users' scientific requirements.

These are specific end-user scientific, technical, and functional requirements to meet the scientific objectives of the mission, separated in three distinct applications:

- Requirements for Fire Weather.
- Requirements for Aviation, Severe convection, NWP, Tropical cyclones.
- Requirements for Climate Monitoring and Cross-Calibration (polar satellite, possible pathfinder instrument)

The requirement categories use the following EUMETSAT nomenclature, namely:

- "Threshold": Minimum required to meet user needs.
- "Breakthrough": Something that will make the instrument able to provide new services or a noticeable step up in performance.
- "Objective": The goal; this may or may not be attainable in conjunction with other requirements, but indicates what users really want.

Note that the International Meteorological community expects a good performance if not better than the existing geostationary instruments GLM and MTG-LI. While the performance of MTG-LI is yet to be demonstrated, the specifications are mentioned here in the expectation that it delivers improved nominal noise, sensitivity, and resolution. Results from MTG-LI (launched December 2022) in the next year will be important to monitor and add an element of uncertainty to the existing requirements at the present time.

From interviews and the user survey conducted by the Bureau, the two main areas of interest for the Bureau are severe convection and fire weather. The former is of interest to nowcasting and aviation forecasters. The breakthrough requirements for convective storms are nominally easier to meet than the fire requirements.

The fire weather requirements are more stringent than the severe convection and tropical cyclone requirements due to the geolocation accuracy demand from the fire community to enable fire emergency works to rapidly identify the location of the fire and deploy resources appropriately.

Fire weather requirements have not driven previous US and European mission requirements but are an emerging application area. The requirements are likely only realistically met through a combination of ground- and space-based instruments.

The other key point to note is that the lightning information is most valuable over radar-sparse regions and importantly over the ocean where the detection efficiency of the ground sensors decreases. The fire applications are of course over land. Consequently, if considering trade-offs regarding reduced coverage, these two main areas of application have competing requirements.

The following tables provide a summary of user requirements related to the specific areas of Fire Weather (Table 3), Severe Convection and Tropical Cyclones (Table 4), and Climate Monitoring and Cross-Calibration (Table 5) applications.

Table 3: Requirements for Fire Weather.

ID	Type	Requirement	Threshold	Breakthrough	Objective
CDF-R-LD-1	**Spatial**	Spatial resolution – GSD (km) at SSP [12]	As per MTG-LI	≤ 2	≤ 1
CDF-R-LD-2	**Temporal**	L1 (ms) L2 Data latency (minutes)	2 <5	2 <2	1 <1
CDF-R–LD-3	**Coverage**	Geographical Coverage/orbit	Australia	Himawari disk	Himawari disk
CDF-R–LD-4	**Other Instrument specs**	SNR, sensitivity, temporal resolution, location accuracy, spacecraft lifetime, product latency	Slightly better than GLM and MTG-LI	Better than GLM and MTG-LI	To meet temporal and spatial without loss of detection efficiency and sensitivity
CDF-R-LD-5	**Detection efficiency**	of total lightning	>80%	>90%	>90%
CDF-R-LD-6	**False Alarm Rate**	of total lightning	<5%	<5%	<5%

Table 4: Requirements for Aviation, Severe convection, NWP, Tropical cyclones.

ID	Type	Requirement	Threshold	Breakthrough	Objective
CDF-R-LD-7	**Spatial**	Spatial resolution – GSD (km) at SSP	As per MTG-LI	≤ 4	≤ 1
CDF-R-LD-8	**Temporal**	L1 (ms) L2 Data latency (minutes)	2 <5	2 <2	2 <1
CDF-R-LD-3	**Coverage**	Geographical Coverage/orbit	Australia	Himawari disk	Himawari disk
CDF-R-LD-4	**Other Instrument specs**	SNR, sensitivity, temporal resolution, location accuracy, space craft lifetime, product latency	Slightly better than GLM and MTG-LI	Better than GLM and MTG-LI	To meet temporal and spatial without loss of detection efficiency and sensitivity
CDF-R-LD-9	**Detection efficiency**	of total lightning	>70%	>80%	>90%
CDF-R-LD-6	**False Alarm Rate**	of total lightning	<5%	<5%	<5%

[12] Dr. Hugh Christian, LIS and GLM instrument specialist, recommends a GSD of no less than 3 km to ensure detector performance; anything below 3 km is likely to degrade the mission's data quality.

Table 5: Requirements for Climate Monitoring and Cross-Calibration (polar satellite, possible pathfinder instrument)

ID	Type	Requirement	Threshold	Breakthrough	Objective
CDF-R-LD-10	**Spatial**	Spatial resolution – GSD (km) [13]	3-6	3	3
CDF-R-LD-11	**Swath**	Swath Width (km)	600	>600	1000
CDF-R-LD-12	**Temporal**	L1 (ms) L2 Data latency	2 —	2 —	1 —
CDF-R-LD-13	**Coverage**	Geographical Coverage/orbit	±35°	±55°	global
CDF-R-LD-14	**Instrument specs**	SNR, sensitivity, temporal resolution	As per GLM	Better than GLM and MTG-LI	3km footprint and 2x sensitivity
CDF-R-LD-9	**Detection efficiency**	of total lightning	>70%	>80%	>90%
CDF-R-LD-6	**False Alarm Rate**	of total lightning	<5%	<5%	<5%

2.5 Key Design Considerations Derived from Requirements

The following list represents the key requirement drivers to be considered in the design of a Lightning Detector Mission to meet operational needs as well as budget constraints. This section identifies the issues that need to be taken into account as part of the design process, but does not provide explicit answers:

- **Geographical Coverage:** Based on the preceding requirements and considering the primary application areas detailed in Section 2.1, the ideal orbit for this mission is geostationary (GEO), providing continuous full earth disk coverage and extremely low data latency as part of a wider global network of satellite and ground-based detectors. This also addresses the currently identified observational data gap in global satellite coverage over the Asia-Pacific hemisphere.
- **Detector Performance:** Continual reduction in spatial resolution is not required nor desirable, with current instrument performances of 3 km pixel resolution being achievable and adequate for the mission[13]. Instrument development should focus on optimising detector sensitivity and SNR whilst ensuring minimal false event detection. Note that a LEO pathfinder mission will absolutely require solar blocking filters; as the sunlight reflecting from cloud tops is very wideband and must be high-pass and low-pass filtered to within the range of the narrowband filter fringe patterns.
- **Data Acquisition:** On-board data acquisition needs to be configurable to achieve suitably low false event detection whilst meeting data latency (timeliness) and downlink bandwidth

[13] Dr. Hugh Christian, LIS and GLM instrument specialist, advises that in this instance a GSD of 3 km would provide a new research baseline that does not presently exist; however, anything smaller than 3 km will very likely degrade performance.

(data volume) constraints. Low data latency is a key driver, with less than one minute being achievable from a geostationary platform.

- **Australian Contributions to the Global Community:** The gap in lightning data coverage over the Australian region, as well as the Australian and global scientific data applications, provides an opportunity for Australia to provide key scientific data to the global community whilst developing an Australian capability in satellite and payload development, integration, testing and operations.
- **Pathfinder Mission:** Regarding a possible pathfinder mission for proof-of-concept, Australian industry development, and/or GEO mission development risk mitigation purposes, a low-earth-orbit (LEO) pathfinder satellite concept will also be explored in this report. This is similar to the development pathway followed by the US in developing their lightning detector capability.

Based on these key areas derived from the Bureau's programmatic, mission and user requirements inputs, this report addresses key aspects related to the development of an Australian GEO lightning detector capability (Section 4) as well as a potential LEO pathfinder capability (Section 5) towards that objective.

3 General Space Mission Design Considerations

3.1 General Space Mission Segment Concepts

The three basic elements of every space mission are depicted in Figure 6:

- Space Segment.
- Mission Operations Segment.
- Payload Data Processing Ground Segment.

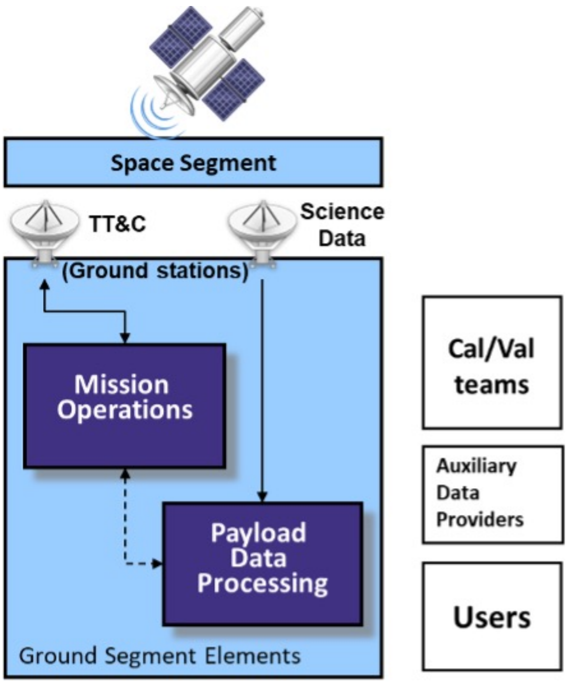

Figure 6: Typical subsystems of a satellite system.

Briefly, the various functions of these elements in Figure 6 are as follows:

a. Space Segment: consisting of the satellite platform, or bus, hosting the mission payload(s). The satellite bus provides all essential functions to allow the satellite to maintain orbital control, generate and store power, manage overall attitude, power, and thermal control, perform all on-board-computer and data-handling functions, manage space-to-ground communications for telemetry, tracking and commanding (TT&C) as well as manage all payload (science) data acquisition, storage, and downlinking.

b. Mission Operations: consists of ground-based systems required to manage flight operations for the satellite system, including orbit determination and control, telemetry monitoring and processing, mission planning and operations commanding, on-board software updates and system maintenance activities, TT&C ground station operations, and any other activities related to satellite flight operations, health, and safety.

c. Payload Data Processing: primarily related to processing and utilisation of the on-board data acquired by the payload(s). This function is often quite separate from the flight control activities; however, there is often data exchanged between these elements required to ensure necessary inputs for mission planning and sometimes updates/reconfigurations of the payload may be provided by the instrument or scientific experts within the data production area. Similarly, data processing may require transfer of telemetry or flight dynamics information from the flight operations segment to optimise data product generation (essential housekeeping telemetry required for data production is often packaged within the payload data stream). This part of the ground segment also includes external elements such a specialist payload calibration / validation teams, auxiliary data providers needed for product generation, and the wider science data user community.

3.2 Space Segment Concepts

Figure 7 provides an overview of the typical subsystems of a satellite system:

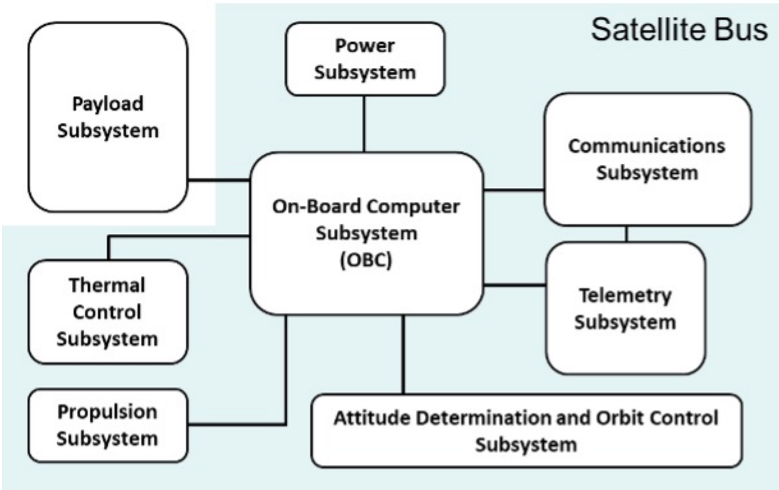

Figure 7: Typical subsystem elements comprising a satellite system.

The various functions are as follows:

d. Satellite Bus: the platform or structure that comprises the distinct types of subsystems required to operate a satellite in orbit:

   a. On-Board Computer (OBC) Subsystem – the central nervous system for the satellite, providing all on-board computing functions, monitoring, data handling and control / commanding functions for the various other subsystems and payloads.

   b. Communications Subsystem – to provide space-to-ground communications data links for TT&C functions as well as payload data downlinking (often requiring higher frequency bands than TT&C due to data bandwidth requirements).

   c. Telemetry Subsystem – may be part of the OBC; this is required to monitor onboard systems and generate telemetry data for downlinking to ground monitoring and control.
   d. Power Subsystem – to provide all necessary power to support the satellite and payload functions; primary power is derived from solar cells, which feed the various subsystems and charge on-board batteries that provide a backup power source during launch and early orbit acquisition phases and eclipses.
   e. Thermal Control Subsystem – required to manage the thermal environment for the payload and satellite subsystems, providing heating/cooling and dissipating excess heat via radiators, as required.
   f. Propulsion Subsystem – to allow the satellite to be manoeuvred to attain and maintain its desired orbital location.
   g. Attitude Determination and Orbit Control Subsystem (ADCS or AOCS) – to provide stabilisation for the satellite and to maintain desired orientation and orbital position.

e. Payload(s): a variety of subsystems integrated into the satellite platform to achieve the defined mission objectives (e.g., scientific observations, telecommunications, experiments).

4 Considerations for a GEO Satellite Lightning Detector Mission

4.1 Overview

The Bureau mission requirements are detailed in the Lightning Detector pre-CDF report (refer to Reference Document 10 from the list on page 18), the key points of which are summarised in section 2 of this report. The programmatic and mission requirements, as well as the primary data applications specified, indicates a GEO-based platform with low data latency and continuous full earth-disk coverage to be the best solution for operational lightning data observations. This is consistent with existing operational lightning detector missions currently being flown over the American and the European/African hemispheres on the NOAA GOES satellites and the recently launched EUMETSAT MTG-I mission, respectively.

Such a GEO solution may challenge the current technical capabilities in Australia. This was highlighted by the various industry assessments conducted by the ANCDF team in researching this report, and supported further by the FrontierSI Lightning Detector Mission Australian Workforce Capability Assessment (see Reference Document 11 from the list on page 18). For this reason, a LEO pathfinder mission is also discussed in this report (see section 5) to provide an option for Australian technology capability development and possible risk mitigation, leading to a future Australian GEO mission.

Whether implemented in GEO or LEO, lightning observations would help fill the current observational gap as well as augmenting existing global lightning measurements. In particular, over the Australian region of interest there are currently no observations from GEO, and the current LEO measurements from the NASA Lightning Image Sensor (LIS) deployed on-board the International Space Station (ISS) will be decommissioned in 2024.

Based on the Bureau's primary lightning detector mission needs, a GEO mission is considered the goal of any development programme, in order to meet the primary scientific objectives. Possible pathways to a GEO mission are discussed in the subsequent sections of this report, either implemented as a first mission or as a follow-on mission to a LEO pathfinder. As discussed in section 2.4, the scientific applications of lightning data from a LEO mission addresses a different set of user needs, so the benefit of such a mission would also need to be assessed on the basis of possible advances to be made in those areas.

4.2 Comparison of GEO and LEO Missions

Several factors differentiate a GEO lightning detector mission from a LEO pathfinder.

- GEO satellites:
    - Characteristics: 35,786 km altitude, in a "fixed" position over Earth due to synchronisation with Earth's rotation rate.
    - Advantages:
        - Meets the Bureau requirements for near real time forecasting of severe weather.
        - Fixed positioning ensures that satellite observations and transmissions remain consistent and focused on a particular region of the planet.
        - A GEO network of like satellites would ensure almost global coverage (limited at polar regions due to earth curvature).
    - Disadvantages:
        - A single satellite will not provide global coverage (2-3 GEO satellites needed to cover all hemispheres).
        - Cost and technical challenges to develop and launch a satellite to GEO altitude (radiation hardening requirements, generally larger design size/mass due to fuel, power, thermal requirements, etc.).
        - Dedicated ground station capability to ensure low-latency science data downlink and operational monitoring and control of the satellite.
- LEO satellites:
    - Characteristics: Altitude of 200 km to 2,000 km, global coverage is possible (within defined orbital repeat cycle constraints).
    - Advantages:
        - Meets the Bureau requirements for climate monitoring of lightning.
        - Global coverage (within constraints of the defined repeat cycle duration).
        - Can be tailored to unique mission observational requirements (e.g. include polar observations (full global), low- or mid-latitude inclination, sun-synchronous for consistent local observation times).
        - Low radiation environment and lower power needs for communications.
        - Depending on sensors, better resolution and lower noise issues with data acquisition.
        - Generally lower cost and complexity with getting a satellite to LEO.
    - Disadvantages:
        - Global coverage takes time, so regional events will be missed when not in view.

- Data latency (from sensing time to downlink / processing on ground).
- On-board storage and computing essential to manage satellite operations and data during extended periods out of contact with ground stations.

4.3 Possible Pathways to an Australian GEO Mission

An Australian developed GEO mission may be too challenging in terms of technology and capabilities, so other pathways towards an eventual GEO mission could be considered. Figure 8 depicts various pathways to an eventual fully Australian GEO mission (although a hosted GEO payload with suitable international partners may also be an acceptable end-goal).

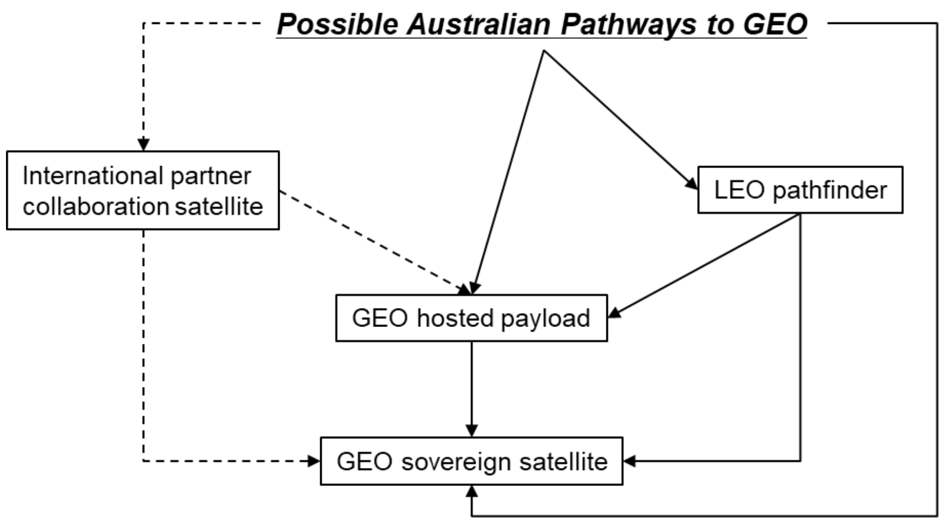

Figure 8: Possible pathways to an Australian GEO capability.

Note that one option for an initial GEO mission would be a GEO lightning sensor payload on a GEO communications satellite (GEO hosted payload in Figure 8). These satellites often have excess mass and power margins that could be exploited because their mission does not require a full load of transponders.

Opting for a simpler, lower cost, lower risk LEO pathfinder mission may help development of critical Australian industry capability to meet more challenging space mission projects in the future, as well as specifically providing some degree of risk assessment and mitigation towards an eventual GEO development. This can be seen from the development pathway followed by the US in their lightning sensor missions, with a LEO proof of concept instrument eventually leading to development of an operational sensor on a series of GEO satellites.

A comparison of risks and requirements was performed to assess what level of upscaling might be needed to go from a LEO pathfinder development to a GEO capability, what risk mitigation might be accomplished in first developing a LEO capability, and what level of overall benefit might be possible in developing an interim LEO capability prior to embarking on a GEO payload or mission.

An initial assessment was made regarding key risk areas for the GEO concept, with possible mitigation benefits that a LEO pathfinder mission might offer being identified as follows:

- **Risk:** Program exceeds budget/schedule due to complexity of a GEO payload:
  - The LEO mission would build Australian expertise and experience in designing lightning mapper instruments.
  - The LEO mission could be designed, built, tested, and commissioned within 3 years.
- **Risk:** Australian industry's participation to the GEO mission is too small:
  - The LEO mission would involve, leverage, and build the Australian industry as much as possible within schedule.
  - The LEO mission will identify areas requiring external procurement (e.g. Narrow-band optical filters).
- **Risk:** Australian testing / calibration facilities / personnel cannot support testing / calibration requirements:
  - The LEO mission would involve and leverage Australian AIT facilities and personnel as much as possible and identify areas requiring external procurement.
  - The LEO mission will develop and establish procedures and expertise for lightning mapper assembly, integration and testing to be used for the GEO mission.
- **Risk:** Data quality/quantity insufficient – e.g. False Event Rate found to be too high late in program due to software/hardware design:
  - The LEO mission would fly a lightning detector instrument that features the key relevant (risk-wise) design aspects (hardware, software, and build) of the final GEO instrument.
  - The LEO mission would develop a ground processing infrastructure (algorithms and processing pipeline) that is as similar as possible to that of the GEO mission.
  - The LEO mission could also fly a configurable payload processing capability to allow experimentation with on-board processing to allow analysis and improvement in the overall on-board processing functions for the final GEO mission.

Based on this initial risk assessment, the payload expertise available during the study, and the corresponding LEO pathfinder mission analysis provided in section 5, the following are identified as likely modifications needed to progress along the pathway from a LEO design to a GEO mission:

Design items to maintain from LEO mission to GEO mission:

- Critical elements:
  - Same sensor technology (given current technology, likely CMOS);
  - Front-end electronics should be the same;
  - Back-end electronics should be the same (architecture and specifications);
  - Same narrowband-filter technology;
  - Same onboard and ground-segment software/algorithms;

        - Same lens materials (different lens specifications due to altitude and field-of-view – see below).
    - Less-critical items:
        - Baffle still needed in LEO to prevent stray-light;
        - Same materials for overall structure;
        - Passive thermal management design (heat pipes, radiators, etc.).

Design items requiring change from LEO mission to GEO:

- Lens specifications and number of elements can be different, but still radiation-resistant;
- LEO sensor can have fewer pixels for same ground resolution and field-of-view;
- Front-End Electronics (FEE) size and power may need to change;
- LEO does not have to be rigorously radiation-qualified, but GEO does;
- Narrowband filter can be physically smaller for LEO;
- Baffle size increased for GEO.

Given the main application of severe weather forecasting as well as heritage lightning detector missions and current operational developments, a GEO capability best meets the Bureau's operational requirements. To build Australian industry capability, a logical pathway towards building that capability would be a LEO pathfinder, which will be discussed next in section 5. Implementation issues related to an eventual GEO mission will then be discussed after that in section 6.

The Bureau could also explore opportunities for international collaboration on lightning sensor development, in particular with countries that have developed or are currently developing lightning sensor capabilities.

5 LEO Pathfinder Satellite Lightning Detector Mission

5.1 Overview

This section discusses the LEO pathfinder precursor mission to a possible GEO lightning detector mission.

Consistent with the previous sections, both LEO and GEO lightning detector missions would contribute to improving gaps in global lightning datasets due to the lack of GEO lightning observations over the Asia Pacific region as well as the planned 2024 decommissioning of the NASA Lightning Image Sensor (LIS) currently on board the International Space Station (ISS).

Choosing a LEO pathfinder as a precursor to a GEO lightning detector mission also presents an opportunity to advance other areas of lightning research and develop an Australian-developed capability in lightning sensor technology and sophisticated algorithm design that is directly transferable to GEO sensors. Building such heritage will aid in establishing a suitable and risk-assured pathway to a larger GEO mission.

Additionally, it is reasonable to expect that a LEO pathfinder is cheaper than a full GEO lightning detector mission. Resources that would otherwise be spent towards a potentially highly costly Commercial-off-the-Shelf (COTS) GEO platform could instead fund Australian lightning detector payload development and heritage towards future GEO-based payload or satellite capabilities.

Implementation of the space segment and other mission elements is discussed in section 7.

5.2 LEO Pathfinder Mission Considerations

As discussed in Section 2, mission scope objectives for a LEO pathfinder mission hosting a lightning detector would differ from the primary objectives of a GEO sensor, including aspects such as:

- Reduced payload size, mass, and power.
- Increased field-of-view and lens design to accommodate lower altitude.
- Identification and focus on risk mitigation towards an eventual GEO mission.
- Possible proof of concept development for new or innovative payload designs, data quality improvements, processing algorithms, or other aspects for eventual GEO development.
- Ramp-up of Australian industry towards increased capability for design, development, integration, testing and/or operations for a GEO mission.
- The LEO mission would provide continuity in lightning climate observations as the current polar orbiting lightning mission[14] will soon be decommissioned.

[14] https://www.eoportal.org/satellite-missions/iss-lis

- Extending global lightning observations to include polar regions, as well as improved sensor performance (e.g. 3 km sensor resolution, improved SNR and sensitivity), would provide a new scientific research baseline that does not presently exist.

5.3 LEO Concept of Operations

This section presents a high-level concept of operations (ConOps) of the proposed satellite. This ConOps was developed jointly by the ANCDF team and the customer team during the study week. It describes when and how the spacecraft performs certain tasks or behaves in specific scenarios. This information, in turn, informs the design of the mission.

The spacecraft hosts a lightning imager as its primary payload. The pathfinder LEO mission is envisaged as a single spacecraft intending to act as an interim step towards development of an operational GEO payload and mission.

The spacecraft will provide near-global data collection for lightning observations (inclined orbits will not provide polar coverage). The mission will fly a primary lightning detector payload in an inclined or polar orbit at an altitude of approximately 550 km. The spacecraft will maintain a constant attitude for the mission duration, with the lightning detector and payload-radio antenna nadir-facing. On-board propulsion will not be available, nor would it be required, as the proposed platform is an off-the-shelf 12U CubeSat solution suitable to support the payload requirements (mass, volume, power, pointing, data downlink and so on). Payload data will be transmitted to commercial ground stations and processed by a commercial data processing and archiving system, with higher-level data products being transferred to the Bureau.

Data will be acquired over all orbits (i.e. no duty-cycle limitation), and downlinked on a per-orbit basis. Additional downlinking may be available over the Australian regions via direct broadcast, significantly reducing data latency.

5.4 LEO Pathfinder Spacecraft Design

5.4.1 LEO Payload Specifications

The LEO payload user specifications were defined based on the information provided in the Bureau mission requirements document (see Reference Document 10 in the list on page 18 of this report) and the discussions during the study. A summary of the requirements and assumptions made is presented in Table 6:

Table 6: LEO lightning detector pathfinder specification.

ID*	Requirement	Threshold	Breakthrough	Objective	Assumed
CDF-S-LD-19	Spatial resolution – GSD (km)	3-6	3	3	**3**
CDF-S-LD-20	Swath Width (km)	600	> 600	1000	**Min. 600**
CDF-S-LD-21	L1 (ms) L2 Data latency	2 —	2 —	1 —	**2** **—**
CDF-S-LD-22	Geographical Coverage (Latitude Range)	±35°	±55°	Full Globe	**±55°**
CDF-S-LD-23	SNR, sensitivity, temporal resolution	As per GLM	As per MTG-LI	>MTG-LI	**Not evaluated**
CDF-S-LD-24	Detection efficiency of total lightning	>70%	>80%	>90%	**Adjustable threshold**
CDF-S-LD-25	False Alarm Rate	<5%	<5%	<5%	**<5%**

***The specification ID refers to the column titled "Assumed" above.**

5.4.2 LEO Payload Design

This section discusses a possible implementation of the LEO Lightning Detector payload. It is to be noted that this is a concept proposal only. A detailed payload design and optimisation is out of the scope of this study and should be undertaken in future work.

The content in this section was written with inputs from Dr Hugh Christian from the University of Alabama in Huntsville. Dr Christian was the Principal Investigator of the Lightning Imager Sensor (LIS) LEO instrument and the Geostationary Lightning Mapper (GLM) instrument.

5.4.3 High-level Payload Description

A space-borne lightning detector is conceptually a relatively simple instrument. It consists of a high-speed imaging telescope coupled to a narrowband filter associated with an onboard processing unit to filter and reduce the video feed data volume. A typical LEO lightning detector comprises:

- **Optics:** A wide-angle lens assembly to focus light on the focal plane array along with a narrow band filter around the oxygen band of interest (777.4 nm). Even though a LEO instrument will never directly view the sun operationally, a solar blocking filter is still required due to the intensity of sunlight reflecting of cloud cover at such low altitudes.
- **Focal plane array:** A high-speed detector (about 500 frames per second). Traditionally Charge-Coupled Devices (CCD) sensors, it has been suggested during the study that the technology has now moved towards CMOS sensors.

- **Chassis:** A mechanical assembly which comprises isostatic mounts for the optical assembly and a deployable aperture cover (one-time use to protect from debris during launch and commissioning).
- **Electronics unit:** Comprises a payload management module (housekeeping telemetry and thermal control), data storage and interfacing electronics, along with a real-time event processor that processes the raw pixel data into a signal showing the detected events (with a variable detection threshold).

A possible approach for a LEO lightning sensor is to implement a flight-proven design inspired by heritage instruments such as LIS. This would allow for a cheaper, shorter and more risk-controlled payload development.

More novel architectures and technologies could be explored in future work. For example, the payload could include new sensor technologies such as event-based sensors[15] or an increased onboard processing capability and reliance. However, these approaches have not been considered in this study.

Christian and Blakeslee proposed in 2011 an evolved version of the LIS, called the Global Lightning Imaging Sensor (GLIS), which was envisioned to be flown in a 66-satellite LEO constellation[16] (concept proposed prior to the approval of GLM). GLIS builds upon and updates the LIS design to propose a sub-million AUD instrument that, when flown in a constellation, would provide global coverage (including poles) in the continuity of LIS and GLM.

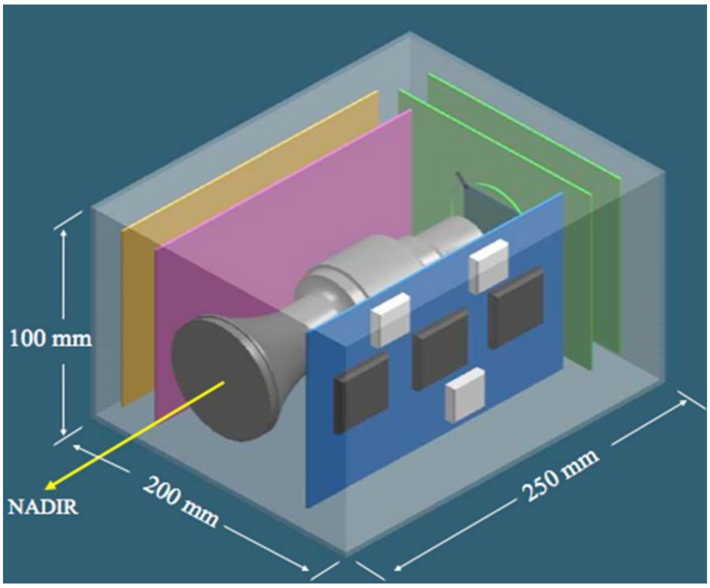

Figure 9. GLIS instrument concept (Credit: Dr H. Christian and Dr R. Blakeslee)

[15] https://www.frontiersin.org/articles/10.3389/fnins.2018.01047/full

[16] Observing Lightning from Space. Hugh J. Christian. The University of Alabama in Huntsville. Presentation provided to UNSW Canberra Space by Dr Christian.

Such an instrument could be onboarded on a constellation of CubeSats, further reducing the cost of the mission given the range of currently available platforms. The proposed specifications of GLIS are presented in Table 7.

Table 7: Proposed specification for GLIS (Christian and Blakeslee).

ID	Specification	Value
CDF-S-LD-26	Mass (kg)	< 10
CDF-S-LD-27	Volume	< 3U
CDF-S-LD-28	Power (W)	< 12
CDF-S-LD-29	Data rate (kbps)	< 50

5.4.4 Payload Technical Specifications

The payload's technical specifications such as mass, volume, power, and data rate can be estimated for the proposed lightning detector instrument. Estimation methods typically involve calculations and analogies with past instruments.

Figure 10 proposes a qualitative representation of the first-order relationships (direct correlations) between several design parameters and requirements, with only key high-level elements represented. Green arrows represent co-increasing relationships whilst orange arrows represent the relationships where increasing one parameter decreases the other, and vice versa.

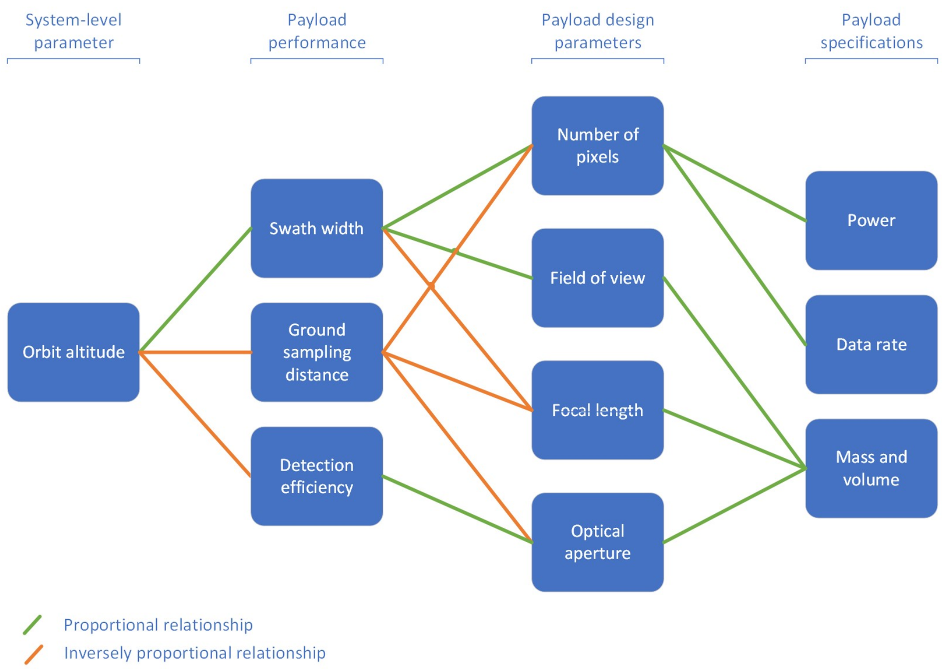

Figure 10: Relationship between payload design parameters, specifications, and requirements.

The diagram presented above should be interpreted as a mapping of the relationships between pairs of parameters, all other parameters being equal while the chosen pair is modified.

It should be noted that the orbit altitude choice would impact all these parameters. In fact, for a given instrument a higher orbit altitude implies a larger swath width but a degraded resolution and flash detection efficiency.

Using the “Assumed” user requirements presented above in Table 6 and a 550-600 km orbital altitude (discussed in section 5.5.1, this is the maximum altitude to ensure de-orbit requirements are met with no propulsion and to maximise the instrument view and performance), initial payload specifications were calculated and are shown below in Table 8:

Table 8: Preliminary lightning detector payload specifications

ID	Specification	Value	Notes
CDF-S-LD-30	F/#	1.46	Assumption.
CDF-S-LD-31	Pixel pitch (µm)	24	Assumption.
CDF-S-LD-32	Optical aperture (mm)	3.3	Derived from F/# and focal length.
CDF-S-LD-33	Focal length (mm)	4.8	Derived from orbit altitude, GSD, and pixel pitch.
CDF-S-LD-34	Half field of view (deg)	28.30	Derived using orbit altitude and swath width.
CDF-S-LD-35	Instantaneous field of view (deg)	0.41	Derived from orbit altitude GSD.

A finer GSD or a larger swath width that the assumptions presented in Table 6 could be accommodated with a larger or more complex optical system. However, it is to be noted that improving on these performance parameters will have implications on the total payload mass, volume, power, and data rate envelope. Determining the magnitude of these implications require a sensitivity analysis that can only be derived from a more detailed payload design that is out of the scope of this study.

The payload output data was estimated based on existing missions. The payload output data rate is mostly determined by the event detection rate of the instrument, including false detections. MTG-LI detects 100k events per second. It was proposed to scale this up to 700k events per second, to increase the obtainable detection efficiency (after additional processing on the ground). This event rate was suggested by Dr Hugh Christian as being a significant step-up in lightning detection capability. The 700k events per second payload event rate was then downscaled by the ratio of viewable surface area of MTG-LI to that of the proposed LEO pathfinder. Finally, each event was assumed to require 64 bits of data, based on GOES-R GLM[17], to obtain 100 kbps (rounded up from the calculated value of 98.31 kbps).

It should be noted that 100 kbps is an average value; the peak data rate would be expected to exceed this number substantially while overflying storm activity. However, the data volumes in question and the modest latency requirement (see CDF-R-LD-27 in Table 15 of section 5.7.1

[17] See Table 4-2 of https:/www.goes-r.gov/downloads/resources/documents/GOES-RSeriesDataBook.pdf

discussing the communications requirements) mean that a modest amount of on-board storage will allow all data to be downlinked while using 100 kbps as a design parameter.

Table 9 provides an initial lightning detector payload sizing based on the above analysis results. Note that these specifications are preliminary in nature and do not result from a payload design exercise. Rather, they should be seen as conservative upper bounds serving the design of the broader mission proposed in this report, and particularly the selection of the platform that will support it. Section 5.4.5 discusses considerations and options for the selection of a platform.

Table 9: Preliminary LEO payload sizing.

ID	Specification	GLIS Value	LD Value	Notes for LD
CDF-S-LD-36*	Mass (kg)	< 10	10	Conservative upper bound based on the GLIS design.
CDF-S-LD-37*	Volume	< 3U	4U	Conservative upper bound based on UNSW Canberra Space's experience with the M2 mission.
CDF-S-LD-38*	Power (W)	< 12	12	Conservative upper bound based on the GLIS design.
CDF-S-LD-39	Data rate, mean (kbps)	< 50	100	See above.
CDF-S-LD-40*	Pointing knowledge (deg)	*Unspecified*	0.2	Half a pixel, as per LIS requirement.

***Calculated using the specifications as listed in column titled "LD Value" in the above table.**

5.4.5 LEO Platform Considerations

Given the relatively modest payload specifications for the LEO pathfinder, a viable, affordable, and effective solution to procure this pathfinder mission is through sourcing an off-the-shelf platform. The payload specifications could be readily accommodated on a 12U CubeSat platform. Off-the-shelf CubeSat platforms are readily available from several suppliers internationally that can meet the size, volume, mass, power and data requirements of the defined lightning detector payload. Australian options also exist and will soon gain flight heritage.

Advantages of procuring an off-the-shelf platform include:

- Significantly reduced schedule (potentially down to 2 years) and schedule risks due to flight heritage of the platform.
- Significantly reduced cost, as there would only be limited engineering work on the platform.
- Ability of the program to focus on the payload development in view of the GEO mission.

The following table provides an overview of currently available options for a COTS CubeSat able to support the specified LEO payload:

Table 10: Examples of suitable spacecraft platform providers for a LEO pathfinder mission.

Australian platforms	International platforms
Gilmour Space *Headquarters: Gold Coast, Queensland* *COTS Platform: G-SAT* *Platform launch heritage: Scheduled 2024*	**Blue Canyon LLC** *Headquarters:* Colorado, USA COTS *Platform: XB Satellite range* *Platform launch heritage: From 2018*
Inovor *Headquarters: Adelaide, South Australia* *COTS Platform: Apogee Nanosatellite* *Platform launch heritage: Scheduled 2023-2024*	**Terran Orbital (previously Tyvak)** *Headquarters: Florida, USA* *Platform: TRESTLES range and Mavericks Microsat* *Platform launch heritage: From 2018*
Skykraft *Headquarters: Canberra, ACT* *COTS Platform: Block-II Satellite* *Platform launch heritage: Launched 2023*	**AAC ClydeSpace (and all subsidiaries)** *Headquarters: Uppsala, Sweden* *COTS Platforms: EPIC LINK and EPIC VIEW* *Platform launch heritage: From 2023*
	Endurosat *Headquarters: Sofia, Bulgaria* *COTS Platform: Various* *Platform launch heritage: From 2018*
	Nanoavionics *Headquarters: Vilnius, Lithuania* *COTS Platform: Nano and Micro satellite buses* *Platform launch heritage: From 2019*

5.5 LEO Pathfinder Orbit

The characteristics of LEOs are invariably different to GEOs. Accordingly, a LEO Lightning Detector pathfinder mission presents an opportunity to collect lightning observation data that is distinct from, and complementary to, that obtained from a GEO mission. Moreover, there are numerous families of orbits within the LEO altitude range that offer different combinations of desirable properties.

The intent of this section is not to prescribe a single candidate orbit that best meets the Bureau's requirements. Instead, this section will outline the various types of LEO orbits available for selection and discuss their relative merits. It is necessary, however, to select a baseline orbit to perform the concurrent engineering analysis presented in this report. The selection of a baseline orbit in this context is not prescriptive.

5.5.1 Derived LEO orbit requirements

This section presents a set of derived orbit requirements specific to a LEO Lightning Detector pathfinder mission. The Bureau's desire for an eventual GEO platform underlies the programmatic and mission requirements summarised in Section 2. Therefore, this section presents some optional requirements that can constrain the selection of a LEO but are not explicitly addressed in the Bureau mission requirements document (see Reference Document 10 on page 18 of this report). Table 11 below presents the derived orbit requirements:

Table 11: LD LEO pathfinder derived orbit requirements.

ID	Derived Orbit Requirement	Driving Requirements
CDF-R-LD-21	The orbit shall facilitate vacation of the LEO protected region within 25 years after the end of the nominal mission[18].	PRG-4, relating to the responsible use of space.
CDF-R-LD-22	The orbit shall enable lightning observations over the entire Australian continent and its coastal waters with no gaps.	MIS-1
CDF-R-LD-23	The orbit shall enable lightning observations over regions of the Earth with significant lightning activity.	MIS-5, MIS-9
CDF-R-LD-24 (optional)	The orbit shall enable lightning observations over the entire globe. *Rationale: no lightning detector has provided global coverage since the OTD sensor on Microlab-1, which ceased operations in March 2000[19].*	Objective user requirements for climate monitoring and cross-calibration, Table 5.
CDF-R-LD-25 (optional)	The orbit shall enable lightning observations above fixed locations on the Earth with consistent mean solar time. *Rationale: continental lightning exhibits a strong diurnal variation; continental lightning activity peaks in the late afternoon, between 15:00 and 17:00[20]. The LD LEO pathfinder orbit could fix the local time of observations to one of peak lightning activity.*	

Note: the optional orbit requirement, CDF-R-LD-24, implicitly meets the requirement CDF-R-LD-23.

End-of-life de-orbit requirements constrain the altitude range for any orbit selected for the LD LEO pathfinder. Atmospheric drag can ensure the passive de-orbit of typical small satellites at altitudes less than approximately 600 km[21]. Meanwhile, altitudes below 550 km are subject to greater atmospheric drag, particularly during periods of heightened solar activity, and consequently, require active propulsion for orbit maintenance. Therefore, the orbit altitude is constrained to between 550 km and approximately 600 km to satisfy CDF-R-LD-21.

[18] Inter-Agency Space Debris Coordination Committee (IADC). (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

[19] Christian, H., Blakeslee, R., Bocippio, D., Boeck, W., Buechler, D., Driscoll, K., Goodman, S., Hall, J., Koshak, W., Mach, D., Stewart, M. (2003, January). Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. Journal of Geophysical Research, 108(D1). https://doi.org/10.1029/2002jd002347

[20] Blakeslee, R., Mach, D., Bateman, M., Bailey, J. (2014). Seasonal variations in the lightning diurnal cycle and implications for the global electric circuit. *Atmospheric Research, 135–136,* 228–243. https://doi.org/10.1016/j.atmosres.2012.09.023

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

5.5.2 Discussion of LEO orbits

The LD LEO pathfinder requirements outlined in Table 11 do not impose many constraints on orbit selection. Therefore, this section will outline the categories of LEO orbits available for selection. The orbit categories are:

- Mid-inclination orbits (typically with inclinations between 35 degrees and 60 degrees),
- Polar orbits (inclinations between 60 degrees and 120 degrees), and
- Sun-Synchronous Orbits (SSOs); a subset of polar orbits.

Mid-Inclination Orbits:

The inclination of a satellite's orbit with respect to the Earth's equatorial plane constrains the range of latitudes the spacecraft can overfly. The relationship is simple: the orbit's inclination is equal to the maximum latitude attained by the spacecraft. For example, the ISS travels in an orbit with 51.6° inclination, and consequently its footprint lies between +/-51.6° latitude.

Research indicates that 78% of global lightning production occurs between +/-30° latitude[22], and therefore any orbit with inclination greater than 30° may satisfy CDF-R-LD-23. However, CDF-R-LD-22 necessitates coverage of the Australian continent, which extends to approximately 43°S. Given the LD sensor's 600 km swath width, CDF-R-LD-22 imposes a minimum inclination bound of approximately 41°.

Past LEO lightning imagers that have flown in mid-inclination orbits are:

- Lightning Imaging Sensor (LIS) on the TRMM satellite: 35° inclination[23].
- Lightning Imaging Sensor (LIS) on the ISS: 51.6° inclination[24].

Polar Orbits:

Spacecraft in polar orbits pass over the polar regions in every orbit due to their higher inclination. The relationship between inclination and latitude is identical to mid-inclined orbits. Therefore, selecting a polar orbit allows the LD pathfinder to satisfy CDF-R-LD-24 by including all latitudes up to the polar regions. The Optical Transient Detector (OTD) lightning detection instrument flew on the MicroLab-1 satellite in a 70° inclination polar orbit[25].

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[22] Christian, H., Blakeslee, R., Bocippio, D., Boeck, W., Buechler, D., Driscoll, K., Goodman, S., Hall, J., Koshak, W., Mach, D., Stewart, M. (2003, January). Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. Journal of Geophysical Research, 108(D1). https://doi.org/10.1029/2002jd002347

[23] Christian, H., Blakeslee, R., Goodman, S., Mach, D., Stewart, M., Buechler, D., Koshak, W., Hall, J., Boeck, W., Driscoll, K., Bocippio, D. (1999, June). The lightning imaging sensor. In NASA conference publication (pp. 746-749). NASA.

[24] Blakeslee, R., Lang, T., Koshak, W., Buechler, D., Gatlin, P., Mach, D, Stano, T., Virts, K., Walker, K., Cecil, D., Ellett, W., Goodman, S., Harrison, S., Hawkins, D., Heumesser, M., Lin, H., Maskey, M., Schultz, C., Stewart, M., & Christian, H. (2020). Three years of the lightning imaging sensor onboard the international space station: Expanded global coverage and enhanced applications. Journal of Geophysical Research: Atmospheres, 125(16), https://doi.org/10.1029/2020JD032918

[25] Christian, H., Blakeslee, R., Bocippio, D., Boeck, W., Buechler, D., Driscoll, K., Goodman, S., Hall, J., Koshak, W., Mach, D., Stewart, M. (2003, January). Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. Journal of Geophysical Research, 108(D1). https://doi.org/10.1029/2002jd002347

Sun-Synchronous Orbits:

SSOs are polar orbits that leverage the Earth's gravitational field to precess the orbital plane at a rate matching the Earth's orbit around the Sun[26]. Careful selection of both altitude and inclination yields this desirable property. Consequently, spacecraft in SSO overfly any given point on the Earth with consistent local mean solar time. The Local Time of the Ascending Node (LTAN) describes the local solar time when the spacecraft crosses the equator travelling North.

Continental lightning, which comprises a significant majority of global lightning flashes, exhibits a strong diurnal variance. Analysis of data obtained from previous LEO LD missions suggests that peak lightning activity occurs in the late afternoon, mostly between 15:00 and 17:00[27]. Selecting an SSO with a 16:00 LTAN would allow the LD pathfinder instrument to view the entire globe over the duration of its orbital repeat cycle (satisfying CDF-R-LD-24) and cross the equator at a time of heightened lightning activity every orbit (satisfying CDF-R-LD-25).

Launch Considerations:

Orbits in high inclinations require the launch vehicle to expend more energy for orbit insertion. Rockets can utilise the West-to-East rotation of the Earth to provide a velocity boost that minimises the energy expenditure of a launch. Therefore, launching directly East from the launch site maximises the velocity contribution from the Earth's rotation and allows a rocket to carry more mass to orbit[28]. However, launching due East inserts payloads into an orbit with inclination equal to the launch site's latitude. Therefore, launching into a high inclination orbit requires a launch azimuth that is misaligned relative to the Earth's rotation direction. Consequently, high inclination launches insert lower total mass into orbit, increasing the cost per unit mass of the launch.

Summary:

Table 12 below outlines the differences between mid-inclination orbits, polar orbits and SSOs. Note this table is intended to provide the reader with a generalised 'rule-of-thumb' comparison of the LEO orbit categories available for the LD LEO pathfinder. Different launch providers operate from launch sites with varying geographic location and operate launch vehicles with performances optimised for meeting different scenarios.

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[26] Boain, R. J. (2004b). A-B-Cs of Sun-Synchronous Orbit Mission Design. In 14th AAS/AIAA Space Flight Mechanics Meeting. Jet Propulsion Laboratory, National Aeronautics and Space Administration. http://hdl.handle.net/2014/37900

[27] Blakeslee, R., Mach, D., Bateman, M., Bailey, J. (2014). Seasonal variations in the lightning diurnal cycle and implications for the global electric circuit. *Atmospheric Research, 135–136,* 228–243. https://doi.org/10.1016/j.atmosres.2012.09.023

[28] Doody, D. (2022). Section 3: Operations, Chapter 14: Launch. In D. Fisher (Ed.), Basics of Space Flight (2017th ed.). Jet Propulsion Laboratory, National Aeronautics and Space Administration. https://solarsystem.nasa.gov/basics/chapter14-1/

Table 12: Generalised comparison of mid-inclination, polar and sun-synchronous orbits.

Orbit	Mid-Inclination	Polar	SSO
Inclination Range [degrees]	35 – 60	60 – 120	96 – 98
Relative Energy Expenditure for Orbit Insertion	LOW – MEDIUM	MEDIUM – HIGH	MEDIUM – HIGH
Geographic Coverage Region	Mid-Latitudes	Complete coverage, including poles	Complete coverage, including poles
Temporally Consistent Observations	NO	NO	YES (fixed mean local solar time for observations)

5.5.3 Design baseline orbit: 45-degree mid-inclination orbit

The discussion of mid-inclination orbits in Section 5.5.2 concluded that an orbit with inclination between 43° and 60° could satisfy requirements derived explicitly from the Bureau's programmatic and mission requirements. Specifically, such an orbit satisfies CDF-R-LD-21, -CDF-R-LD-22, and CDF-R-LD-23 and is also likely to reduce the cost of launch. However, a mid-inclination orbit cannot provide coverage of the polar regions and will produce observations of fixed locations across the diurnal cycle.

The concurrent engineering analysis presented in this report for the LD LEO pathfinder uses a 550 km altitude 45° inclination orbit as a baseline input. Once again, this is for analysis purposes only and is not prescriptive of a preferred or recommended orbit choice for this mission.

Table 13 summarises the relevant properties of this orbit. The choice to select a mid-inclination orbit as the design baseline is not prescriptive; rather, it best addresses the Bureau's stated requirements and is likely to minimise launch cost.

Table 13: Orbit parameters of M2 spacecraft, representative of a generic mid-inclination orbit.

ID	Orbit Parameter	Value
CDF-S-LD-41	Altitude [km]	550
CDF-S-LD-42	Inclination [deg]	45
CDF-S-LD-43	Period [minutes]	95.65

Figure 11 to Figure 13 below illustrates the lightning detector instrument's geographic coverage after 12 hours, 24 hours and 7 days, respectively. Given the sensor's field-of-view specified in Table 8, the sensor's swath width at a 550 km altitude is 600 km.

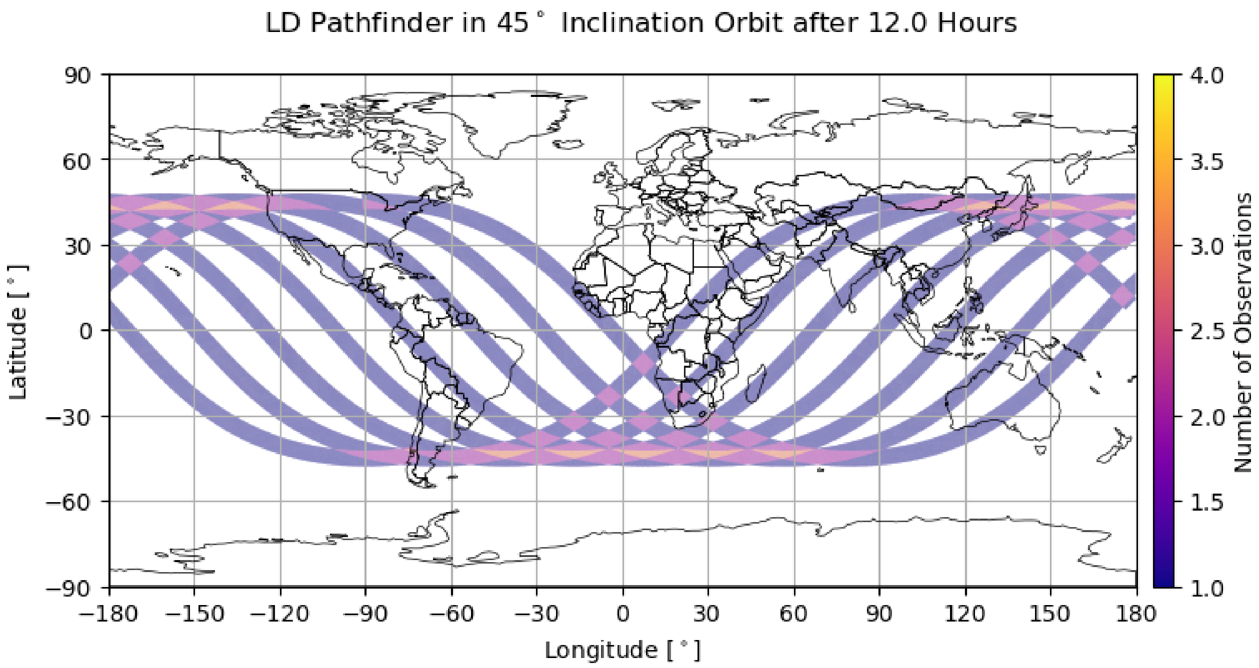

Figure 11: Lightning Detector LEO pathfinder sensor coverage in a 45-degree / 550 km orbit after 24 hours.

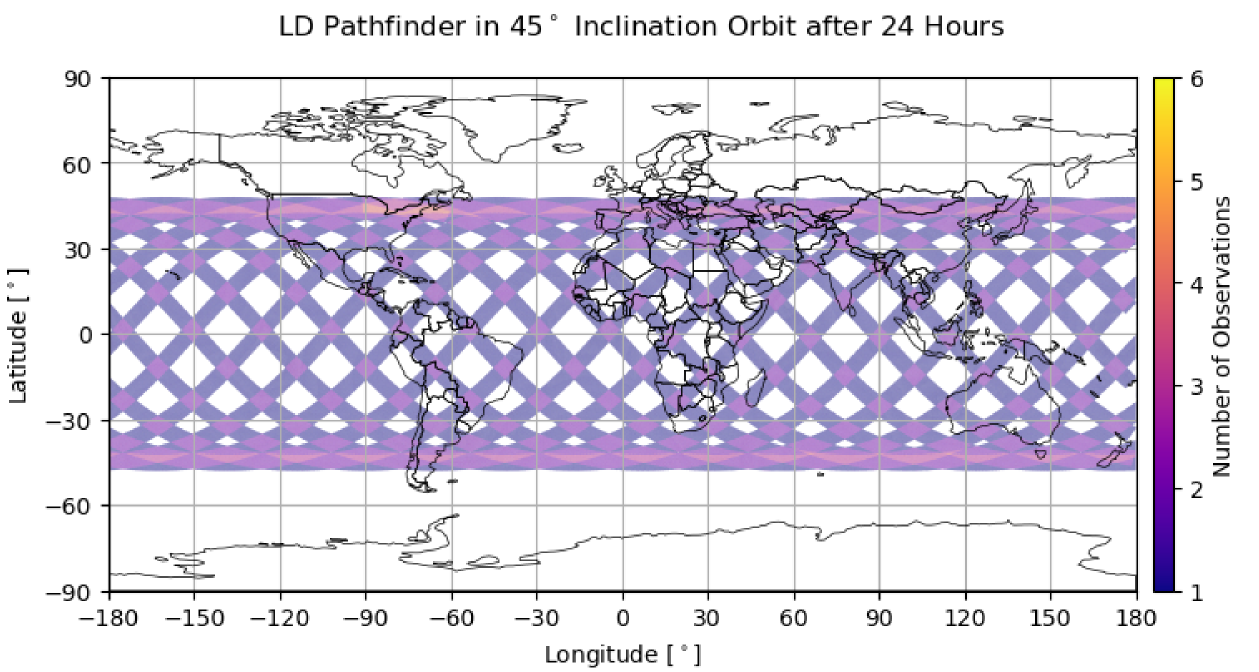

Figure 12: Lightning Detector LEO pathfinder sensor coverage in a 45-degree / 550 km orbit after 24 hours.

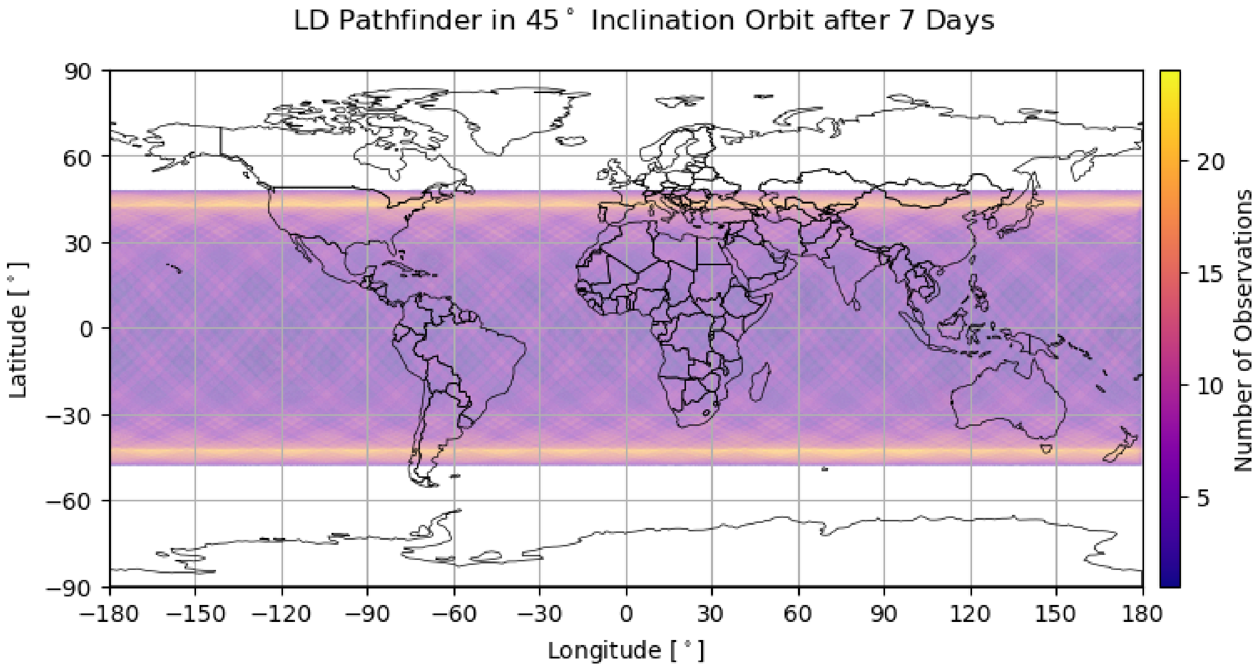

Figure 13: Lightning Detector LEO pathfinder sensor coverage in a 45-degree / 550km orbit after 7 days.

5.5.4 Consideration of a sun-synchronous orbit against requirements

The discussion in Section 5.5.2 concluded that an SSO could satisfy optional, LEO-specific derived orbit requirements alongside those derived from the Bureau's programmatic and mission requirements. Specifically, an SSO could satisfy CDF-R-LD-21, CDF-R-LD-22, CDF-R-LD-24, and CDF-R-LD-25. The two major benefits of an SSO compared to a mid-inclination LEO are:

- The lightning detector instrument will collect observations with consistent local solar time every orbit. Selecting a local time of ascending node (LTAN) of 16:00 would maximise the chance of lightning activity during observations.
- The lightning detector sensor can extend global coverage and collect observations over the polar regions.

These advantages are traded against the potentially greater launch cost incurred by the energy expenditure required for orbit insertion. Table 14 outlines the parameters of an example SSO that could satisfy the optional requirements for the LD LEO pathfinder.

Table 14: Orbit parameters of an illustrative 16:00 LTAN SSO.

ID	Orbit Parameter	Value
CDF-S-LD-44	Altitude [km]	605.52
CDF-S-LD-45	Inclination [deg]	97.83
CDF-S-LD-46	Period [minutes]	96.92
CDF-S-LD-47	Repeat Cycle [days]	7
CDF-S-LD-48	Recurrence Grid Interval [km]	385.34
CDF-S-LD-49	Mean Local Time at Equator	16:00

Figure 14 to Figure 16 visualise the accumulated sensor swath coverage from this orbit after 12 hours, 24 hours, and 7 days, respectively. Note that the sensor's field of view specified in Table 8 yields a 600 km swath width for a 550 km altitude. Therefore, at 605.52 km altitude, the lightning detector instrument's swath width increases to at least 661.6 km.

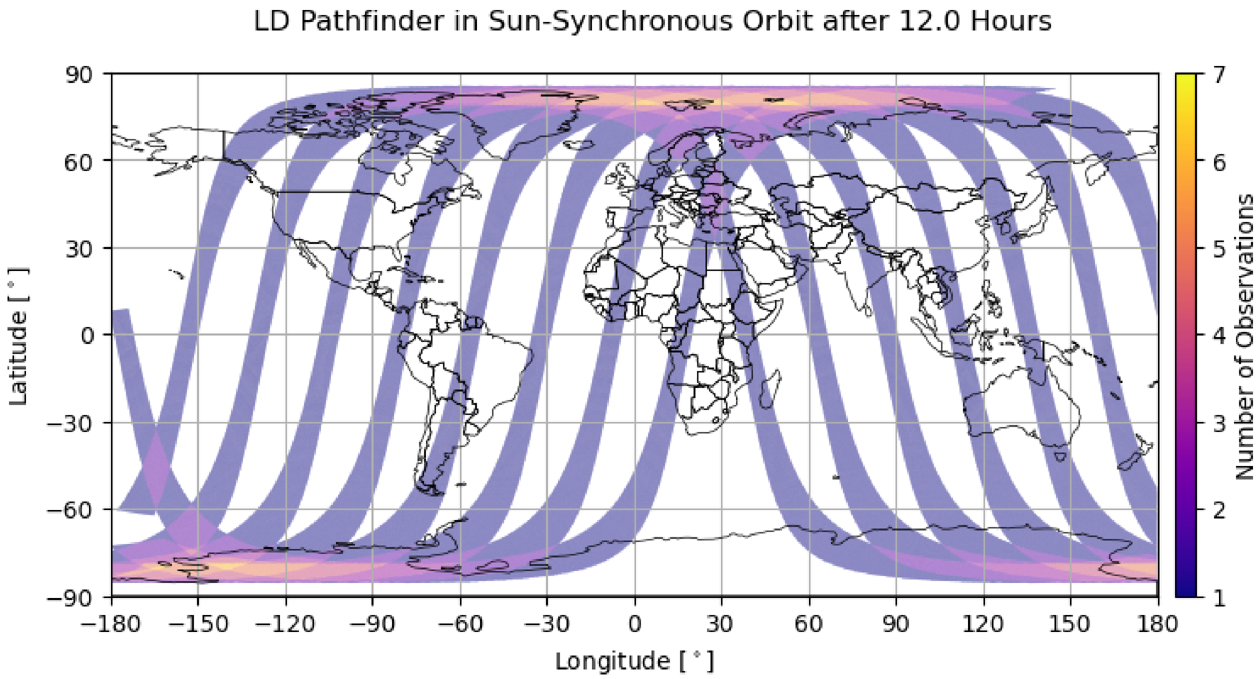

Figure 14: Lightning Detector LEO pathfinder sensor coverage in an illustrative 13:30 LTAN SSO after 12 hours.

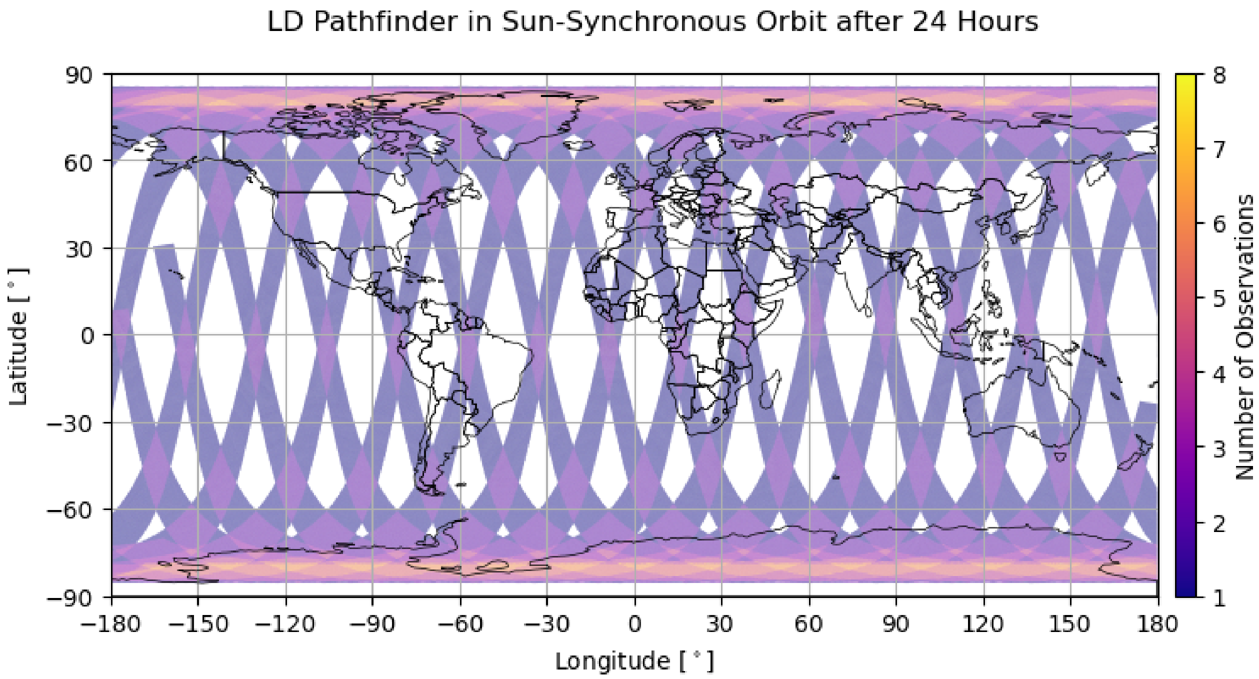

Figure 15: Lightning Detector LEO pathfinder sensor coverage in an illustrative 13:30 LTAN SSO after 24 hours.

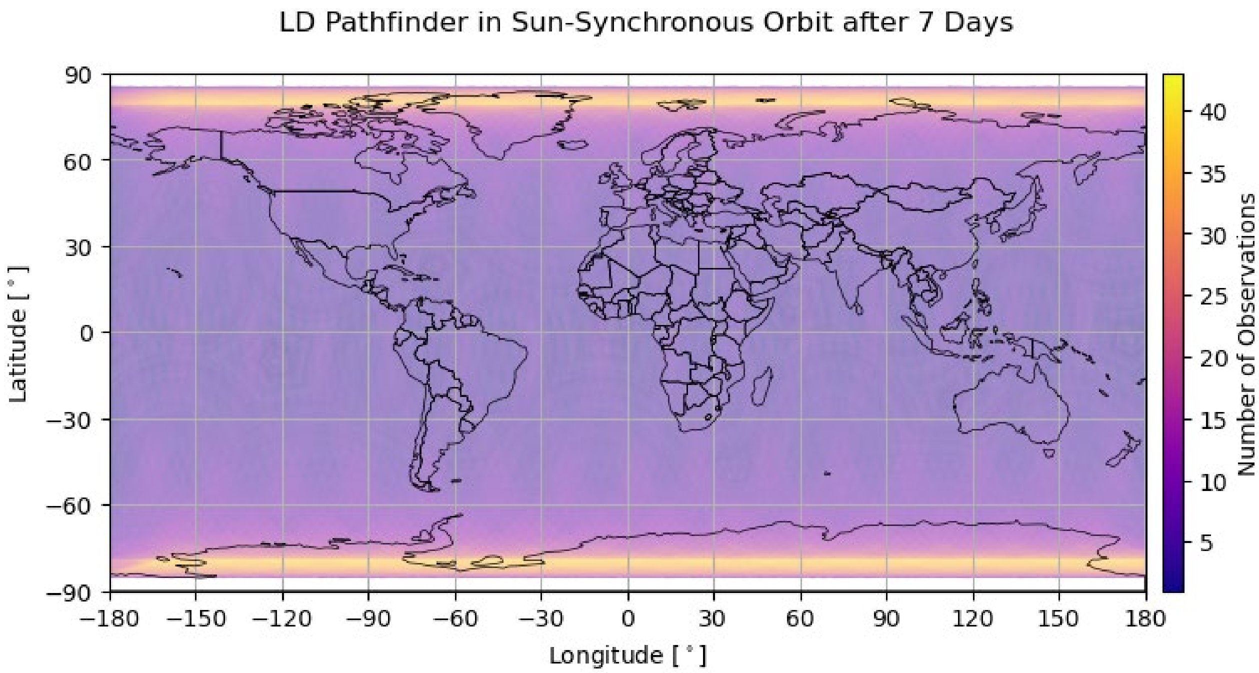

Figure 16: Lightning Detector LEO pathfinder sensor coverage in an illustrative 13:30 LTAN SSO after 7 days.

5.5.5 Additional orbit selection criteria

During discussions after the CDF study, the Bureau asked about the feasibility of flying the lightning detector LEO pathfinder in train with NASA's recently announced Investigation of Convective UpdraftS (INCUS) mission. NASA intends for INCUS to comprise three SmallSats that will fly in a tight formation, separated along-track from one another by 30 and 90 seconds[29]. At the time of writing, the intended launch date for INCUS is 2027[30]. Little additional information is publicly available. Therefore, it is currently not possible to provide a detailed analysis of the INCUS orbit against the orbit requirements derived previously in Table 11. However, the following considerations would require thorough investigation were the LD LEO pathfinder to fly in train with the INCUS mission:

- The LD LEO pathfinder would require a propulsion subsystem to perform station keeping and formation maintenance.
- Formation flying with an operational NASA mission would require a high degree of collaboration and coordination between the LD LEO pathfinder and INCUS mission operations teams (such as continual exchange of orbit determination and manoeuvre planning data to maintain formation and ensure safe separation for all satellites).
- Formation flying with an operational NASA mission will necessitate a more demanding level of mission assurance and risk mitigation, as well as a more operational mission focus, than is typical for a pathfinder.

5.6 On-Board Data Handling

The subsystem should be capable of handling burst event rates, with the mean data rate calculated to be 100 kbps (Table 16). It will need to store event data until the data can be downlinked to the ground, which may be many orbits after the event itself. In anomalous conditions, the system may need to store data on-board for several days. This is discussed further in Section 5.7.2.

5.7 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 to control the spacecraft.

[29] van den Heever, S., Haddad, Z., Tanelli, S., Stephens, G., Posselt, D., Kim, Y., Brown, S., Braun, S., Grant, L., Kollias, P., Luo, Z. J., Mace, G., Marinescu, P., Padmanabhan, S., Partain, P., Petersent, W., Prasanth, S., Rasmussen, K., Reising, S., Schumacher, C. (2022). The INCUS Mission. *EGU General Assembly*, EGU22-9021. https://doi.org/10.5194/egusphere-egu22-9021

[30] Potter, S. (2021, November 5). NASA Selects New Mission to Study Storms, Impacts on Climate Models. NASA. https://www.nasa.gov/press-release/nasa-selects-new-mission-to-study-storms-impacts-on-climate-models/

5.7.1 Derived Requirements

This section elaborates on key user requirements that were derived from the mission requirements during the study. The data volume to be downlinked is also derived herein from the mission requirements.

Table 15: Derived communications requirements.

ID	Requirement	Upstream
CDF-R-LD-26	The space and ground segments shall be operated in accordance with the ITU Radio Regulations, and any applicable national regulations where the downlink system is to be operated.	PRG-04
CDF-R-LD-27	During normal operations, payload data shall reach the ground segment at most 24 hours after the data was created. *Rationale: Whilst there is no explicit upstream requirement, setting a reasonable and non-restrictive data latency requirement assists in constraining the solution space.*	PRG-02, MIS-03
CDF-R-LD-28	During abnormal operations, the mission shall operate for up to four days without the ability to downlink data, without loss of any data. *Rationale: This duration balances the need for a backup ground segment with the desire to maintain continuity in the science data.*	
CDF-R-LD-29	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-LD-30	The spacecraft shall be capable of transferring payload data to the ground segment in a nadir pointing configuration. *Rationale: As the system should operate the lightning detector continuously, this implies the satellite must always nadir point.*	
CDF-R-LD-31	All communication links shall be designed with a nominal link margin of at least 3 dB. *Rationale: A 3 dB link margin is considered typical for LEO communication systems, with 6 dB link margin desirable where possible[31].*	

[31] See section 11.5.3 of the NASA State-of-the-Art of Small Spacecraft Technology 2021 document, retrieved from https://www.nasa.gov/sites/default/files/atoms/files/11.soa_gds_2021_1.pdf, and ECSS-E-ST-50-05C Rev. 2, retrieved from https://ecss.nl/standard/ecss-e-st-50-05c-rev2-radio-frequency-and-modulation-4-october-2011/

Other considerations that did not result in a requirement:

- The system may not require redundancy in the telecommand/telemetry system, or in the payload communications system. Pathfinder missions generally accept a higher risk tolerance in exchange for lowering other mission characteristics (such as schedule, cost, complexity, or scope).
- The system should avoid using components that could include vibrations or jitter in the spacecrafts attitude. For example, steerable or gimballed antenna movement will result in a change in spacecraft pointing. Undesired spacecraft attitude changes can result in degraded imaging quality and image co-registration.
- The error performance supported by the DVB-S2[32] 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[33], performs close to theoretical limits[34], and off-the-shelf radios supporting it are available.

5.7.2 Payload Data Volume Estimation

The science data volume was calculated using the payload data rate of 100 kbps (refer to CDF-S-LD-39 in Table 9), acquiring at 100% duty cycle. The analysis summarised below in Table 16 shows that 8.64 Gb of payload data would be generated per day, resulting in 9.50 Gb (1.19 GB) to downlink per day with packeting overheads.

Table 16: Lightning detector data volume assessment.

ID	Parameter	Value
CDF-S-LD-50	Acquisition Time (min/orbit)	95.65 (CDF-S-LD-42)
CDF-S-LD-51	Payload Output Data Rate (Kbps)	100 (CDF-S-LD-39)
	Derivation	
CDF-S-LD-52	Payload Data Generated (Gb/day)	**8.64**
CDF-S-LD-53	Packeting Overhead (%)	**10%**
CDF-S-LD-54	Required Data Downlink (Gb/day)	**9.50**

[32] 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)

https://www.etsi.org/deliver/etsi_en/302300_302399/302307/01.02.01_60/en_302307v010201p.pdf

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

[34] See section 9.5.7 of the NASA State-of-the-Art of Small Spacecraft Technology 2021 document, retrieved from https://www.nasa.gov/sites/default/files/atoms/files/9.soa_comm_2021_0.pdf.

5.7.3 Telemetry Data Volume Estimation

This section considers the telemetry data required for the operation of the payload and management of the satellite (housekeeping data such as battery monitoring, solar panel efficiency, system performance metrics and diagnostics). Housekeeping telemetry is handled by the satellite platform and depends on the specific design, but usually is not onerous compared to the payload data. UNSW Canberra Space's previous LEO experience has been with systems that generate 100 to 200 Bytes per second of housekeeping data.

The design study did not identify any unusual or onerous payload telemetry requirements. as such, any payload telemetry needs could be handled by the platform telemetry system. High-frequency payload telemetry is likely to be directly related to the science output of the payload, and as such was assumed to be handled via the science data downlink pathway.

5.8 Electrical Power Subsystem

The electrical power subsystem (EPS) provides the lifeblood of the satellite, electrical power. Its objective is to provide power to all the other subsystems (including the payload) to enable operations. It typically consists of solar arrays, batteries, harnesses, and a power management and distribution unit (non-exhaustive list).

As a commercial off-the-shelf bus is being considered for this mission, no bottom-up power budget is required here. It is assumed that commercial off-the-shelf platforms will be able to support lightning detection payload power consumption.

5.9 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 communication antennas, and solar arrays. It typically consists of actuators and sensors. Actuators include reaction wheels and magnetic torquers. Sensors include star trackers, magnetometers, and inertial measurement units.

During the lifetime of LEO satellites, its attitude is continuously affected by disturbances in the form of gravity gradients, solar radiation pressure, magnetic fields and aerodynamic torques. It is these disturbance torque fields that need to be reacted against to maintain satellite pointing requirements. For effective attitude determination and control, there is a requirement to control the satellite attitude using reactions wheels or magnetic torquers.

Attitude control systems in turn need input from star trackers, sun sensors, earth sensors, inertial sensors, or GPS receivers etc. to close the attitude control system loop. Commercial suppliers of satellite bus systems provide integrated attitude control systems guidance, navigation, and control (GNC) subsystems. It is important to maintain communication with the bus system supplier to ensure the increase in moment of inertia because of the satellite sensor hardware, can be accommodated by the proposed reaction wheels/magnetic torquer assemblies.

As a commercial off-the-shelf bus is being considered for this mission, no detailed ADCS design is required here. Commercial off-the-shelf platforms are available that will be able to support lightning detection payload pointing requirements.

5.9.1 Derived Pointing Requirements

Table 17: Derived pointing requirements.

ID	Requirement	Upstream
CDF-R-LD-32	The attitude determination and control system architecture for the lightning detector sensor must provide a 10 km or less ground plane resolution for a LEO orbit at 550 to 600 km and at 35 788 km for a GEO orbit.	
CDF-R-LD-33	In support of both the LEO and GEO ADCS, the spacecraft must be able to support no less than 3 years of operational manoeuvres including station-keeping.	

Storm supercells can cover many hundreds of kilometres in width down to isolated storm cells in the tens of kilometres. Therefore, pointing requirements, in the order of 10 kilometres, would suffice to cover all storm cell sizes.

At the proposed LEO altitude of 550 to 600 kilometres while over Australia, this would require a pointing accuracy in the order of 1° minimum. For a GEO platform at altitude of 35 788 km, the pointing accuracy requirements become more refined and equates to approximately 0.016 degrees.

Derivation of the above comes from:

- LEO 550 km orbit: (arctan (5/550)) x 2 ~ 1.04 degrees.
- LEO 600 km orbit: (arctan (5/600)) x 2 ~ 0.96 degrees.
- GEO orbit: (arctan (5/35788)) x 2 ~ 0.016 degrees.

5.10 Propulsion Subsystem

A propulsion subsystem typically consists of one or several thrusters and tanks and would enable the spacecraft to alter its orbit by performing orbital manoeuvres. Propulsion systems are typically suitable for high LEO orbits (>1000 km) to ensure de-orbit within a controlled time frame, or for missions that are required to adhere to a precise orbit or ground track (i.e. regular station-keeping is required).

It was determined that no propulsion system would be required as this is a low LEO (<1000 km) mission and there are no specific ground track mission requirements. Orbital manoeuvres such as small altitude adjustments and station keeping can be completed using a combination of low, medium, and high drag manoeuvres assisted by charge plates.

5.11 Structure Subsystem

The structure subsystem holds together and protects all the other spacecraft subsystems during launch and operations. It is the mechanical backbone of the spacecraft and typically consists in a chassis, articulations, and deployables.

5.11.1 Structural Requirements

Structural requirements usually originate from the launch service provider, and typically consist of:

1. Qualification against structural loads expected during launch, including:
    a. Acceleration loads.
    b. Vibration loads.
    c. Shock loads.
2. Lower limits on resonant frequencies.
3. Restricted materials (limited to materials that do not degrade in the space environment)

Points 1 and 2 above are typically unique for each launch vehicle and are specified in the launch service provider's Payload User's Guide (see [35] [36] [37] [38] for examples). Alternatively, NASA created the General Environmental Verification Standard (GEVS [39]) as a general benchmark for spacecraft environmental requirements, including structural requirements, although individual launch vehicle requirements supersede this.

Restricted materials are typically limited to materials that have a Total Mass Loss (TML) <1% and a Collected Volatile Condensable Material (CVCM) <0.1% when exposed to vacuum, as well as materials that do not degrade when exposed to radiation, UV, and atomic oxygen.

5.11.2 Volume Requirements

The launch service provider typically places volume restriction on the spacecraft, however, considering the spacecraft will likely be 12U CubeSat, the volume restrictions are mostly limited to the chosen spacecraft dispenser.

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

[36] https://www.rocketlabusa.com/assets/Uploads/Electron-Payload-User-Guide-7.0.pdf

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

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

[39] https://standards.nasa.gov/standard/gsfc/gsfc-std-7000

Numerous 12U COTS dispenser exist, each with their unique features (see detailed dispenser requirements in their respective documentation such as [40] [41]). However, most dispensers restrict the spacecraft dimensions to the following:

- Length: 345 or 366 mm
- Width: 226.3 mm (excluding volume for stowed deployables such as solar arrays)
- Height: 226.3 mm (excluding volume for stowed deployables such as solar arrays)

5.11.3 Mass Requirements

Mass of 12U CubeSats are typically limited to no greater than 24kg, with typical masses around 20kg. This limitation is typically defined by both the dispenser and launch service provider. Further note that the launch service price is typically proportional to mass, so a lighter spacecraft is preferred.

5.12 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, strain sensitive components, such as optics, may have thermal stability requirements that limit not only its temperature range, but also the amount of temperature difference (thermal gradient) across the component.

At this preliminary stage of the mission design, only the primary thermal requirements mentioned above have been considered.

[40] https://www.rocketlabusa.com/assets/Uploads/2002337G-CSD-Data-Sheet-compressed2.pdf

[41] https://exolaunch.com/documents/EXOpod_User_Manual_September_2022.pdf

6 GEO Satellite Lightning Detector Mission Development

6.1 GEO Lightning Detector Mission Implementation

6.1.1 Expected Coverage

The coverage provided by a GEO-located lightning detector would primarily depend on the final GEO spot longitude and the optical configuration of the instrument.

Sample instrument footprints have been produced for a GLM-like instrument, an MTG-LI-like instrument, and a dual-telescope instrument located on the Himawari longitude (140.7°) or a 115° longitude.

Note that the dual-telescope option presented in Figure 17 has had angles adjusted to provide as much coverage as possible over Australia, Japan, and India. A field of view equivalent to that of the MTG-LI optical heads was assumed.

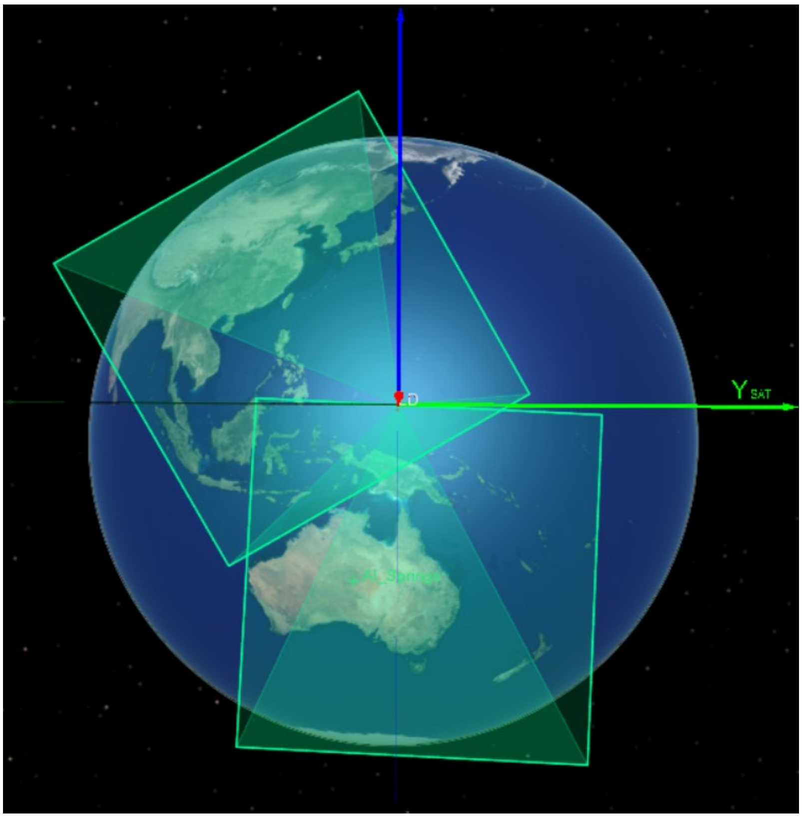

Figure 17: Dual-telescope instrument located in the Himawari longitude (140.7 deg).

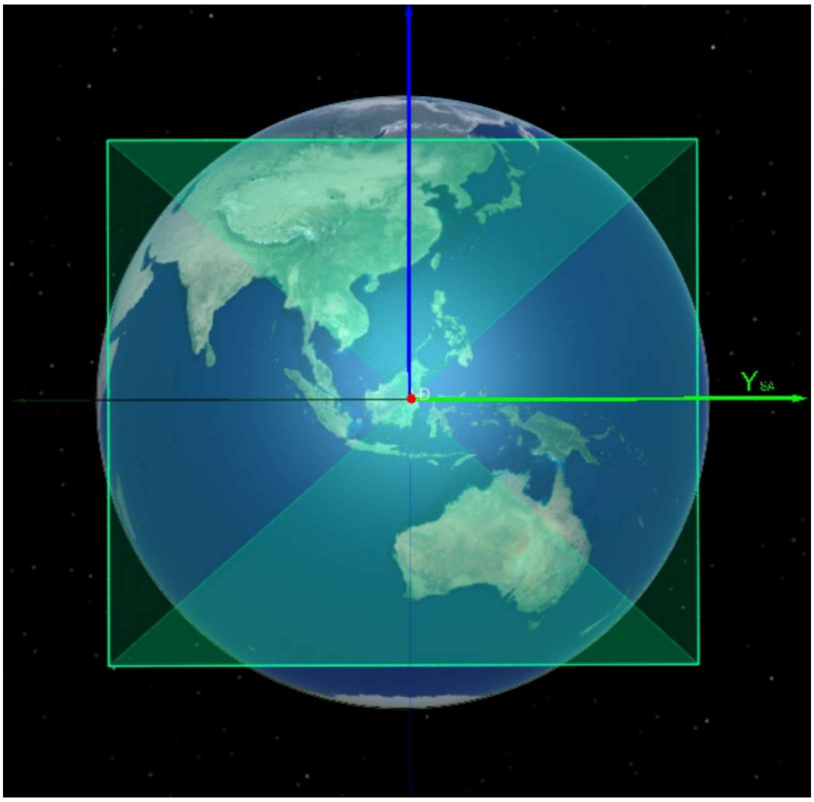

Figure 18: GLM-like field of view at 115 deg longitude.

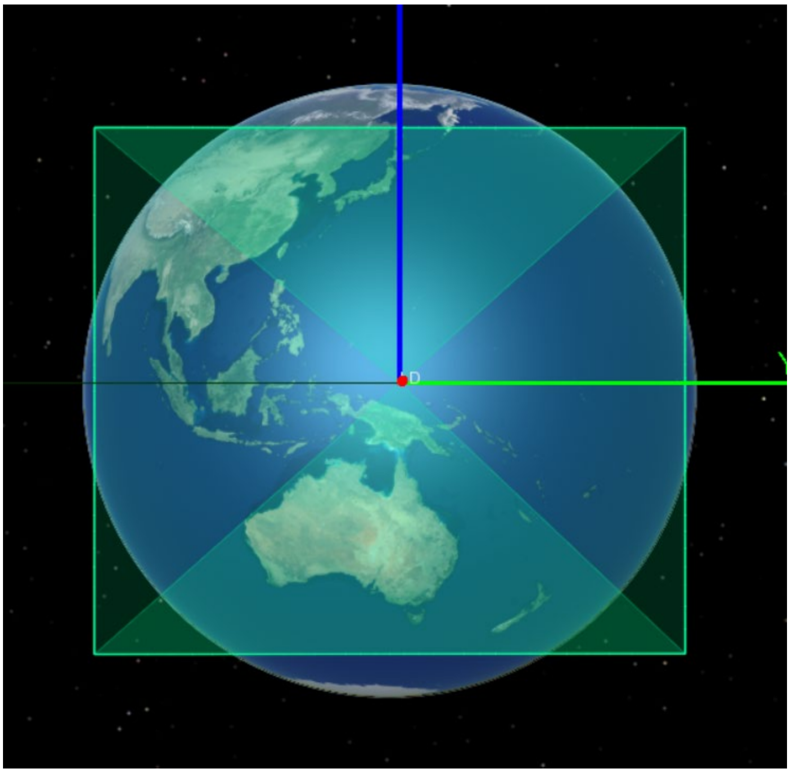

Figure 19: GLM-like field of view at the Himawari longitude (140.7 deg).

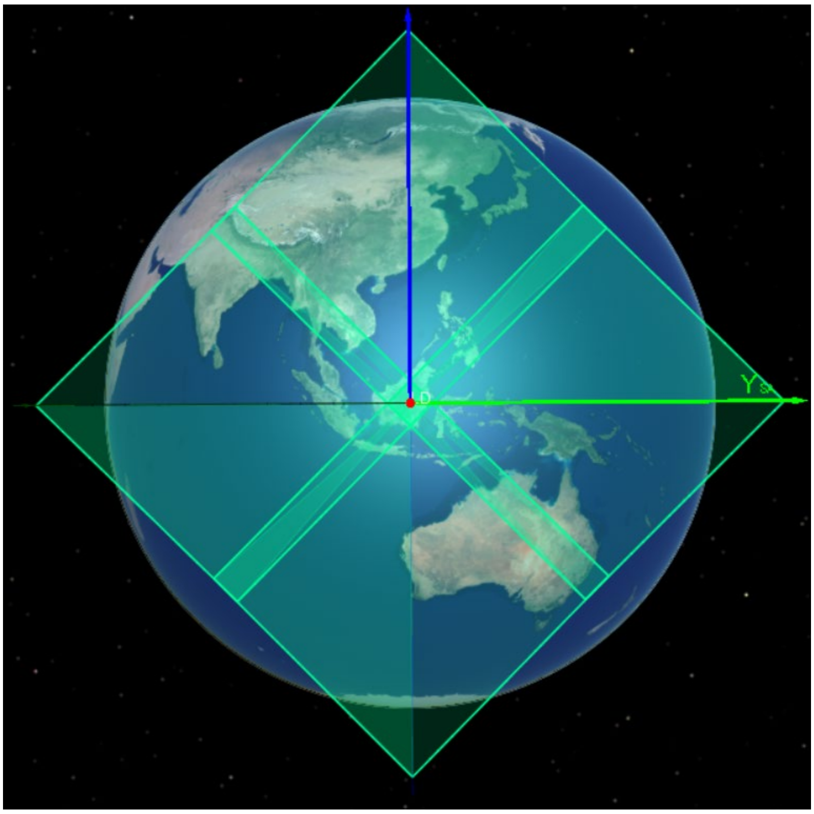

Figure 20: MTG-LI-like field of view at 115 deg longitude.

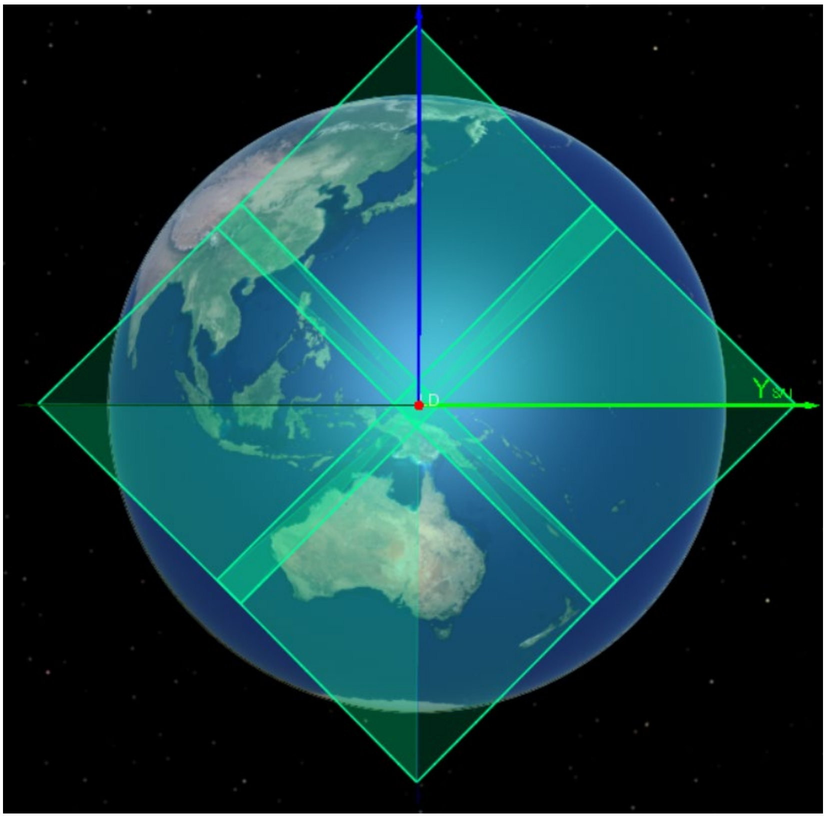

Figure 21: MTG-LI-like field of view at the Himawari longitude (140.7 deg).

Note that all sample footprints presented here are for reference only and that future work will be needed to develop both the optical design (number of optical heads, field of view and angles) and determine the final available GEO spot longitude to provide an optimal coverage.

The final optical design choices will be dictated by various factors including size and mass of the instrument, onboard processing requirements, manufacturability (particularly the narrowband filter), cost, key regions of interest, and the final GEO spot longitude, as determined by the mission-level analyses.

6.1.2 Australian GEO Payload Hosted on a Third-Party Satellite

One feasible option for an near-term GEO capability would be to develop an advanced payload to operate on-board a third-party GEO satellite. This could be done by:

- Participating in an international consortium to develop a GEO capability;
- Partnering with a third-party country on a particular satellite programme or to ride-share;
- Arranging to host the payload on another type of satellite, such as a communications satellite, which typically has adequate mass, power and data margins to support operations.

This would have the benefit of reducing the risk to Australian stakeholders that would otherwise bear all costs and risks associated with developing a satellite completely, as well as launch into GEO and full mission operations. Instead, Australia could focus on development of the lightning detector instrument and integration into a larger satellite. The overall satellite development, launch and operations responsibility would be shared with the other partner agencies, including possibly Australia for ground station, mission and/or data processing operations activities.

Overall, this option would mitigate much of the greater satellite development risks while still allowing Australia to benefit from being part of a complex satellite project. However, being part of a larger project that will likely be driven by another country or agency will introduce new risks of delays, cost increases and other unexpected technical or programmatic challenges outside of Australia's control and not directly related to the Australian needs.

These aspects should be carefully considered when embarking on a joint mission. However, it should be noted that most complex and expensive space missions tend to be implemented as multi-national or at least multi-agency / multi-organisational endeavours.

6.1.3 Australian GEO Satellite Development

The alternative to partnering on a larger international GEO development would be to embark on a completely Australian GEO capability. Whilst all technological and budget risks would be solely with Australia in this case, it would also provide Australia with complete control regarding management and mitigation of these risks.

A small GEO satellite dedicated to hosting a lightning detector only would provide significant scientific data to meet the primary use cases already discussed; however, without complementary payloads there would not be collocated imagery or sounding data that could be collected simultaneously via a larger multi-sensor capability.

A possible hybrid consideration in this regard would be for Australia to be the lead on a larger multi-national satellite mission development where other partners provide instruments to be hosted on an Australian platform. This would mean more risk for Australia embarking on a more complex and expensive project; however, suitable choices on partnering with experienced agencies such as NASA or JAXA would mitigate this somewhat whilst allowing Australia to benefit from the experience of the partner agencies and industries.

Commercially available platforms suitable to operate from LEO to GEO orbits are available, including options for launch and even mission operations. However, these cannot be fully specified at this point as they typically require extensive tailoring to meet the mission needs; this could be done as part of a future study.

6.2 GEO Satellite Orbit Considerations

General Description:

Geostationary orbits allow a spacecraft's position to remain fixed relative to the Earth's surface. This phenomenon is achievable by ensuring the orbit satisfies three requirements:

1. The orbit must be geosynchronous: the satellite's motion must match the direction and magnitude of the Earth's rotation,
2. The orbit's inclination must be 0°, and
3. The orbit must be circular (eccentricity is 0)

To satisfy the first requirement, the orbital altitude must be exactly 35,788 km.[42]

Launch and Insertion into GEO:

There is a considerable amount of expertise and technology used to ensure that satellites enter their orbits in the most energy efficient ways possible. This ensures that the amount of fuel required is kept to a minimum; an important factor as the fuel itself has to be transported until it is used. If too much fuel is transported, then this increases the size of the launcher and in turn this can greatly increase the costs.

A common method to reach a GEO orbit is based on the Hohmann transfer principle. This is a method whereby the satellite is placed into a low earth orbit (the altitude may be as low as 300km) and once in the correct position in this orbit rockets are fired to put the satellite into an elliptical orbit with the perigee at the low earth orbit and the apogee at the geostationary orbit altitude as shown in Figure 22. When the satellite reaches the final altitude the rocket or booster is again fired to retain it in the geostationary orbit with the correct velocity.

[42] Capderou, M. (2005). Satellites: Orbits and Missions (S. Lyle, Trans.; 1st ed.). Springer.

Alternatively, when launch vehicles like Ariane are used the satellite is launched directly into the elliptical transfer orbit. Again, when the satellite is at the required altitude the rockets are fired to transfer it into the required GEO orbit with the correct velocity.

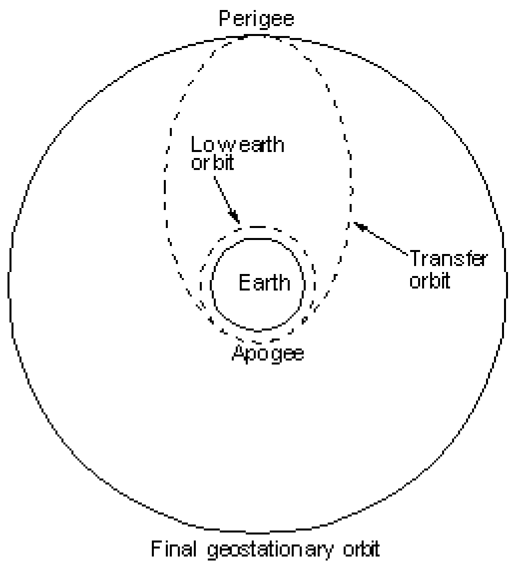

Figure 22. Geostationary orbit insertion using a Hohmann transfer.

Station-Keeping:

Spacecraft in GEO are subject to many perturbing forces; for example, the uneven gravitational field of the Earth, and attraction by the Sun and Moon all influence the motion of a satellite in GEO. These perturbing forces cause the spacecraft's motion to drift from its intended orbit which, in turn, causes the sub-satellite point (SSP) to drift in both latitude and longitude.

Longitudinal drift is caused by variations in the satellite's altitude. Increasing altitude lengthens the orbital period, which causes the spacecraft to rotate slower than the Earth's rotation. Therefore, increasing altitude results in a Westward drift in the sub-satellite point. Conversely, decreasing the altitude results in an Eastward drift. The relationship between altitude Δh drift and the resulting change in longitude Δl is:

$$\Delta l = -1.4295\Delta h\ (per\ day)$$ [43]

For example, an altitude drift of $\Delta h = 50m$ results in a longitude drift of $\Delta l = -71.475m/day$. Here, the negative sign convention corresponds to a Westward drift. Predominantly, the altitude of a GEO spacecraft is perturbed by the Earth's uneven gravitational field[43].

Latitudinal drift is induced by drift in the orbital inclination. If the inclination i is non-zero, latitude $\emptyset$ will oscillate between $\emptyset = +i$ and $\emptyset = -i$ during one orbit. To a viewer on the ground, the spacecraft will trace a figure-of-eight pattern in the sky. The attractive forces of the Moon and the Sun are the primary drivers of inclination drift[43].

[43] Capderou, M. (2005). Satellites: Orbits and Missions (S. Lyle, Trans.; 1st ed.). Springer.

In addition to latitudinal and longitudinal drift, induced by perturbations in inclination and altitude, respectively, the orbit's eccentricity is influenced by solar radiation pressure[43]. Non-zero eccentricity results in an elliptical orbit.

Due to the drift in altitude, inclination and eccentricity, geostationary spacecraft perform station keeping manoeuvres. These manoeuvres are planned and executed by the mission operations team, who aim to keep the spacecraft in a pre-defined window of acceptable positions. A typical window could allow for 1° of East-West deviation, and +/-0.1° of North-South deviation[43].

Seasonal Eclipse:

Geostationary orbits are co-planar with the Earth's equatorial plane, which is inclined 23.4° relative to the ecliptic plane (the Sun's equatorial plane). From the perspective of a geostationary spacecraft, the Sun moves between +23.4° above the equatorial plane to -23.4° below the plane over the course of a year as the Earth orbits the Sun. Therefore, geostationary spacecraft spend a significant amount of the year in full view of the Sun with zero time in eclipse. However, during the spring and autumnal equinoxes the Sun transits the equatorial plane, casting a portion of the geostationary orbit in shadow. Therefore, spacecraft in GEO experience seasonal eclipse periods; the eclipse periods begin 23 days before the equinox and finish 23 days afterwards. During this period, the eclipse time varies between a minimum of 10 minutes to a maximum of 72 minutes[44]. Before each eclipse season, the mission flight team will perform operations to calibrate and balance the battery modules to ensure nominal performance and minimal degradation[45].

Spacecraft in GEO are also subject to lunar eclipses. Lunar eclipses do not occur with any pattern; however, a particular spacecraft may experience them twice per year on average[46]. Many lunar eclipses are partial eclipses and vary in duration from half an hour to an hour. Given this duration is shorter than the maximum seasonal eclipse duration, lunar eclipses are generally not disruptive to GEO operations. However, should a lunar eclipse occur near a seasonal eclipse the batteries may not provide sufficient energy to operate continuously.

Additionally, the eclipse season can pose a unique problem for lightning detectors in GEO; the GLM instrument team noticed a high rate of false flash detections at certain times during the eclipse season[47]. As the Sun crosses the equatorial plane, direct solar illumination almost reaches the instrument's focal plane and causes false flash detections. The GLM team had to introduce a blooming filter into the GOES ground system to address the issue.

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[44] Roddy, D. (2006). Satellite Communications (4th ed). New York: McGraw-Hill. https://www.accessengineeringlibrary.com/content/book/9780071462983

[45] Mattesco, P. (2008). EADS-Astrium Lithium Technology Experiences. *8th European Space Power Conference, 661*, 100. https://ui.adsabs.harvard.edu/abs/2008ESASP.661E.100M

[46] Gordon, G., & Fronduti, A. (1992). Effect of moon's shadow on geostationary satellites. In *14th International Communication Satellite Systems Conference and Exhibit* (p. 1986).

[47] Rudlosky, S., Goodman, S., Virts, K., Bruning, E. (2019). Initial geostationary lightning mapper observations. *Geophysical Research Letters*, 46, 1097– 1104. https://doi.org/10.1029/2018GL081052

Ground Station Operations:

Antennas for geostationary spacecraft are fixed in position as the spacecraft doesn't move relative to the Earth's surface. The ground segment maintains continuous contact with the spacecraft, and therefore the spacecraft can broadcast uninterrupted telemetry and data streams to the ground network. Likewise, the ground segment can issue commands to the spacecraft at any time. The ground segment collects the spacecraft's telemetry and science data and disseminates it to data processing facilities. The data can be processed directly on-site or transferred via a fibre connection to an off-site facility.

One physical phenomenon can predictably disrupt the continuous communications link between the spacecraft and ground segment. Not only does the Sun's transit of the equatorial plane during the equinoxes cause eclipses, but it also induces communications outages. Once per day, the satellite will transit between the Earth and Sun, causing the Sun to fall within the beamwidth of the ground station's antenna. The Sun creates noise that can entirely mask signals from the spacecraft, causing a so-called 'Sun transit outage'. These outages generally occur for 6 days around the equinoxes, and last for a maximum of 10 minutes[48].

6.3 GEO Lightning Detector Payload Design

Table 18 below provides preliminary specifications for a potential downscaled GEO lightning detector. The downscaling was based on the MTG-LI instrument's specifications, assuming that only one optical head (out of four) is kept. Performance specifications (e.g. ground sampling distance, detection efficiency or frame rate) are assumed to be equal to those of MTG-LI.

Such an instrument could potentially be flown on a micro-GEO platform but with a reduced coverage compared to existing GEO instruments. The achievable coverage can be visualised in Figure 17 (keeping only one of the two areas covered). A full-scale instrument would require a much larger platform such as the Japanese Himawari satellite.

[48] Roddy, D. (2006). Satellite Communications (4th ed). New York: McGraw-Hill. https://www.accessengineeringlibrary.com/content/book/9780071462983

Table 18: GEO lightning detector payload specifications.

ID	Specification	Value	Derivation
CDF-S-LD-1	Mass (kg)	31	MTG-LI weighs 93 kg[49]. A third of this mass was assumed for a single optical head.
CDF-S-LD-2	Volume (mm^3)	400 x 400 x 1200	MTG-LI has a 718 mm x 1200 mm x 1456 mm volume envelope. The volume was scaled down by about a fourth.
CDF-S-LD-3	Power (W)	100	MTG-LI consumes 300 W[50]. A third of this power was assumed for a single optical head.
CDF-S-LD-4	Data rate (Mbps)	7.5	MTG-LI operates at 30 Mbps[50] with four optical heads. The proposed concept uses one optical head, hence will generate data at 7.5 Mbps.
CDF-S-LD-5	Pointing knowledge (arc min)	0.2	Derived from the requirement to geolocate within half a GSD from the GEO altitude as proposed during the study (half of 4.5 km[50] from 35,786 km).
CDF-S-LD-6	Duty cycle	100%	The lightning detector must be operating constantly.

Note: these initial specifications are estimates only, and do not result from an actual payload design.

[49] https://www.eoportal.org/satellite-missions/meteosat-third-generation#li-lightning-imager

[50] https://digitalcommons.usu.edu/cgi/viewcontent.cgi?filename=0&article=1228&context=calcon&type=additional

6.4 GEO Propulsion Sub-System Requirements

A GEO-based lightning detection platform requires a propulsion subsystem to fulfil requirements from MIS-6 and MIS-8. Table 19 summarises the propulsion subsystem requirements that are directly related to high-level mission requirements.

Table 19: GEO platform propulsion subsystem requirements.

ID	Requirement	Upstream
CDF-R-LD-15	The GEO spacecraft must be placed in the desired operational GEO slot in less than 8-12 years	MIS-8
CDF-R-LD-16	The GEO spacecraft must be able to support no less than 5 years of operational manoeuvres including station-keeping.	MIS-6
CDF-R-LD-17	The propulsion subsystem of the GEO spacecraft must be able to place the spacecraft into an appropriate disposal orbit after no less than 5 years of operations has been completed.	MIS-6

6.4.1 Propulsive manoeuvre options

The spacecraft must carry enough propellant to perform all manoeuvres implied by the mission requirements above. Each anticipated manoeuvre is associated with a velocity change quantity. The itemised total of the spacecraft's velocity changes is referred to as a Delta-V budget.

Two Delta-V budgets are presented in the following sections to represent trades between compliance risk and launch cost.

6.4.2 Delta-V Budget Option 1 (GTO to GEO transfer)

The Delta-V budget in Table 20 describes the manoeuvres that the spacecraft would perform throughout its mission life if a Geostationary Transfer Orbit (GTO) were used for orbit insertion. To enter mission orbit from GTO, the spacecraft uses on-board propulsion to circularise and declinate its orbit at GTO apogee, which is equal in altitude to its desired GEO slot. To end the mission, the spacecraft would propel itself to a higher altitude for disposal, referred to as a GEO graveyard orbit.

This Delta-V budget option trades potentially higher compliance risk for lower launch cost. Assuming the satellite is operable (i.e. it survives the launch), a GTO orbit is highly elliptical with perigee in low-LEO (altitude below 1000 km) and apogee at GEO altitude. A launch vehicle only needs to insert the spacecraft into a GTO perigee altitude and inclination.

For a Delta-V budget total of 2063 m/s, the propellant mass at launch is estimated to be 105.8kg[51]. This propellant mass assumes a chemical propulsion system is used for all manoeuvres[52]. Though it is possible to use electric propulsion to lower on-board propellant mass, the cost of this decision is higher power consumption and lower achievable thrust. The effect of lower thrust causes GTO to GEO insertion time to increase from several hours (if chemical propulsion was used) to roughly 325 days[53]. As a result, choosing electric propulsion over chemical propulsion for this stage may affect compliance with CDF-R-LD-15.

This Delta-V budget does not account for evasive manoeuvres.

Table 20: Option 1 for Delta-V Budget of GEO lightning detector platform.

ID	Manoeuvre	Assumption	Delta-V (m/s)
CDF-S-LD-7	**Orbit-raise from GTO**	Launch vehicle inserts satellite into highly elliptical Geostationary Transfer Orbit (GTO) at a LEO altitude[54]. Perform a thruster burn at GTO apogee to correct inclination and circularise into desired GEO altitude. Circularising when the spacecraft is at GTO apogee (at GEO altitude) is assumed to lead to lower Delta-V and monetary costs when compared to direct launch into GEO or Hohmann transfer from a LEO insertion.	1496
CDF-S-LD-8	**Station-keeping**	Preliminary calculations indicate that station keeping for a 5-year mission, consisting of East-West and North-South burns, requires 235 m/s. This Delta-V figure has been rounded up to 250 m/s to add margin that accounts for 46 – 50 m/s estimates found in existing literature[55].	250
CDF-S-LD-9	**GEO Disposal**	A circular GEO graveyard orbit is assumed, so a Hohmann transfer with a total perigee change of 302 km is targeted.	277
CDF-S-LD-10	**Total**	Add 2% Delta-V to running total to account for errors such as launcher injection, thruster pointing inaccuracies[56].	**2063**

[51] The rocket equation relates fuel mass to change of velocity, so propellant mass at launch is obtained by solving the equation for propellant mass. A 10% mass margin is applied to this propellant mass figure. For reference, a summary of the rocket equation may be found here: https://www.grc.nasa.gov/www/k-12/rocket/rktpow.html

[52] A representative Isp figure of 285s is obtained from the customisable TRL 9 Dawn Aerospace B20 thruster which uses performant green propellant (nitrous oxide and propene). Datasheet can be found at https://www.dawnaerospace.com/s/DA-B20-Thruster-Specifications.pdf

[53] Thomas, D. (2016) A comparison of GEO Satellites Using Chemical and Electric Propulsion. University of Colorado.

[54] Ariane-5 standard mission profile for GTO is used for reference GTO insertion delta-V calculations. Source https://www.arianespace.com/wp-content/uploads/2020/06/Arianespace_Brochure_Ariane5_Sept2019.pdf

[55] The 45-50 m/s per year figure is an estimate provided in Soop, Erik Mattias. Handbook of geostationary orbits. Vol. 3. Springer Science & Business Media, 1994

[56] The 2% figure is to account for "Dispersion burns" as noted in Gülgönül, S., & Sözbir, N. (2018). Propellant Budget Calculation of Geostationary Satellites.

6.4.3 Delta-V Budget Option 2 (Graveyard to GEO transfer)

This section contains an alternative Delta-V budget where the spacecraft is initially inserted into an above-GEO orbit at “disposal” altitude. After initial placement, the spacecraft descends to its mission orbit by way of Hohmann transfer to its desired GEO slot. At the end of the mission, the spacecraft completes a second Hohmann transfer to return to an above-GEO graveyard orbit for disposal.

This Delta-V budget option trades potentially higher launch costs for lower compliance risk. Though direct insertion and facilitation with an orbital transfer vehicle of the spacecraft into an above-GEO graveyard orbit may be costly, this option all but ensures compliance with orbital debris disposal regulations in case of dead-on-arrival failures or catastrophic in-orbit commissioning faults (CDF-R-LD-17).

The Delta-V budget in Table 21 below describes the manoeuvres that the spacecraft would make throughout its mission life if a Geostationary Transfer Orbit (GTO) were used for orbit insertion. This Delta-V budget is 814 m/s, while propellant mass is estimated at 41.7 kg. This Delta-V budget does not account for evasive manoeuvres.

Table 21: Option 2 for Delta-V Budget of GEO lightning detector platform.

ID	Manoeuvre	Assumption	Delta-V (m/s)
CDF-S-LD-11	**Hohmann transfer to mission GEO slot from above-GEO Graveyard orbit**	After the launch vehicle inserts satellite 300 km above GEO, return spacecraft to desired GEO slot as a circular-to-circular Hohmann transfer.	277
CDF-S-LD-12	**Station-keeping**	Preliminary calculations indicate that station keeping for a 5-year mission, consisting of East-West and North-South burns, requires 235 m/s. This delta-V figure has been rounded up to 250 m/s to add margin that accounts for 46 – 50 m/s estimates found in existing literature[57].	250
CDF-S-LD-13	**GEO Disposal**	At the end of the mission, return the spacecraft to a circular GEO graveyard orbit 300 km above GEO.	277
CDF-S-LD-14	**Total**	Add 2% delta-V to running total to account for errors such as launcher injection, thruster pointing inaccuracies[58].	**814**

[57] The 45-50 m/s per year figure is an estimate provided in Soop, Erik Mattias. Handbook of geostationary orbits. Vol. 3. Springer Science & Business Media, 1994

[58] The 2% figure is to account for “Dispersion burns” as noted in Gülgönül, S., & Sözbir, N. (2018). Propellant Budget Calculation of Geostationary Satellites.

6.4.4 Propulsion Technology Discussion

For the purposes of estimating propellant mass, chemical propulsion is assumed over electric propulsion. Chemical propulsion is associated with higher thrust, higher impulse and lower development cost when compared to electric propulsion systems[59].

Of the possible chemical propellants available, the propellant mass is baselined from a “green” propellant thruster. Green propellants are preferred as they are less toxic[60] and tend to be more stable to store than traditional space-grade propellants such as hydrazine.

Electric propulsion is becoming increasingly prevalent in modern satellite missions[61] for low-thrust applications such as station-keeping in GEO. For non-chemical missions requiring a high-impulse kick stage, the potential for spacecraft to carry both chemical and electric propulsion systems has recently begun to garner experimental interest[62,63].

Though technologies for electric thrusters capable of GTO transfers are also emerging[64], this report assumes chemical propulsion as “green” propellant options are viable for the general combination of high-TRLs, high-thrust and lower power consumption.

6.5 Commercially Available GEO Platform Options

As mentioned previously in section 6.1.3, commercially available platforms suitable to operate from LEO to GEO are available, including options for launch and mission operations. However, these cannot be fully specified at this point as they typically require extensive tailoring to meet the mission needs; this could be done as part of a future study.

6.6 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 communication antennas, and solar arrays. It typically consists of actuators and

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[59] NASA (2021) Small Spacecraft State of the Art Technology.

[60] In 2011, the European Commission’s Registration of Evaluation Authorisation and Restriction of Chemicals framework legislation added Hydrazine, a common satellite monopropellant at this time, to the list of “substances of very high concern”. As a result, the ESA encourages development of more ‘green propellants’ such as ECAPS LMP-103S as older, more volatile propellants like hydrazine are likely to be restricted in the short to medium term. The ESA’s perspective on this discussion may be found here: https://www.esa.int/Space_Safety/Clean_Space/Considering_hydrazine-free_satellite_propulsion

[61] Electric propulsion has been used in GEO communications satellites since at least the 1990s, albeit for station keeping. For an example using the SPT-100 thruster, see Sankovic.J et. al. (1993) Performance Evaluation of the Russian SPT-100 Thruster at NASA LeRC.

[62] For instance, the recent NASA DART (asteroid redirection) demonstrated a hybrid chemical hydrazine and electric Xenon-based propulsion system. See https://www.rocket.com/article/aerojet-rocketdyne-delivers-dart-spacecraft-propulsion-systems-ahead-2021-asteroid-impact

[63] Due to lack of heritage in GEO of mixed propulsion systems, mixed propulsion systems are ignored in this report so that design complexity is limited. For interest, a high-level discussion on the trends towards hybrid chemical and electric on-board propulsion systems for small satellites may be found here: https://idstch.com/space/space-propulsion-moving-to-hybrid-chemical-and-electric-propulsion-system-to-power-cubesats-to-asteriod-missions/

[64] Emsellem. G, Hallock. A (2017) The Rise of the Electric Age for Satellite Propulsion. New Space ,Vol. 5, Issue 1, 4-14.

sensors. Actuators include reaction wheels and magnetic torquers. Sensors include star trackers, magnetometers, and inertial measurement units.

During the lifetime of GEO satellites, its attitude is continuously affected by disturbances in the form of gravity gradients, solar radiation pressure, magnetic fields and aerodynamic torques. It is these disturbance torque fields that need to be reacted against to maintain satellite pointing requirements. For effective attitude determination and control, there is a requirement to control the satellite attitude using reactions wheels or magnetic torquers.

Attitude control systems in turn need input from star trackers, sun sensors, earth sensors, inertial sensors, or GPS receivers etc. to close the attitude control system loop. Commercial suppliers of satellite bus systems provide integrated attitude control systems guidance, navigation, and control (GNC) subsystems. It is important to maintain communication with the bus system supplier to ensure the increase in moment of inertia because of the satellite sensor hardware, can be accommodated by the proposed reaction wheels/magnetic torquer assemblies.

As a commercial off-the-shelf bus is being considered for this mission, no detailed ADCS design is required. Commercial off-the-shelf platforms are available that will be able to support lightning detection payload pointing requirements.

6.6.1 Derived Pointing Requirements

Table 22: Derived pointing requirements.

ID	Requirement	Upstream
CDF-R-LD-32	The attitude determination and control system architecture for the lightning detector sensor must provide a 10 km or less ground plane resolution for a LEO orbit at 550 to 600 km and at 35 788 km for a GEO orbit.	
CDF-R-LD-33	In support of both the LEO and GEO ADCS, the spacecraft must be able to support no less than 5 years of operational manoeuvres including station-keeping.	

Storm supercells can cover many hundreds of kilometres in width down to isolated storm cells in the tens of kilometres. Therefore, pointing requirements, in the order of 10 kilometres, would suffice to cover all storm cell sizes.

At the proposed LEO altitude of 550 to 600 kilometres while over Australia, this would require a pointing accuracy in the order of 1° minimum. For a GEO platform at altitude of 35 788 km, the pointing requirements become more refined and equates to approximately 0.016 degrees.

Derivation of the above comes from:

- LEO 550 km orbit: (arctan (5/550)) x 2 ~ 1.04 degrees.
- LEO 600 km orbit: (arctan (5/600)) x 2 ~ 0.96 degrees.
- GEO orbit: (arctan (5/35788)) x 2 ~ 0.016 degrees.

6.7 Electrical and Thermal Sub-Systems

As no specific payload design has been performed, the bus specifications cannot be derived at this time.

6.8 On-Board Data Handling

A GEO mission can downlink data to the ground at any time, as discussed in Section 6.2, and must do so within 20 seconds of data collection to meet requirement MIS-04. As such, lightning strike data only needs to be stored long-term on-board when there is a communications outage; in all other cases having a small on-board data buffer is sufficient.

Table 23: GEO platform on-board data handling requirements.

ID	Requirement	Upstream
CDF-R-LD-18	During abnormal operations, the mission shall operate for up to four days without the ability to downlink data, without loss of any data. *Rationale: Whilst untimely data cannot be used for real-time lightning strike reporting, the event data may still be useful in the context of providing a continuous/uninterrupted time-series data product. Four days is a generally recommended timespan that balances the possible length of an operational outage with a need to store excessive amounts of data. This requirement is a recommendation by UNSW Canberra Space.*	

The on-board data storage needs of the satellite are calculated below in Table 24:

Table 24: GEO platform on-board data storage specification.

ID	Specification	Value	Derivation
CDF-S-LD-15	On-board data storage (Gbit)	2592	Four days of data collection from the payload, which is generating data at 7.5 Mbps (CDF-S-LD-4).

6.8.1 Communications Subsystem Derived Requirements

The LEO pathfinder communications system requirements derived in Section 5.7.1 are generally applicable to a GEO mission. Additional requirements for a GEO mission are given here and take priority over the requirements for a LEO mission if there is a conflict.

Table 25: GEO platform communications requirements.

ID	Requirement	Upstream
CDF-R-LD-19	During normal operations, payload data shall reach the ground segment at most 20 seconds after the data was created.	MIS-04
CDF-R-LD-20	The communications system shall have an in-orbit operational life of at least five years post-commissioning.	MIS-06

6.8.2 Payload Data Volume Estimation

The science data volume was calculated using the payload data rate of 7.5 Mbps (given by CDF-S-LD-15) (see Table 24), acquiring 100% of the time, giving similar lightning detection performance to the GOES-R GLM instrument[65]. In GEO, the detector operates and generates a continuous stream of event data. Always-available ground station coverage can be attained with a single ground station within view of the satellite, as the satellite remains stationary with respect to a ground observer. The data latency and downlink capacity requirements are satisfied when the payload data rate is lower than the radio downlink rate; that is, when data can be downlinked faster than it is generated. This simplifies the ground segment design and analysis.

Table 26: Lightning detector data volume assessment.

ID	Parameter	Value
CDF-S-LD-16	Payload Output Data Rate (Mbps)	7.5[66]
	Derivation	
CDF-S-LD-17	Packeting Overhead (%)	**10%**
CDF-S-LD-18	Required Data Downlink Rate (Mbps)	**8.25**

[65] Samantha Edgington, Clemens Tillier, Mark Anderson, "Design, calibration, and on-orbit testing of the geostationary lightning mapper on the GOES-R series weather satellite," Proc. SPIE 11180, International Conference on Space Optics — ICSO 2018, 1118040 (12 July 2019); https://doi.org/10.1117/12.2536063

[66] Value taken from CDF-S-LD-4, Table 18, page 75.

6.8.3 Telemetry Data Volume Estimation

This section considers the telemetry data required for the operation of the payload; it does not consider needs for general housekeeping (such as battery monitoring, solar panel efficiency, system performance metrics and diagnostics). Housekeeping telemetry is handled by the satellite platform and depends on the specific design. UNSW Canberra Space's previous LEO experience has been with systems that generate 100 to 200 B/s of housekeeping data.

The design study did not identify any onerous payload telemetry requirements. As such, any payload telemetry needs could be handled by the platform telemetry system. A dedicated telemetry radio is not required for this mission. High-frequency payload telemetry is likely to be directly related to the science output of the payload, and as such should be handled via the science data downlink pathway.

7 Space Segment Implementation

This section considers some of the implementation issues related to development of an Australian lightning detector space mission. FrontierSI have prepared an Australian Capability Assessment report which should be referred to for more detailed analysis related to Australian industry capabilities.

7.1 Instrument

7.1.1 Description

Optical lightning detector systems essentially consist of the following four critical subsystems:

- Image sensors
- Control Electronics
- Optical System
- Payload Data Handling and Onboard Processing Systems.

According to FrontierSI, it is entirely feasible for the Australian space sector to deliver a complete lightning detector payload for a LEO mission within a 3- to 5-year development timeframe, although this may be extended by the need to develop capability as a lead-in to an eventual GEO mission. Nearly all of the components and subsystems can be designed, manufactured, integrated, and tested in Australia, with the exception of the sensor arrays and potentially some optical elements, such as narrowband filters and custom lenses or mirrors, which may need to be sourced from international suppliers depending on risk and timeline budgets. The design, selection and integration of the focal plane arrays and optical elements can be performed in Australia, however, and adequate support and risk appetite could enable the optical elements to also potentially be partially manufactured in Australia.

There are currently significant gaps in critical capabilities to delivering a GEO-class lightning detector, including in large scale filter and sensor array production, optical testing facilities and program management, systems engineering, and quality management. Ongoing investment will be needed to build up this capability, and any LEO pathfinder mission must be implemented with a long-term vision towards a GEO payload.

Although the LEO mission is intended as a pathfinder, the GEO mission should be defined in parallel to allow for specific capability gaps and potential risk mitigation schemes to be identified. The LEO mission design can then support closing these gaps towards an eventual GEO mission. This may result in an over-engineered or more complex system than if a LEO mission was the primary focus, but will result in significant reduction in risk, and possibly cost and schedule, for a GEO mission development.

7.2 Satellite Bus

7.2.1 Description

The spacecraft bus serves to provide the necessary functions of the spacecraft that are not specific to the payload. These functions consist of:

- Mounting to and release from the launch vehicle
- Power generation and distribution
- Command and data handling
- Telemetry and communications
- Thermal control
- Radiation shielding
- Guidance, navigation, and control.

These functions are typically divided among the spacecraft subsystems and their subsequent components as shown in Table 27.

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

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

The former option typically costs less and has lower inherit risk due its flight heritage but may not have sufficient performances to meet the minimum requirements. Conversely, the latter option will typically meet the minimum requirements, as it has been custom-built to do so, but the custom-build incurs a higher risk due the lack of flight heritage and a higher cost.

Table 27: Spacecraft bus subsystems and associated components.

Subsystem	Components
Structures & mechanisms	• Structure • Separation System • Hold-Down Release Mechanisms (HDRMs) • Radiation shielding
Thermal management	• Heaters • Radiators • Insulation
Power management	• Solar arrays • Solar array drive assemblies (SADA) • Batteries • Power Control Unit (PCU)
On Board Data Handling (OBDH)	• Flight Computers • Flight Software
Communications	• Radios • Antennae
Attitude Determination and Control System (ADCS)	• ADCS Computer • Coarse Sun Sensors • Earth Horizon Sensors • Magnetometers • Gyroscopes • GPS • Star Trackers • Reaction Wheels • Magnetorquers
Propulsion	• Thruster • Tanks • Propellant
Other	• Harnessing (electrical & signal) • Balance mass

7.2.2 Australian Space Industry Capability

A few Australian spacecraft busses are in development but are not currently at a level of maturity that would meet the reliability requirements. However, they may reach suitable maturity by the time of mission launch.

Such busses are produced by Inovor Technologies and by Skykraft and are designed for use in LEO. The details of their platforms that are suitable for the LEO Pathfinder mission are listed in Table 28. Australia does not currently produce any busses suitable for GEO.

Australia also has few flight-proven subsystems. A small number of companies such as Advanced Navigation and Infinity Avionics[67] provide some avionics components which would require additional integration into a subsystem. For this analysis, no Australian subsystems are considered as additional technology readiness raising would be required.

7.2.3 LEO Platform options

For the LEO Pathfinder platform, three implementation options exist:

1. Procure a COTS platform within the existing available options,
2. Procure and customise a COTS platform to suit requirements of the mission, or
3. Develop a fully customised platform to suit the requirements of the mission.

Due to the limitations of this study, time was only afforded to explore existing COTS options. From a survey of (soon to be available) Australian and existing international platforms, existing COTS platforms appear to have sufficient capability to meet the mission requirements and therefore any platform customisation does not appear warranted. Table 28 presents a selection of 12U CubeSat COTS platforms deemed suitable for the LEO pathfinder mission.

[67] Infinity Avionics is a spin-out company of UNSW Canberra Space. They are quoted here for completeness.

Table 28: Platform options for a LEO pathfinder.

	Model	Country of Origin	Payload Size	Max. Payload Mass (kg)	Average Payload Power (W)	Data Downlink (Mbps)	Pointing Accuracy (degrees)	Heritage
Payload Requirements			*100 x 200 x 250 mm*	*10*	*12*	*<1*	*0.2*	
Inovor[68]	12U Apogee	Australia	-	-	-	-	-	Nil
Skykraft[69]	Block 2	Australia	Approx. 360 x 240 x 135mm	N/A	-	-	-	Launched technology demonstrator in Jan. 2023
Blue Canyon Technologies[70]	XB12	USA	8U	-	92 – 108 (total S/C power)	2 – 10	±0.002	Yes
EnduroSat[71]	12U	Bulgaria	9U (197 x 197 x 225mm)	14 – 16	20 – 45	Up to 1000	<0.1°	Yes
GOMspace[72]	12U	Sweden	8U	14.0 (max)	39.5 – 100 (total S/C power)	0.5 to 225	0.07°	Yes
Kongsberg Nanoavionics[73]	M12P	Lithuania	Up to 8U	16.0	~20	-	0.1°	Yes

[68] https://www.inovor.com.au/space-technology/bus-platform/

[69] https://www.unsw.adfa.edu.au/sites/default/files/documents/990391422%20-%20OzFuel%20Report%20Publication_FA_0.pdf

[70] https://storage.googleapis.com/blue-canyon-tech-news/1/2022/04/BCT_DataSheet_Spacecraft_XB6.pdf

[71] https://www.endurosat.com/cubesat-store/cubesat-platforms/12u-cubesat-platform/

[72] https://gomspace.com/12u.aspx

[73] https://nanoavionics.com/small-satellite-buses/12u-nanosatellite-bus-m12p-m12p-r/

	Model	Country of Origin	Payload Size	Max. Payload Mass (kg)	Average Payload Power (W)	Data Downlink (Mbps)	Pointing Accuracy (degrees)	Heritage
Space Inventor[74]	12U	Denmark	6U – 8U	6 – 9	-	4 – 200	0.01°	-
Tyvak[75]	Trestles 6U	Italy	9U	13	180 (peak)	2 – 50	-	Yes

[74] https://space-inventor.com/satellites/12u-satellite/ (100W payload power is likely peak power.)

[75] https://www.tyvak.eu/platforms/

7.2.4 GEO Platform Options

Like the LEO Pathfinder platform, three implementation options exist:

1. Procure a COTS platform within the existing available options,
2. Procure and customise a COTS platform to suit requirements of the mission, or
3. Develop a fully customised platform to suit the requirements of the mission.

Existing COTS platforms suitable for the GEO instrument are quite limited and a fully customised platform would be very expensive to develop, so with the time afforded for this study, only customisable GEO platforms were explored. Table 29 presents the available information on GEO platforms that could be customised to suit the GEO mission.

Table 29: Platform options for GEO spacecraft.

	Model	Country of Origin	Spacecraft Mass (kg)	Payload Size	Payload Mass (kg)	Average Payload Power (W)	Data Downlink (Mb/s)	Pointing Accuracy (degrees)	Lifespan	Heritage
Payload Requirements				*400 x 400 x 1200 mm*	*31*	*100*	*7.5*	*0.4*		
Astranis[76]	MicroGEO	USA	~350	-	-	-	-	-	-	-
Blue Canyon Technologies[77]	X-SAT Saturn Class	USA	-	17" x 16.4" x 27" (431.8 x 416.6 x 685.8 mm)	200	222 (total S/C power)	-	±0.002	> 2 years	Yes
Lockheed Martin[78]	LM400	USA	400-800	-	-	-	-	-	-	-
Rocket Lab[79]	Photon	USA	Launch vehicle dependent	-	-	Tailored	-	-	Dependent on path to orbit	Yes
Space Inventor[80]	Microsatellite		150	Custom	5 – 100	-	-	-	-	-
Terran Orbital[81]	GapSat-1	USA	-	-	-	-	-	-	-	-

[76] https://www.astranis.com/microgeo

[77] https://storage.googleapis.com/blue-canyon-tech-news/1/2022/04/BCT_DataSheet_Spacecraft_Microsat_Saturn.pdf

[78] https://www.lockheedmartin.com/content/dam/lockheed-martin/space/documents/satellite/LM400_Product_Card_Fact_Sheet.pdf

[79] https://www.rocketlabusa.com/space-systems/photon/ & conversation with RocketLab Business Development Manager

[80] https://space-inventor.com/satellites/microsatellite/

[81] https://advanced-television.com/2019/06/28/gapsat-plans-for-mini-geo-satellites/

7.2.5 Recommended Approach

For the LEO Pathfinder mission, the abundance of COTS 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 cost and risk. Without deeper analysis of each COTS platform, recommendations on a particular platform or 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.

For the GEO platform, given the lack of fully COTS options, a customisation of an existing platform is likely the best option. The performance requirements to reach and survive in GEO are higher than LEO, and therefore a customised platform will better suit the mission needs. Due to this customisation, and the lack of available information on existing GEO platforms, a recommended supplier or recommended list of shortlisted suppliers, cannot be made at this stage. The degree of customisation will need to be negotiated in conjunction with the platform developer and possibly the launch service provider. Again, an open-tender process where responses from the prospective suppliers are evaluated on their ability to meet the mission requirements is the recommended approach.

8 Assembly, Integration and Testing

8.1 General AIT Considerations

UNSW Canberra Space recommends a “test like you fly” Assembly, Integration and Testing (AIT) philosophy. This approach is important to ensure the following:

a. Validation of a system’s ability to perform its mission, and not just a verification of system requirements.

b. Assessment of mission concepts for testing and calculation of the risk for those concepts that are not readily testable.

c. The acquired systems can accomplish the intended mission.

d. A testing process for mission assurance at all levels of assembly, even across interface boundaries.

The principle of a “test like 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. When it is not possible to “test like you fly”, risk management becomes more important.

For the Lightning Detector mission, effective “test like you fly” is driven by mission operations concepts, flight constraints, flight conditions and mission considerations. To this end, appropriate documentation, hardware, software, trained personnel, etc., is required as well as identifying what is feasible and practical to test.

An AIT Plan (see Reference Documents 1 – 9), which serves as a roadmap for all AIT and “test like you fly” activities, must be drawn up very early in the development program.

a. The AIT Plan describes the complete AIT process and demonstrates, together with the verification plan, how the requirements are verified by inspection and test.

b. It contains the overall AIT activities and related verification tools (Ground Support Equipment (GSE), facilities etc), the involved documentation, AIT management and organisation, as well as the AIT schedule.

c. 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 very close to the final issue, where only late modifications are implemented.

d. 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.

e. 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.

f. The AIT Plan will be complementary to the Verification Plan (a prerequisite to the preparation of the AIT Plan) and takes into account the test standards defined in the customer requirements.

The AIT programme associated with the Lightning Detector mission should:

a. Document AIT activities and associated planning.
b. Include AIT matrices that link the various AIT activities with AIT specifications, AIT procedures, AIT blocks and hardware models.
c. AIT programmes, including inspections to be detailed through dedicated activity sheets.
d. The activity sheets will include descriptions of the activity, including the tools and Ground Support Equipment (GSE) to be used, the expected duration of the activity and the relevant safety or operational constraints.
e. The sequence of activities is presented as flow charts.

AIT and Engineering should work:

a. In an iterative and communicative way, AIT specifications (at the equipment level and at the element level) are developed by the engineering staff.
b. In an iterative and communicative way, the AIT specifications are turned into step-by-step AIT procedures by the AIT staff.
c. 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:

a. 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.
b. PTR (Post-Test Review) – The focus of the PTR is to come to 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.
c. 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.

For the purposes of AIT and from an Australian capability aspect, a non-exhaustive summary of current capabilities is provided below with reference to 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.

8.2 Australian Space Industry Capability

The FrontierSI report provides some analysis of Australian AIT capabilities. The following test facilities relevant to this mission have been identified within Australia:

Australian National University (ANU) National Space Test Facility (NSTF)[82]

a. 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.

b. Shock / Vibration – Maximum random force 22.2 kN Root Mean Square (RMS), maximum test item mass 500 kg.

c. EMI / EMC – Internal dimensions 3.7 m x 2.7 m x 2.3 m.

d. 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

1. 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/m^3. Separate vacuum chamber with an internal diameter of 1.5 m and length of 4.79 m. The maximum weight of the test article is 900 kg.
2. Shock / Vibration – Maximum test item mass 700 kg.
3. EMI / EMC – No test capability at this facility.
4. Radiation – No test capability at this facility.

8.3 Recommended Approach for a Lightning Detector Mission[83]

The assembly and integration of a lightning detector and associated support hardware requires a standard laboratory and a 'clean' room facility. Laboratory tests encompasses certification of lightning detector ground test equipment. Clean room facilities required during assembly and testing of satellite engineering and flight hardware.

The lightning detector and associated satellite assembly will require shock, vibration, thermal, vacuum, EMC / EMI testing with additional radiation test of onboard electronics and associated hardware. This is especially important for a geostationary orbit configuration.

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

[83] Resource from Hugh J. Christian University of Alabama via https://doi.org/10.1175/1520-0426(2000)017<0905:LCOTOT>2.0.CO;2

Key AIT related testing of a space borne lightning detector must encompass more than a calibration and radiometric testing and must include the illumination of the sensor with both a bright background signal and pulses of light.

The following ground based transient response tests are required to determine detection efficiency, false alarm rates and threshold levels for the instrument:

- A diffuse cloud-top (using an integrating sphere) test to determine responsivity of each pixel to a steady optical source.
- A ‘field of view’ test to determine its extremities and to determine the lens transfer function which is fundamental to lightning geolocation.
- A spectral test to determine sensor end-to-end relative spectral response near and within the passband of the narrowband interference filter.
- A test to determine the transient response of the lightning detector to pulses of various integrated energies against different levels of steady-state background radiance.

There is also a requirement to provide an in-flight calibration process to ensure optical alignment and movement of the narrowband filter centre wavelength. This is required to ensure that the effects of launch, thermal cycling has not affected the pre-launch calibration.

9 Calibration and Validation

9.1 Description

Calibration and Validation (Cal/Val) of the instrument is essential for the accuracy of acquired data, and to enable the data to be combined with data from other EO satellites. Cal/Val must be planned and implemented in conjunction with the instrument development to ensure overall performance requirements are met. An on-board calibration subsystem may be necessary to maintain low uncertainties in radiometric output, uniformity, and stability. On-board calibration options include passive-solar or active-LED lamp source systems, which provide a known an accurate radiometric input to the instrument. Further analysis is required at a later phase of the mission design to determine whether the benefits of an on-board calibration system justify the added mass, volume, and complexity. Cal/Val will begin before launch and continue for the life of the mission. The Cal/Val phases and their estimated durations are outlined below.

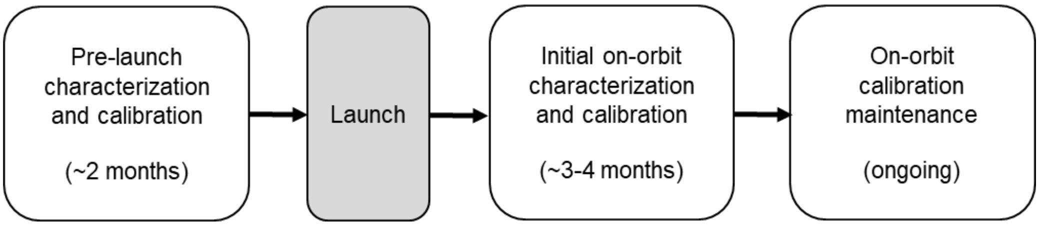

Figure 23. Satellite Mission Cal/Val Phases[84]

9.2 Australian Space Industry Capability

FrontierSI have prepared an Australian Capability Assessment report which should be referred to for more detailed analysis related to Australian industry capabilities.

With respect to calibration and validation of a lightning detector (comprising an optical transient detector and lightning imaging sensor), an optical calibration facility is required. Dedicated optical calibration facilities exits in Australia such as:

- Australian Government, Department of Industry, Science and Resources – Lindfield Laboratory (Accredited by the National Association of Testing Authorities "NATA")
- Kingfisher International Pty Ltd. – Melbourne Laboratory (Accredited by the National Association of Testing Authorities "NATA")

It must be noted that the above two facilities provide calibration and testing of reference measurement instruments such as an integrated sphere (optical transmitter) and does not indicate provision for validating and calibrating a dedicated flight instrument. In other words, the above facilities can provide calibration of the instrumentation to be used as a source of light but not the

[84] Resource from Hugh J. Christian University of Alabama via https://doi.org/10.1029/JD094iD11p13329

proposed sensor instrument. The Lindfield Laboratory does, however, provide consultancy services and training in calibration and optical measurements.

9.3 Implementation Options

Calibration and validation of the satellite sensor, for both a LEO and GEO configuration 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[85].

The alternative option is to contract out the calibration and validation of the satellite sensor head at increased cost to the customer.

9.4 Recommended Approach

For calibration and testing, the satellite optical sensor should be mounted on an assembly of two motorised positioning systems (for example Newport/Klinger P/N RTN160PP or similar). This will provide accurate pitching and yawing positioning of the sensor so that any pixel across the CMOS sensor will be illuminated. Illumination of the sensor should be carried out using an integrating sphere (Optronics Laboratories, Inc., P/N OL 455-8-1 or similar) to simulate deep convection radiance.

For the testing and calculating the lens field of view and transfer function (required for accurate lightning geolocation), the satellite sensor head should be illuminated with a near infrared light-emitting diode (P/N 1A330 or similar by ABB HAFO, Inc.) coupled to a 9-inch diameter, off-axis paraboloid mirror.

For determining spectral response of any narrowband filters, the use of a high-resolution grating monochromator such as an Omni-λ 750I series or similar coupled with a quartz tungsten halogen lamp and a krypton rare gas discharge lamp as a wavelength reference. Output from the monochromator is collimated by a small off-axis paraboloid mirror. Uncertainties in the spectral response measurements should be monitored by repeat calibrations of the monochromator.

For transient response testing against various levels of steady-state background radiance, a 2-inch SPECTRALON integrating sphere containing a near-infrared LED and small quartz tungsten halogen lamp[86].

85 https://doi.org/10.1175/1520-0426(2000)017<0905:LCOTOT>2.0.CO;2

86 A more in-depth description of the above can be found in https://doi.org/10.1175/1520-0426(2000)017<0905:LCOTOT>2.0.CO;2

10 Launch Services

10.1 Description

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

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

Launch services typically fall into two categories:

- Dedicated launch,
- Rideshare.

10.1.1 Dedicated Launch

For a dedicated launch, a customer purchases the entire launch and thus can dictate the launch date (and time) and insertion orbit within the launch vehicle’s specifications and capabilities. This option offers the greatest mission flexibility but is also more expensive than a rideshare launch.

10.1.2 Rideshare Launch

For a rideshare launch, a customer purchases an available capacity on a launch vehicle that has a predefined launch date and insertion orbit. The launch date and orbit are either determined by the launch service provider or by the ‘prime’ customer (i.e., the organisation that has purchased most of the launch). This option gives limited mission flexibility but is much less expensive than a dedicated launch.

All launch service providers provide integration facilities at the launch site where the satellite is mounted to the launch vehicle. These consist of cleanrooms where customers can prepare their spacecraft prior to launch (check basic avionics functionalities, charge batteries, fill propellant, etc.) and support the integration of the spacecraft into the launch vehicle. For these activities, the satellite developer will need to provide suitable ground support equipment.

10.2 Australian Space Industry Capability

FrontierSI have prepared an Australian Capability Assessment report which should be referred to for more detailed analysis related to Australian industry capabilities.

Currently, there exists three Australian companies developing launch services from Australia, as follows:

1. Equatorial Launch Australia
2. Gilmour Space Technologies
3. Southern Launch

Gilmour Space Technologies is the only Australian launch service provider (LSP) that designs and builds its own launch vehicle, Eris, which is stated to conduct its first launch in 2023. Their launch site is situated at Bowen, in Queensland. While Gilmour Space Technologies indicate that they will provide launch services to LEO, MEO, GEO, and LLO (Low Lunar Orbit), only expected performance figures for LEO insertion are provided[87].

Alternatively, both Equatorial Launch Australia and Southern Launch facilitate launch sites for launch vehicles, with the launch sites located at Arnhem Space Centre, Northern Territory and Whalers Way, South Australia for the two companies respectively. These launch sites are being designed to accommodate launch vehicles produced by other companies, such as AtSpace's Kestrel I & V at Southern Launch's facility.

Lastly, Space Machines Company is developing an Orbital Transfer Vehicle (OTV) that will be capable of manoeuvring spacecraft to different orbits than that achieved by the launch vehicle. Their OTV, Optimus, is stated to have its first flight in 2023 on board a SpaceX Falcon 9 launch vehicle[88].

10.3 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 capacity:
  - Insertion orbit,
  - Mass to insertion orbit,
- Cost,

[87] https://www.gspacetech.com/launch

[88] https://www.spaceconnectonline.com.au/launch/5450-spacex-to-carry-space-machines-2023-satellite-taxi-into-orbit

- Ability to re-schedule the launch, should the project be delayed,
- Launch success history,
- Launch environment:
  - Acceleration,
  - Shock,
  - Acoustics,
- Launch site,
- Launch site facilities,
- Geopolitical factors with launch country.

10.3.1 LEO Pathfinder Launch Options

For the LEO Pathfinder, there are plenty of available launch services that cater for CubeSats, those being all rideshare launches. Moreover, the availability of such launch services is expected to increase as more small satellite launch vehicles that are currently under development become operational. Within those rideshare launches, there are options to either contract to the launch service provider directly (e.g. SpaceX, RocketLab, Virgin Orbit, FireFly, etc.), or through launch service brokers (e.g. SpaceFlight, EXO Launch, ISILaunch, etc.).

Table 30 list suitable launch service providers for the LEO Pathfinder mission.

10.3.2 GEO Mission Launch Options

For the GEO mission, there exist two options for the spacecraft to be launched and to arrive at its operational geosynchronous equatorial orbit GEO:

1. Spacecraft is inserted into a geosynchronous transfer orbit (GTO) by the launch vehicle; once there, the satellite in-orbit verification can be done and commissioning started. Once commissioned to some specified level, the spacecraft propels itself to GEO for completion of commissioning and start of routine operations. Once operations are completed, the spacecraft manoeuvres itself into a graveyard GEO for decommissioning.
2. The spacecraft is integrated onto an orbital transfer vehicle (OTV), which is then integrated onto the launch vehicle. The launch vehicle and OTV are responsible for delivering the spacecraft to a graveyard GEO, where the spacecraft undergoes commissioning[89]. Once commissioned, the spacecraft manoeuvres itself to a GEO to perform operations. Once operations are completed, the spacecraft manoeuvres itself into a graveyard GEO for decommissioning.

These options are shown diagrammatically in Figure 24.

[89] It is conceived that delivering the spacecraft to a graveyard GEO for commissioning is lower risk to existing GEO spacecraft given the possibility of the spacecraft failing commissioning.

Launch and orbital transfer services to GTO and GEO are significantly rarer than launch operations to LEO, as the number of spacecrafts at geosynchronous orbits are much fewer and typically designed to last longer than spacecraft at LEO. Furthermore, GEO spacecraft tend to be significantly larger than micro and/or small satellites and tend to purchase a dedicated launch vehicle for their mission.

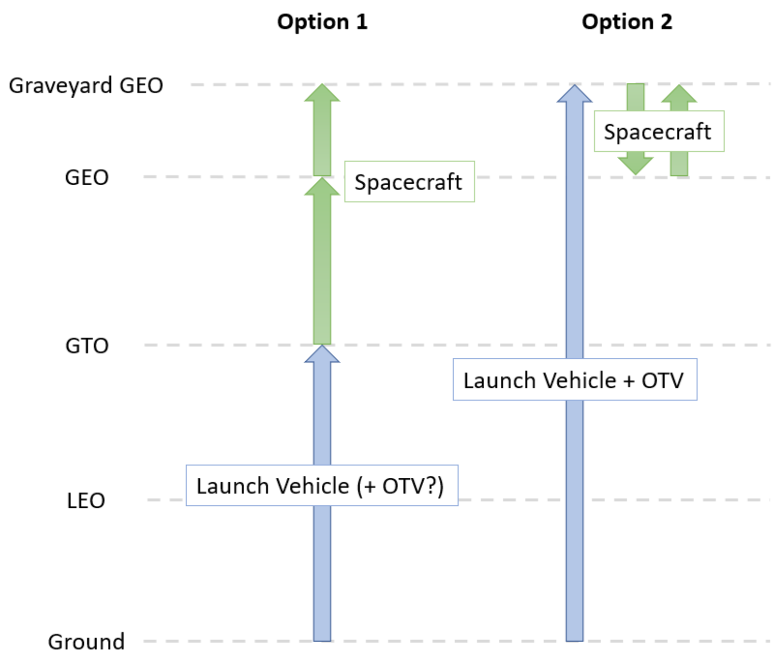

Figure 24: Launch options to GEO.

Table 31 lists the current, most applicable launch & orbital transfer service providers for delivering a micro or small satellite to either GTO or to GEO.

Table 30: Suitable LEO launch service providers.

Organisation	Country	Launch Vehicle	Launch Site	Available Orbit Inclinations	Launch Mass	Cost	Status	References
Gilmour Space	Australia	Eris	Bowen, Queensland, Australia		LEO: max. 305kg		*Under development, first launch scheduled for early 2023 [1]*	[90]
Arianespace	France	Vega	Spaceport, French Guiana		SSO (700km): max. 1500kg		Operational	[91], [92], [93]
		Vega C			SSO (600km): max. 2300kg			
FireFly Aerospace	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	[94], [95]

[90] https://www.gspacetech.com/launch

[91] https://www.arianespace.com/wp-content/uploads/2018/07/Vega-C-user-manual-Issue-0-Revision-0_20180705.pdf

[92] https://www.arianespace.com/vehicle/vega/

[93] https://www.arianespace.com/spaceport-facility/#

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

[95] https://www.space.com/firefly-aerospace-first-alpha-rocket-launch-failure

<table>
<tr><th>Organisation</th><th>Country</th><th>Launch Vehicle</th><th>Launch Site</th><th>Available Orbit Inclinations</th><th>Launch Mass</th><th>Cost</th><th>Status</th><th>References</th></tr>
<tr><td>Rocket Lab</td><td>USA (with NZ subsidiary)</td><td>Electron</td><td>Mahia Peninsula, NZ

Wallops, Virginia, USA (soon)</td><td>30 degrees to sun-synchronous

38 – 60 deg.</td><td>SSO (500km): max. 200kg
LEO (500km, 40° inclination): max. 265kg</td><td>~USD7.5M (dedicated launch)</td><td>Operational</td><td>[96], [97]</td></tr>
<tr><td>Virgin Orbit</td><td>USA</td><td>LauncherOne</td><td>Mojave, California, USA
Cornwall, UK</td><td>Any</td><td>SSO (500km): max. 300kg
LEO (230km): max. 500kg</td><td>~USD12M (dedicated launch)</td><td>Operational</td><td>[98], [99]</td></tr>
<tr><td>EXO Launch</td><td>Germany</td><td colspan="3" rowspan="3">Various. Coordinates payload launch services with launch service providers; mostly for rideshare missions.</td><td></td><td></td><td>Operational</td><td></td></tr>
<tr><td>ISILaunch</td><td>The Netherlands</td><td></td><td></td><td>Operational</td><td>[100]</td></tr>
<tr><td>Spaceflight</td><td>USA</td><td>LEO: min. 5kg (3U)
LEO: 200kg</td><td>USD145k
USD1.35M</td><td>Operational</td><td>[101]</td></tr>
</table>

[96] https://www.rocketlabusa.com/assets/Uploads/Electron-Payload-User-Guide-7.0.pdf

[97] https://spacenews.com/rocket-lab-to-launch-remaining-nasa-tropics-satellites/

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

[99] https://www.roundnews.com/science/space-astronomy/70113-virgin-orbit-failed-in-its-missio-to-launch-nine-satellites-in-orbit.html

[100] https://www.isilaunch.com/services/rideshare-launch/

[101] https://spaceflight.com/schedule-pricing/

Table 31: Suitable GEO launch service providers.

Organisation	Country	Launch Vehicle	Launch Site	Available Orbit Inclinations	Launch Mass	Cost	Status	References
Gilmour Space	Australia	Eris	Bowen, Queensland, Australia	-	-	-	*Under development, first launch scheduled in first half of 2023*	[102], [103]
Space Machines Company	Australia	Optimus (OTV)	Various	-	-	-	*Under development, first launch scheduled for April 2023.* [104]	[105], [106]
Arianespace	France	Vega	Spaceport, French Guiana	6 – 100 deg.	-		Operational	[107]
		Vega C			-			
FireFly Aerospace	USA	Alpha + SUV	Cape Canaveral, Florida, USA Wallops, Virginia, USA Vandenburg, California, USA	39 – 57 deg. 38 – 75 deg. 58 – 144 deg.	GEO: max. >600kg	~USD22M (dedicated launch)	Initial operations	[108]

[102] https://www.gspacetech.com/launch

[103] https://www.gspacetech.com/post/gilmour-space-completes-final-qualification-test-of-sirius-rocket-engine

[104] https://www.businessnewsaustralia.com/articles/space-machine-company-partners-with-spacex-for-2023-launch-of-its-optimus-orbital-transfer-vehicle.html

[105] https://www.spacemachines.co/

[106] https://www.businessnewsaustralia.com/articles/space-machine-company-partners-with-spacex-for-2023-launch-of-its-optimus-orbital-transfer-vehicle.html

[107] http://www.astronautix.com/k/kourou.html

[108] https://fireflyspace.com/wp-content/uploads/2022/01/Firefly_Aerospace_SUV_PUG-1.pdf

Organisation	Country	Launch Vehicle	Launch Site	Available Orbit Inclinations	Launch Mass	Cost	Status	References
Rocket Lab [7, 8]	USA (with NZ subsidiary)	Electron + Photon	Mahia Peninsula, NZ *Wallops, Virginia, USA (soon)*	30 degrees to sun-synchronous 38 – 60 deg.	SSO (500km): max. 200kg LEO (500km, 40° inclination): max. 265kg	~USD7.5M (dedicated launch)	Operational	
SpaceX	USA	Falcon 9	Cape Canaveral, Florida, USA Meritt Island, Florida, USA Vandenburg, California, USA		GTO: 5500kg	~USD67M (dedicated launch, re-used 1st stage)	Operational	[109]
ISILaunch	The Netherlands	Various. Coordinates spacecraft launch services with launch service providers; mostly for rideshare missions.					Operational	[110]
Spaceflight	USA				GTO: 200kg	USD11.2M	Operational	[111]

[109] https://www.spacex.com/media/Capabilities&Services.pdf

[110] https://www.isilaunch.com/services/special-orbits/

[111] https://spaceflight.com/schedule-pricing/

10.4 Recommended Approach

10.4.1 LEO Pathfinder

For the LEO Pathfinder mission, the only available options are rideshare launches that are managed either by a launch service provider or by a launch service broker. Either of these options are viable and it is recommended that rideshare launch service providers be assessed on the factors listed in Section 10.3.

10.4.2 GEO mission

For the GEO mission, the recommended approach is to procure services that can deliver the spacecraft into a GTO, or better, a GEO.

If possible, procuring services that can deliver the spacecraft directly to GEO is likely the best option. Orbital transfer manoeuvres from GTO to GEO require a lot of energy, which either mostly equates to a lot of propellant mass for chemical propulsion systems, or a lot of time and larger power systems for electrical propulsion systems. Either way, requiring the spacecraft to perform this manoeuvre puts considerable additional complexity on the spacecraft. If this manoeuvre can be performed by an orbital transfer vehicle (OTV) with the spacecraft attached, this additional spacecraft complexity is mitigated.

Should the option of procuring services to directly insert the spacecraft into a GEO be explored, it is recommended that the spacecraft not be inserted directly into its final GEO, as this puts an un-commissioned spacecraft in an orbit shared with other (expensive and critically utilised) spacecraft. Instead, inserting the spacecraft into a graveyard GEO, commissioning the spacecraft there, and then manoeuvring the spacecraft into its final GEO would likely be the better option as it reduces the risk of placing a defunct spacecraft into a valuable orbit.

If it is not possible to procuring services that place the spacecraft into GEO, then the next best option is to procure services that can deliver the spacecraft to GTO and then have the spacecraft be capable of manoeuvring itself to GEO.

11 Ground Segment Implementation

11.1 Operations Aspects

UNSW Canberra Space analysed the system operations aspects in two ways:

- from the group's own experience integrating and operating missions,
- from information provided by a commercial Australian-based satellite operations facility.

For this report, the mission operations segment was defined to include the following elements:

- Appropriately trained people to operate the spacecraft;
- Relevant software tooling, systems, and processes necessary to operate the spacecraft;
- Integration and testing of the satellite at the mission operations interface level (training of operators is included in this activity).

For this report, the costing of the mission operations segment does not include the following elements:

- A physically secure office space (i.e. a Mission Operations Centre);
- Access to a ground station network for TT&C or science data downlink (these costs are included in the ground station section within each mission analysis).

11.1.1 Operations Personnel

The following overview applies to each of the Bureau candidate missions studied (i.e. separate operations are assumed for each mission).

For business-hours-only spacecraft monitoring, a team of two full-time and one part-time operator (2.5 FTE) is recommended, which allows for personnel illness and general unavailability without compromising on monitoring quality or introducing additional risk.

For 24/7 monitoring, a team of 8 FTE is recommended. There is a fixed component in satellite operations that is independent of the monitoring scheme (e.g. manoeuvre planning, calibration planning, software updates and reconfigurations); these do not need to be scaled up in going from a business-hours to a 24/7 monitoring scheme, and as such the cost increase is lower than a simple scaled-up business hours cost would suggest.

11.1.2 Operations Tooling, Systems and Processes

Relevant operations software, tools, and handbooks will need to be developed. These may be developed by the prime contractor or by the mission operations provider.

The predicted rate of effort for this task is estimated to be a team of 5 FTE for 2 years.

11.1.3 Operations Integration and Testing

One Australian operations services provider has been contacted so far, and they indicate a Rough order of Magnitude (ROM) cost of AUD750k to AUD2M for integration and preparation for operations support. This cost may have included non-recurrent engineering (NRE) costs for software systems that need to be included in the overall operations costings.

11.2 Mission Operations Centre (MOC)

11.2.1 Description

A Mission Operations Centre (MOC) is required for the satellite operators to control the spacecraft's on-orbit operations which include monitoring the satellite's health, responding to anomalies, and making payload data available to mission stakeholders.

The level of staffing and infrastructure required for the MOC depends on the complexity of the spacecraft, the level of autonomy built into the spacecraft and operations software, the risk tolerance for the mission, and the data volume to be handled. For example, it is possible to reduce staffing levels if certain anomalies are handled autonomously by the spacecraft, and/or anomalies can be detected by the operations software and an on-call operator automatically notified. A 'lights out' approach is recommended, where the level of ground segment and space segment automation reduces the person-hours required for operations and removes the need for a dedicated operations centre with 24/7 staffing. A modern MOC implementation features a secure web-based approach to operations, that allows the operators to work from anywhere with an internet connection without being restricted to a dedicated control room.

11.2.2 Australian Space Industry Capability

FrontierSI have prepared an Australian Capability Assessment report which should be referred to for more detailed analysis related to Australian industry capabilities.

Two commercial services currently operate in Australia offering a MOC as a service. Saber Astronautics offer a mission operations service through their Responsive Space Operations Centre (RSOC) in Adelaide. Fugro opened the Perth-based Space Automation, Artificial Intelligence and Robotics Control Complex (SpAARC) in late 2022, which features a MOC component[112].

Several commercial companies in Australia are expected to acquire mission operations experience through the operation of their own satellite platforms over the next few years, including Fleet Space, Inovor, and Gilmour Space.

[112] https://www.fugro.com/media-centre/news/fulldetails/2022/11/03/fugro-opens-state-of-the-art-space-control-centre-spaarc-in-perth-australia

UNSW Canberra Space and Curtin University have experience developing mission operations infrastructure for bus and payload operations, demonstrated with on-orbit CubeSats.

11.2.3 Implementation Options

The infrastructure required for the MOC is both hardware and software. This software could be developed from the ground up, or an existing local or overseas system could be adapted to meet the needs of the spacecraft.

11.2.4 Recommended Approach

Commercial Mission Operations Centres are likely to provide a cost-effective and technically capable solution to the need for operating the spacecraft. Approaching the commercial market by tender is an appropriate method to procure MOC services. Alternatively, the prime contractor for the mission may be able to provide such services themselves and should be given the option to do so. A decision on approach should be made as early in the program as reasonably possible, to allow for system design and engineering to proceed with all stakeholders input. Integrating a satellite platform with a MOC can be a significant undertaking, requiring substantial verification and validation activities across the end-to-end system (ground segment included).

11.3 Ground Stations Network

11.3.1 Description

A ground station network provides a conduit for the spacecraft operators to command the spacecraft, monitor its health, and to retrieve mission data. A direct-to-earth approach was chosen for both the LEO and GEO missions. Other implementation options such as optical or in-space relay systems were considered and deemed to have additional complexity, cost, and risk, and do not improve mission function or performance.

A ground station can be used for commanding and telemetry, science data downlink, or both. Multiple same-type ground stations should be separated geographically for maximum usefulness, as the spacecraft can only communicate with one ground station at a time.

A geostationary satellite remains stationary from the perspective of a ground observer. As such, a single ground station placed within the satellite’s view will give 100% coverage availability. For a non-geostationary satellite multiple ground stations may be required to meet the data latency and coverage requirements. A non-geostationary satellite will be visible to different ground stations around the globe at different times as it moves through its orbit. Polar ground stations can typically contact a polar-orbiting spacecraft on every orbit, whereas non-polar stations may only be visible to the spacecraft a few orbits each day.

11.3.2 Ground Station Access

RF ground stations are readily available. They can be accessed in the following ways:

- Customer owned and operated
- Customer leased (exclusive access)
- Customer leased (time-shared scheduled access)

11.3.3 Customer Owned and Operated

LEO Pathfinder

The Bureau owns and operates ground stations used to support operational earth observation missions, such as the main operational sounding and imaging missions from NOAA and EUMETSAT polar orbiters. As this study focused on a LEO pathfinder (a non-operational mission), the Bureau has indicated that it will only consider using its operational ground stations to support pathfinder missions if the tasking does not conflict with operational mission support. As such, this report primarily considers other access methods but does not exclude the possible use of Bureau or related assets in the future.

GEO Mission

The customer may use an existing dedicated asset or will work with a ground station supplier to furnish and install the system on land provided by the customer. The customer owns this capability and can task it as required. The site acquisition and preparation costs may be in the millions, depending on the location. The procurement and installation of the ground infrastructure may also cost in the millions for antenna hardware, power and utility services, and other required facilities, with ongoing operations, support, and maintenance costs as well.

11.3.4 Customer Leased (exclusive access)

LEO Pathfinder

A ground station can be leased on an exclusive basis from another provider. Scaling efficiencies in the areas of site costs, installation costs, and maintenance costs allow the provider to offer the same service at a lower price-point relative to a customer-owned and operated solution.

GEO Mission

Exclusively leased ground stations are appropriate for a GEO mission. Set up and maintenance costs may be lower for GEO (compared to LEO), as fixed-pointing antennae are generally cheaper and require less maintenance due to the absence of a tracking mechanism.

11.3.5 Customer Leased (time-shared scheduled access)

LEO Pathfinder

Time-sharing a ground station with other customers allows for a significant reduction in the cost to the customer and allows access to a wider constellation of ground stations, depending on mission requirements. Whilst the ground station is not dedicated to a given satellite mission, it is possible (via negotiation with the provider) to acquire priority access by scheduling in advance. Typical pricing for these systems is USD$1 – 10 per minute of usage and can scale with operational demands.

Example providers include Amazon Web Services, Microsoft Azure, KSAT and ViaSat.

GEO Mission

This option is not recommended for a GEO mission, as the proposed GEO mission requires continuous ground station availability to meet requirement MIS-4. Time-share pricing for such a system is likely to be more expensive than leasing an exclusive-access system.

11.3.6 Australian Space Industry Capability

FrontierSI have prepared an Australian Capability Assessment report which should be referred to for more detailed analysis related to Australian industry capabilities.

Australia hosts many commercial/industry-based ground stations with varying levels of maturity. Some stations operate independently, whereas others can be accessed as part of a wider international network.

11.3.7 Spectrum Management for Downlink

A COTS satellite platform will be designed to be operable within the constraints of the ITU Radio Regulations (ITU RR). To operate it, the satellite system must undergo international frequency coordination in accordance with the ITU-RR, including submission of relevant technical details to the ITU[113]. For an Australian satellite network, the Australian Communications and Media Authority (ACMA) would deal with the ITU on the operator's behalf. Additionally, to operate an Australian ground station, suitable radiocommunications licences must be obtained from the ACMA.

As radiofrequency 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 take a number of years. There are costs involved, consisting of:

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

1. 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,
2. licencing and service fees charged directly by the ACMA,
3. fees charged by the ITU.

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

1. the complexity of the request,
2. the parameters associated with the request,
3. the number and nature of other authorised spectrum users at potential risk of RF interference,
4. which specific regulations and procedures are applicable to the frequency band of interest,
5. any forthcoming changes in regulation at national or international levels.

A LEO mission of this nature may require the full-time services of an engineer (or equivalent outsourced services). These labour costs may be expected to represent the majority of the costs for spectrum access. However, these values are uncertain and should be the subject of further study, if required. Consulting the ACMA or other subject matter experts about these matters well in advance is highly recommended.

The coordination process for the GEO mission is expected to be considerably more complex than for LEO. Slots in GEO are a finite resource, as minimum separations between spacecraft must be maintained for safety and RF interference reasons. Furthermore, the GEO mission would illuminate the same area of Earth for its whole communications transmit duty cycle. Therefore, RF interference to any other receiver in that footprint would occur a greater amount of the time, and likely thus be of greater concern.

11.3.8 LEO Pathfinder Payload Downlink Approach

Architecture

A direct-to-earth, radiofrequency downlink utilising customer-leased, time-shared, and scheduled access to commercial ground stations is recommended for the LEO pathfinder. This option is feasible and commercially available now (including on off-the-shelf platforms). Leased, time-shared access is most cost effective as the LEO mission can only access and will only require access to any one station for a small proportion of time to meet its objectives.

The following subsections present analysis based on an example design, in order to show feasibility and estimate costs involved with this option. This design was chosen as a reasonable, well-supported, representative design that can meet the communications requirements specified in Section 5.7. There are opportunities to improve the design and to make further trade-offs in parameters such as bandwidth, power requirements, payload downlink requirements, and ground station access. Such trade-offs could improve and trade off cost, risk, and mission capability.

The nominal design orbit in Table 13 has been used. The analysis is considered sufficiently representative enough of any low earth orbit that meets the other requirements of the mission for initial costing and feasibility purposes. For example, the sun-synchronous orbit discussed in section 5.5.4 would have greater access to ground stations near the poles and is therefore shown feasible by this analysis.

The frequency band 8025–8400 MHz, within X band, was chosen for the reference design due to support by off-the-shelf radios, the ITU-RR, and commercial ground stations. It was also considered a reasonable trade of expected available bandwidth and technical difficulty. As discussed in Section 11.3.7, the matter of obtaining access to spectrum can be complex; this design choice is intended to show feasibility of such a system. The actual choice of the particular frequency band for this mission should consider further advice on spectrum access. It is noted that this particular portion of X band is also used by terrestrial systems and militaries worldwide (including in Australia). Therefore, use would be subject to successful coordination with any affected users in those categories.

It has been assumed that dual X- and S-band ground station systems would be used to support simultaneous TT&C communication and payload downlink, and that the cost to use both would be similar as the asset would not be available to other users at the time. As the study has not identified any onerous TT&C requirements (Section 6.8.3), it has been assumed that this communication would take place during the payload downlink, and any additional costs would be negligible or otherwise absorbed within the margins of the payload downlink costs considered below. There are portions of S band that are allocated for and commonly used for satellite communications.

Reference Link Design

Table 32 shows key parameters of a reference payload downlink configuration. This reference configuration has been used for analysis for the LEO pathfinder mission, and comprises:

- characteristics from the EnduroSat X-band transmitter[114] as a ‘reference transmitter’,
- the EnduroSat X-band, single-patch antenna[115] as a feasible solution balancing gain for instantaneous data rate and beamwidth for ground-station access,
- DVB-S2 variable coding and modulation (VCM) as a standard that performs well[33] and is widely supported, including by the reference transmitter.

The reference configuration is supported by the EnduroSat 12U CubeSat with X-band payload communications. Additionally, the components are featured in the NASA State-of-the-Art of Small Spacecraft Technology 2021 report[116], providing assurance that they represent design choices that are both realisable and using current, state-of-the-art technologies for the application.

114 https://www.endurosat.com/cubesat-store/cubesat-communication-modules/x-band-transmitter/

115 https://www.endurosat.com/cubesat-store/cubesat-antennas/x-band-patch-antenna/

116 https://www.nasa.gov/sites/default/files/atoms/files/9.soa_comm_2021_0.pdf.

Table 32: LEO pathfinder payload downlink configuration used for link analysis.

ID	Parameter	Value	Unit	Rationale
CDF-S-LD-55	Frequency Band	8025–8400	MHz	Supported by the reference transmitter. See also the discussion under the sub-heading Architecture above.
CDF-S-LD-56	Output Power	2	W	As per the reference transmitter.
CDF-S-LD-57	Symbol Rate	25	MBd	Assumed reasonable, representative, modest value, noting that higher bandwidths may increase difficulty and complexity of radiocommunications licencing. Appears to be supported by a number of available off-the-shelf CubeSat platforms[117].
CDF-S-LD-58	Satellite Antenna Gain	6	dBi	As per reference antenna.
CDF-S-LD-59	Antenna Beamwidth (half power)	74	°	As per reference antenna.
CDF-S-LD-60	Acceptable Bit Error Rate (approximate)	10^{-7}	bits/bit	Reasonable value supported by DVB-S2[32].
CDF-S-LD-61	Ground Station Antenna Gain	50.5	dBi	5.4 m dish, 55% efficiency, assumed representative of the minimum of a commercial provider[118].

Appendix C provides details of the link analysis. It considered the performance of the downlink system under the best conditions, then estimated the actual performance under a variety of ground-station-view elevations, which correspond to slant range between the satellite and ground station. One particular commercial provider was considered as an example, and access times to this provider's ground stations under each condition were calculated, averaged over thirty days. This analysis, summarised in Table 33, shows that user data rates of up to 67.0 Mbps are attainable, with an average data rate of 1.23 Mbps for this particular provider, or an average of 13.2 GB is able to be downlinked per day, therefore the volume of 1.19 GB per day calculated in section 5.7.2 can be managed.

[117] For example, the EnduroSat 6U Cubesat Platform and larger models—https://www.endurosat.com/cubesat-store/cubesat-platforms/6u-cubesat-platform/

[118] As an example, 5.4 m dishes or larger are available at all of ViaSat's ground stations— https://www.viasat.com/space-innovation/space-and-networking-technology/ground-network/.

Table 33: LEO Pathfinder mission downlink rates attainable at varied slant ranges using one commercial provider.

Slant Range (km)	VCM Mode	User Data rate (Mbps)	Proportion of time mode can be used (30-day average)	Mean Data rate (Mbps)	Average proportion of time mode can be used (Min/day)	Average Data Per day (GB)
500 – 600	8PSK 9/10	67.0	0.31%	0.21	4.5	2.3
600 – 700	8PSK 5/6	62.0	0.70%	0.43	10.1	4.7
700 – 800	QPSK 5/6	41.4	0.73%	0.30	10.6	3.3
800 – 900	QPSK 2/5	19.7	0.76%	0.15	11.0	1.6
900 – 1000	QPSK 1/3	16.4	0.77%	0.13	11.1	1.4
Total	**-**	**-**	**3.29%**	**1.23**	**47.3**	**13.2**

Ground Station Access Requirements

On the basis of the above analysis, analysis summarised in Table 34 estimates that the mission will require, on average, 5.33 billable minutes of downlink time per day, amounting to a cost of approximately 8 770 USD per year. This calculation is an approximation only, but expected to be an upper bound for the communications design presented as higher efficiency passes could be selected, rather than 'average' passes as per the calculations. Additionally, this cost estimate will scale linearly with the data downlink volume requirement (up to the limit of the applicable capacity), should there be a desire to increase it.

Over any 24-hour period, between approximately 8.7 GB and 17.5 GB can be downlinked. Therefore, latency requirement CDF-R-LD-27 can be met, as there is sufficient capacity each day, with the excess capacity used to downlink four days of data in accordance with requirement CDF-R-LD-27.

Table 34: LEO Pathfinder mission downlink ground station access time and cost calculations.

Parameter	Value	Comments
Required data downlink with margin (GB/day)	1.13	*See section 5.7.2*
Mean downlink capacity of passes used (GB)	0.87	Mean of capacity of usable passes from our example provider
Mean number of passes used per day	1.50	*= Required data downlink with margin / Mean downlink capacity of passes used*
Mean duration of passes used (min)	3.33	Mean of duration of passes from our example provider
Pass overhead per pass (min)	2	Assumed one minute set up, and one minute stow for which the provider cannot service any other client, per pass
Mean billable duration per pass (min)	5.33	
Mean billable minutes per day (min)	8.01	
Ground station access cost (USD/min)	3	Rate offered by example provider
Cost per day (USD)	24.02	
Cost per year (k USD)	8.77	

11.3.9 GEO Pathfinder Payload Downlink Approach

A direct-to-earth, radiofrequency downlink utilising either a customer-owned and -operated or an exclusive lease of a commercial ground station is recommended for the reasons discussed in section 11.3.2. By comparison to the LEO pathfinder, the following considerations present greater challenges to the downlink design for a GEO mission:

- The orbit altitude of approximately 65 times that of the LEO orbit will result in an additional 36 dB of free-space path loss than the best case of the LEO orbit.
- Considerations to avoid continual radiofrequency interference to other receivers (mentioned in section 11.3.7) may require tighter constraints on the design of the system.

However, the fixed position of the satellite with respect to a dedicated ground station for a GEO mission has the following advantages to LEO mission:

- Both satellite and ground-station antennas can be highly directional and aligned all of the time with minimal pointing losses, increasing the effective radiated power in the direction of the ground station considerably.

- Constant access to the ground station increases the achievable data volume by increasing the time available to downlink it by significantly by comparison to the LEO mission.
- Constant access to the ground station enables very low latency, making it possible to achieve CDF-R-LD-18, which is not achievable in LEO.
- The ground station antenna can be fixed, reducing complexity, and thus cost in design, construction, and maintenance of the ground station by removing all tracking mechanisms.

11.4 Data Processing, Distribution and Archiving

11.4.1 Data Products Description

The data processing pipeline comprises three stages: Level 0 (L0), Level 1 (L1) and Level 2 (L2). Table 35 summarises the data products definition. The output data products after Level 2 processing are events, groups, and flashes.

The fundamental unit of data relevant to all levels of processing is the event. Events are single occurrences of a pixel in the focal plane registering values above the background threshold and could be caused by either lightning or noise in the detector. A group is defined as one or more simultaneous events that register in adjacent pixels in the focal plane. A flash is defined as a set of groups that are sequentially separated in space and time. The GLM Lightning Cluster-Filter Algorithm (LCFA) identifies groups using time bound of 330 ms and a spatial separation of 16.5 km[119] .

[119] Geostationary Lightning Mapper (GLM) Lightning Cluster-Filter Algorithm Theoretical Basis Document, Version 3.0. https://www.star.nesdis.noaa.gov/goesr/documents/ATBDs/Baseline/ATBD_GOES-R_GLM_v3.0_Jul2012.pdf

Table 35: LD data products definition.

Processing level	Definition
Level 0	Raw observation data after restoration of the chronological data sequence for the instrument operating in observation mode, at full space/time resolution with all supplementary information to be used in subsequent processing (e.g. orbital data, health, time conversion, etc.) appended, after removal of all communication artefacts (e.g., synchronization frames, communications headers, duplicated data). Level 0 data are time-tagged. The precision and accuracy of the time-tag shall be such that the measurement data will be localized to accuracy compatible with the Users requirements. Also includes raw observation data after restoration of the chronological data sequence for the instrument operating in calibration mode.
Level 1	Level 1a: Level 0 data with corresponding radiometric and spectral correction and calibration computed and appended, but not applied. Level 1b: Level 1a data not re-sampled, quality-controlled, and radio-metrically calibrated, spectrally characterised, geometrically characterised, annotated with satellite position and pointing, geolocation inferred from satellite pointing information.
Level 2	Derived lightning data classes (events, groups, flashes) at the same resolution and location as the Level 1 data. If available, the appropriate Analysis Ready Data (ARD) specification should be adhered to for Level 2 products. GLM's Readiness, Implementation and Management Plan (RIMP)[120] is recommended.

11.4.2 Data Processing and Archiving

Data processing functions are tailored to meet the specific mission objectives based on the types of payload data being acquired and scientific products required by users. Data processing may be implemented with various capabilities, such as:

- Archive facilities to store the acquired satellite data (usually stored as Level 0 (L0) data), as well as the higher-level scientific products created.
- Processing algorithms to generate required scientific products from the acquired satellite data.
- Processing infrastructure (processing chains) to host the algorithms and other required software tools to transform the L0 data into Level 1 (L1), Level 2 (L2) and higher-level products (as needed).
- Dissemination functions to manage the distribution of the data between the various processing elements as well as make it available to external users and the global community.

[120] Geostationary Lightning Mapper (GLM) Beta, Provisional and Full Validation Readiness, Implementation and Management Plan (RIMP), 416-R-RIMP-0313, Version 1.2

Typically, raw satellite data is downlinked for the creation of L0 data on-ground, which is archived for further processing and usually stored for future reprocessing. Some level of processing may be performed on board the satellite to reduce data downlink requirements. Additional input data may be required to support L1 / L2 production from other ground segment elements, including satellite housekeeping telemetry (often included within the downlinked science data stream), external auxiliary data (wide-ranging and highly dependent on the type of science data being processed) and additional flight operations data (such as orbit prediction files, instrument parameter files, etc.).

Infrastructure for data processing may utilise one of the following schemes or a combination thereof:

- Existing Bureau processing capabilities.
- Newly developed processing capability to support these missions.
- Available cloud processing resources (becoming more common, such as Amazon Web Services (AWS), Microsoft Azure, etc.).

The types of products being generated will determine the algorithms required, the number and configuration of processing chains and steps per chain needed, and the amount of data storage and processing power to support data production.

For the LEO and GEO LD missions considered in this study, the following aspects regarding science data complexity and volume are key to determining the implementation of the ground processing requirements:

- LEO – Medium-High L0 data volume limited by data downlink capacity (data only downlinked during ground station passes), demanding processing algorithms and data latency requirements.
- GEO – High L0 data volume limited by data downlink capacity, demanding processing algorithms and data latency.

The following factors apply to data archiving considerations for these missions:

- Data should be stored in compliance with government standard record-keeping requirements.
    - Typically, this requires three geographically distinct copies of the full data-set and associated processing tools to be stored for fifteen years.
- PRG-2 mandates the mission data to be stored in Australia.
- When providing long-term continuous data, the data storage time will increase and may be required to be stored ‘forever’.
- Commercial cloud offerings are appropriate; however, some capabilities may be retained in-house.
- Applicable cybersecurity risks and requirements need to be considered.

11.4.3 Data Dissemination

The following factors apply to data dissemination considerations for these missions:

- It is assumed the data will be provided to national and global end users for further usage.
- The data should be made available free of charge to all end users.
- The provision of cost figures for the data storage and processing is based on a commercial cloud offering, where available.

11.4.4 Australian Space Industry Capability

FrontierSI have prepared an Australian Capability Assessment report which should be referred to for more detailed analysis related to Australian industry capabilities.

It is anticipated that the L0, L1 and L2 processors will be developed locally. As discussed in the FrontierSI report, Australia possesses significant capability in data production and downstream applications. These capabilities are present across Government (through agencies such as the Bureau), academia and industry.

11.4.5 Implementation Options

The L0 data processors for both LEO and GEO LD missions will be bespoke for the mission series and must be developed to interface with unprocessed payload data and telemetry from the spacecraft.

L1 and L2 data processors have been developed for both LEO and GEO lightning detection missions in the past. For example, the LCFA algorithm developed for GLM and refined over years of experience with the LIS imager. However, it may be infeasible to obtain existing software solutions to apply to the L0 products produced as part of the Bureau's mission series. Existing processing software may not be releasable, or it may be incompatible with the hardware underlying the Bureau's mission Data Processing and Archive System (DPAS). Therefore, L1 and L2 data processors are likely to be bespoke implementations. However, these processors should leverage the format specifications, ICDs and Algorithm Theoretical Basis Documents (ATBDs) of existing lightning detector data processing systems wherever possible.

11.4.6 Recommended Approach for Lightning Detector Mission

Bespoke software to process L0 products into L1 and subsequently L2 products will be required for both LEO and GEO missions. This development is well suited to a general software consultancy entity as there is a strong Australian industry capability in this domain. Developers with experience in space systems and secure software development would be preferred. Alternatively, the Bureau could leverage its existing expertise in developing NWP products to create the L0, L1 and L2 data processors in-house. The L1 and L2 data processors should leverage format specifications, ICDs and ATBDs for existing lightning missions wherever possible to ensure the data is easily accessible for existing users of lightning datasets.

The L0, L1 and L2 processors will require physical DPAS infrastructure. The Bureau can choose to leverage existing data processing infrastructure used for NWP or build new capability in-house. Alternatively, the Bureau can leverage commercial cloud services to mitigate the costs associated with infrastructure acquisition and operations.

12 Mission Risk Assessment

This Bureau Lightning Detector ANCDF Study is a Pre-Phase A feasibility assessment and a formal risk analysis has not been completed. Some preliminary discussion of risk identification and mitigation was conducted during the study sessions, but this was in the context of risk mitigation for a GEO mission via a LEO pathfinder development.

Formal risk assessment processes are defined for space mission developments (such as ECSS-M-ST-80C, shown in Figure 25). Risk assessments need to be conducted and refined during all phases of the development project.

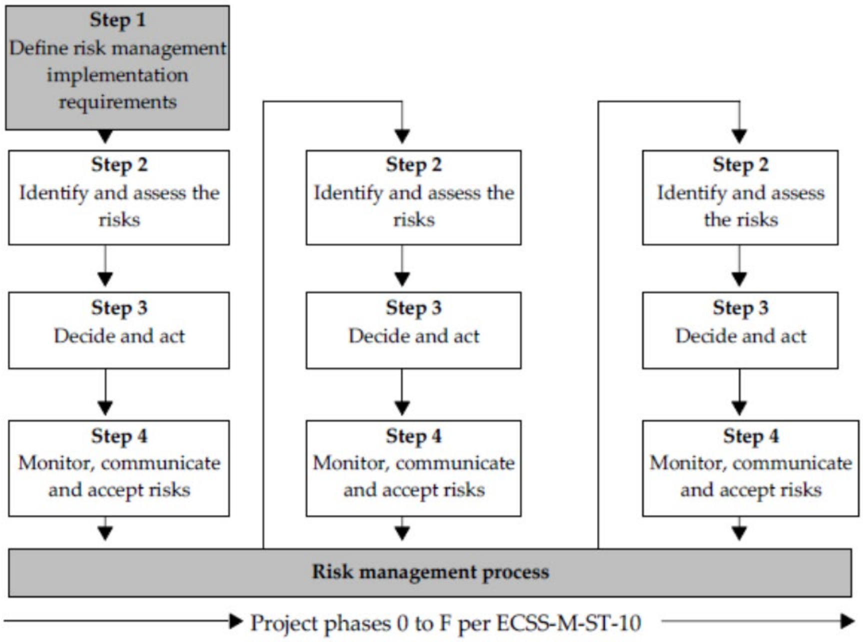

Figure 25. The steps and cycles in the risk management process

Any future CDF studies to support a LEO or GEO lightning detector mission should include a risk assessment.

13 Space Mission Costing

13.1 Costing Confidence Levels

This report uses the Australian Department of Finance's definitions of cost confidence level[121].

13.1.1 Generic Costings

- All costs are taken as that for FY22. No projections have been applied to estimate costs for the missions being undertaken on a future date(s).
- All costs are in AUD 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 (https://www.ato.gov.au/Rates/Foreign-exchange-rates/). Rates were calculated as follows:
    - USD to AUD: 1.343
    - EUR to AUD: 1.547

13.1.2 Labour Rates

Labour rates were calculated for the following professions deemed necessary for the projects:

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

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

- Superannuation,
- Payroll tax,
- Workers' compensation,
- Provision for long service leave,
- Leave loading.

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

[121] RMG500-Defining-P50-and-P80-Manual.pdf (finance.gov.au)

Table 36. Labour Rates

Role	Base Salary Costs (AUD)	On-Cost (%)	FTE incl. On-Costs (AUD)	Reference
Project Manager	$ 125,000.00	0.35	$ 168,750.00	1
Engineer	$ 115,000.00	0.35	$ 155,250.00	2
Technician	$ 72,000.00	0.35	$ 97,200.00	3
Administrator	$ 80,000.00	0.35	$ 108,000.00	4

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

13.1.3 Overheads

A 35% overhead (currently only an estimate) was applied to all expenses (labour, hardware, services), excluding launch, to account for business operating expenses including, but not limited to:

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

13.1.4 Other

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

A 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 contactor may wish to receive for undertaking the project.

13.2 GEO Space Mission Costs (design, build, launch, and commissioning)

13.2.1 Conceptual Schedule

The following depicts a conceptual schedule for development of a GEO lightning detector mission, based on the defined payload and bus design:

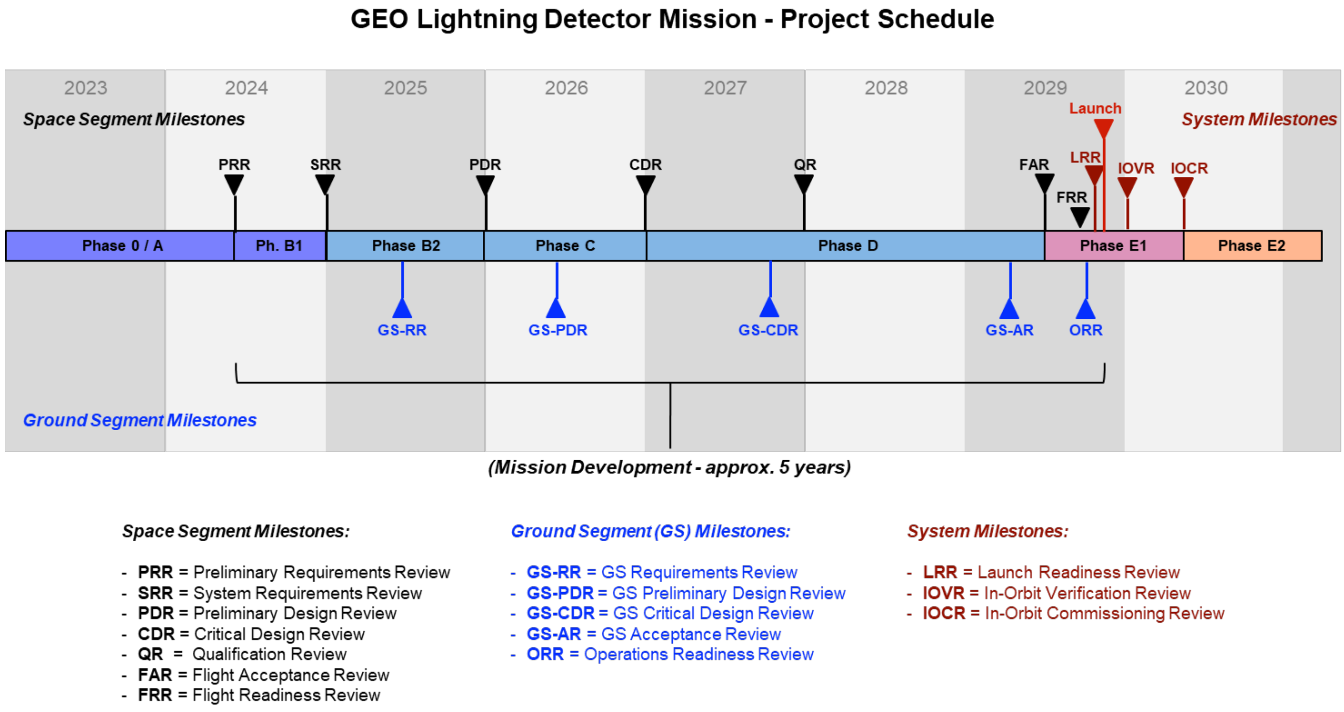

Figure 26. GEO Lightning Detector Mission Conceptual Schedule.

This is based on a generic satellite mission development timeline of 5 years from Phase B to Launch and Commissioning (project phases B and C/D above).

13.2.2 Cost Breakdown

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

- Overall project cost, including margins.
- Combined system cost, including labour, integrated spacecraft testing, launch, regulatory, and operating costs.
- Payload cost, including labour, hardware, and testing.
- Platform cost, including the labour, hardware, and testing for a tailored COTS platform,
- Launch costs, including freight and personnel costs, and
- Operating costs, including labour, operations centre costs, ground station costs, as well as computing and data storage costs.

The cost breakdown is shown below in Table 37. Note that due to the conceptual level of this mission design, many costs were either approximated or estimated.

Table 37: Overall lightning detector project cost breakdown for a GEO mission.

Mission Component	Cost (AUD)	Notes
Combined System Costs	$ 3,653,363	Includes individual margins
Payload Costs	$ 27,152,538	
Platform Costs	$ 24,185,000	Assuming COTS spacecraft
Launch Costs	$ 16,803,600	
Operational Costs	$ 2,421,900	
Sub-Total	**$ 74,216,400**	
Overall Uncertainty Margin (20%)	$ 14,843,280	
Overheads (35%)	$ 4,795,166	Only applied to labour costs
Sub-Total	**$ 93,854,846**	
Net Margin (10%)	$ 9,385,485	
TOTAL MISSION COST	**$ 103,240,331**	

System Level Costs

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

Payload Costs

Payload Costs were broken down into sub-Sections consisting of:

- Labour,
- Components & materials,
- Equipment, and
- AIT activities.

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

Platform Costs

Platform costs included the COTS cost for the spacecraft platform and GSE. Note that the platform cost of USD15M is only a first-order estimate, as no platform supplier would provide a cost with any confidence without performing engineering analyses. Such analyses would need to be paid for, which is out of the scope of this study. Furthermore, there have been no similar missions in which indicative pricing could be based on. The stated cost of USD15M for a platform is approximated from the mission costs found from a small survey of complex smallsat missions, including interplanetary missions.

Launch Costs

Launch costs include all associated costs, including launch, costs for four persons to the launch site (likely to the USA) to assist with integrating the spacecraft to the launch vehicle, and packaging and freight of spacecraft to launch site.

Operating Costs

Operating costs cover personnel and ground station costs for the on-orbit duration of the mission, as well as the computing and storage costs of the data. Since the GEO mission is an operational mission, the BOM indicated services such as the mission operations centre, ground station, computing, and data storage will be provided via BOM infrastructure and therefore do not need to be costed.

13.3 LEO Space Segment (design, build, launch, and commissioning)

13.3.1 Conceptual Schedule

The following depicts a conceptual schedule for development of a LEO lightning detector mission, adjusted for the expected development duration of a LEO pathfinder lightning detector mission:

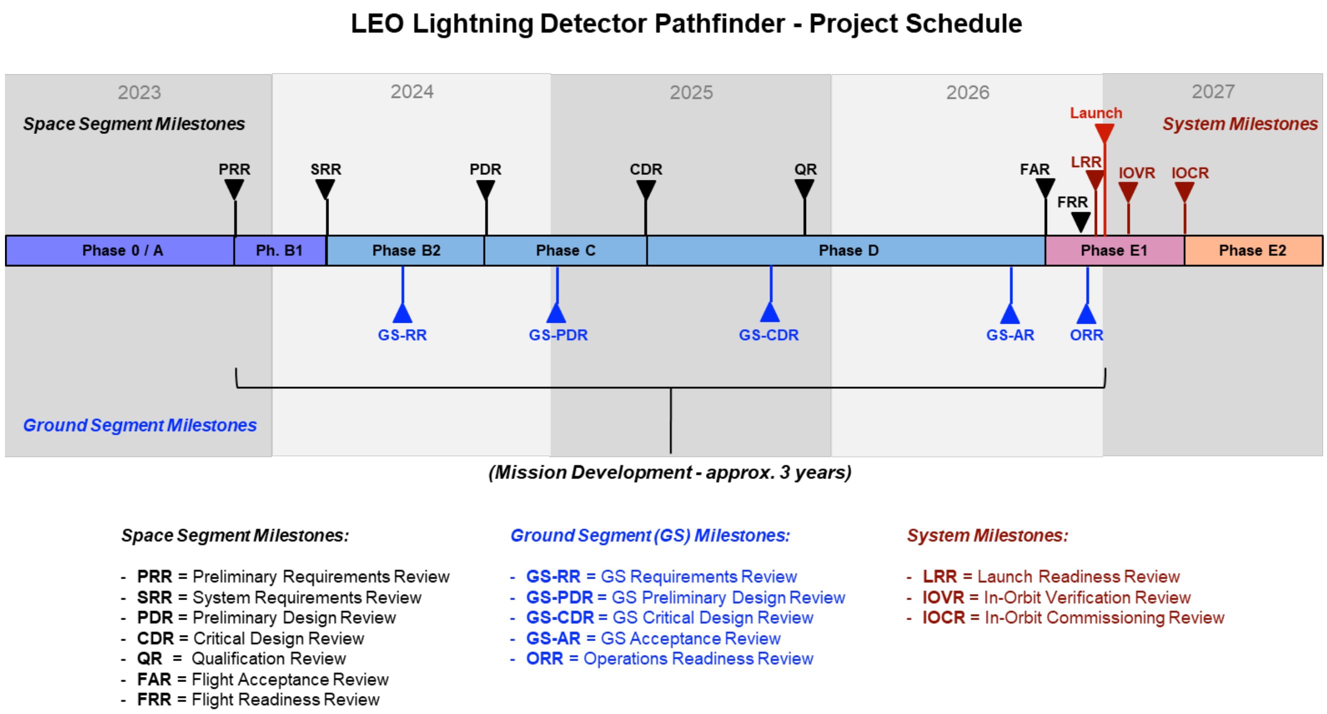

Figure 27: Lightning Detector LEO Pathfinder Conceptual Schedule.

Given that the proposed platform for a LEO pathfinder lightning detector mission is likely to be COTS, the main development effort will be related to sensor development and overall system assembly, integration, and testing. Based on this, the overall system development schedule for the payload and system integration is expected to shorten from 5 years to approximately 2-3 years (project phases B and C/D above).

13.3.2 Cost Breakdown

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

- Overall project cost, including margins.
- Combined system cost, including labour, integrated spacecraft testing, and regulatory costs.
- Payload cost, including labour, hardware, and testing.
- Platform cost, including costs for a COTS platform and dispenser,
- Launch costs, including freight and personnel costs, and
- Operating costs, including labour, operations centre costs, ground station costs, as well as computing and data storage costs.

The costs for each component are shown in Table 38. (Like costs for the GEO mission, many have been either approximated or estimated. Should any of the costs require justification, justifications can be provided in a later version of the report.)

Table 38: Overall lightning detector project cost breakdown for a LEO mission.

Mission Component	Cost (AUD)	Notes
Combined System Costs	$ 2,033,175	Includes individual margins
Payload Costs	$ 7,070,610	
Platform Costs	$ 1,699,486	Assuming COTS spacecraft
Launch Costs	$ 491,190	
Operational Costs	$ 2,690,826	
Sub-Total	**$ 13,985,287**	
Overall Uncertainty Margin (10%)	$ 1,398,529	
Overheads (35%)	$ 2,059,864	Only applied to labour costs
Sub-Total	**$ 17,443,680**	
Net Margin (10%)	$ 1,744,368	
TOTAL MISSION COST	**$ 19,188,048**	

System Level Costs

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

Payload Costs

Payload Costs were broken down into sub-Sections consisting of:

- Labour,
- Components & materials,
- Equipment, and
- AIT activities.

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

Platform Costs

ROM costs for two suitable platforms were obtained;

- a 12U EnduroSat platform of approximately AUD547k, which included platform hardware & early operations commissioning of spacecraft and payload.
- a 12U Kongsberg Nanoavionics platform of approximately AUD1,306k, which included platform hardware, a flatsat, and early operations commissioning of spacecraft and payload.

For the mission cost estimate, the Kongsberg Nanoavionics ROM cost was used as it was the most conservative.

Launch Costs

Launch costs include all associated costs, including launch, costs for four persons to the launch site (likely to the USA) to assist with integrating the spacecraft to the launch vehicle, and packaging and freight of spacecraft to launch site.

Operating Costs

Operating costs cover personnel, ground station, and mission operations centre costs for the on-orbit duration of the mission, as well as the computing and storage costs of the data.

Computing costs are only an initial estimate, as the amount of computing required could not be calculated. Data storage cost were estimated based on storing L0 and L2 data for 15 years.

14 Recommendations and Open Points

14.1 Recommendations

The following recommendations are made:

1. The Bureau should decide which pathway to a GEO mission capability is preferred and plan the next studies / activities based on this choice (section 4.3).
2. If a LEO pathfinder is desired, a further study to refine the mission and payload requirements should be considered.
3. The Bureau should consider a follow-on study for a GEO mission based on the preferred GEO option (ranging from full Australian development to a payload development hosted on a third-party satellite or partnering with a consortium or other agency for GEO mission development).
4. The Bureau should consult as early as possible with Australian-government radio-frequency spectrum subject matter experts (such as the ACMA or Bureau internal experts) to better understand the risks, schedule considerations, resourcing and costs related to spectrum management and access for the proposed satellite missions (see section 11.3.7).

14.2 Open Points

The following open points are identified:

1. The LEO pathfinder payload design requires further iteration and refinement.
2. Depending on the preferred GEO option, the GEO payload design and bus options need further detailed study.
3. Further risk assessment is needed for both LEO and GEO designs to minimise critical risk areas and ensure the risk mitigation benefits of a LEO pathfinder towards a further GEO development.
4. Further research into Australian industry capabilities is required as the payload and mission designs are further understood and refined.

List of acronyms and abbreviations

Abbreviation	Description / meaning
ACT	Australian Capital Territory
ADCS	Attitude determination and control subsystem
AIT	Assembly, Integration, and Test
ANCDF	Australian National Concurrent Design Facility
ANU	Australian National University
AOCS	Attitude and orbit control subsystem
AR	Anomaly Report
ATBD	Algorithm Theoretical Basis Document
AUD	Australian Dollar
AUS	Australian
AWS	Amazon Web Services
BoM	Bureau of Meteorology
CD&H	Command Data and Handling
CDR	Critical Design Review
CMOS	Complementary metal-oxide semiconductor
CNN	Convolutional Neural Network
ConOps	Concept of Operations
COTS	Commercial Off-the-Shelf
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEA	Digital Earth Australia
DPAS	Data Processing and Archive System
DSTG	Defence Science and Technology Group
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EO	Earth Observation
EPS	Electrical Power Subsystem
ESA	European Space Agency
EUR	Euro (currency)
FM	Flight Model
FRR	Flight Readiness Review
FTE	Full-Time Equivalent
GEO	Geostationary Orbit
GOS	Global Observing System
GS	Ground Station or Ground Segment
GSD	Ground Sampling Distance
GSE	Ground Support Equipment
GTO	Geostationary Transfer Orbit
ICD	Interface Control Document
ITU	International Telecommunications Union
INCUS	Investigation of Convective UpdraftS
LCFA	Lightning Cluster-Filter Algorithm

LD	Lightning Detector
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
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
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NCR	Non-Compliance Report
NRE	Non-Recurrent Engineering (costs)
NSTF	National Space Test Facility (ANU)
NWP	Numerical Weather Prediction
OBC	On-board computer
PDR	Preliminary Design Review
PF	Pathfinder
PL	Payload
RF	Radiofrequency
RMP	Risk Management Plan
RMS	Root-Mean-Square
ROI	Region Of Interest
ROM	Rough Order of Magnitude
RR	[ITU] Radio Regulations
SAR	Synthetic Aperture Radar
SM	Structural Model
SNR	Signal-to-Noise Ratio
SRR	System Requirements Review
SSO	Sun-Synchronous Orbit
SSP	Sub-Satellite Point
STM	Structure and Thermal Model
TBC	To Be Confirmed
TBD	To Be Determined
TOA	Top Of Atmosphere
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking, and Commanding
U	CubeSat unit of volume. 1U is about 10 x 10 x 10 cm.
UNSW	University of New South Wales
US	United States
USD	US Dollar
VCM	Variable Coding and Modulation
WMO	World Meteorological Organization

Appendix A – Preliminary Mass Budget (LEO Pathfinder)

This indicative mass budget estimate is provided based on an example upper-limit payload mass of 10 kg and a commercially available 12U CubeSat bus with suitable power, attitude control, payload volume and data rate specifications.

Table 39. LEO COTS spacecraft example mass breakdown

Subsystem	Component	Quantity	Mass (kg)	Margin (%)	Total Mass (kg)
Payload (example)	LD Instrument	1	10.00	20%	12.00
Platform (example)	12U Bus	1	8.00	20%	9.60
Other (harness, balance, launch, etc.)		1	0.50	20%	0.60
TOTAL Mass					***22.2***
System Margin (%)					10%
TOTAL Mass, incl. System Margin					**24.4**

Appendix B – Preliminary Mass Budget (GEO Mission)

Table 40: GEO spacecraft (GTO insertion) mass breakdown.

Subsystem	Mass Fraction Breakdown, High Earth Orbit mission with chemical propulsion [1] (%)	Mass (kg)
Payload	32	31
Structure & Mechanisms	24	23.3
Thermal Control	4	3.9
Power (solar arrays, batteries, EPS)	17	16.5
TT&C	4	3.9
CD&H	3	2.9
AOCS	6	5.8
Propulsion	7	6.8
Other (balance, launch, etc.)	3	2.9
TOTAL, Dry Mass		***96.9***
Propellant (incl. 10% margin)		116.3
TOTAL, Wet Mass		**213.2**

[1] Space Mission Engineering: The New SMAD, Table 14-18 'Average Mass by Subsystem as a Percentage of Dry Mass for 4 Types of Spacecraft'

Table 41: GEO spacecraft (GEO graveyard insertion) mass breakdown.

Subsystem	Mass Fraction Breakdown, High Earth Orbit mission with chemical propulsion [1] (%)	Mass (kg)
Payload	32	31
Structure & Mechanisms	24	23.3
Thermal Control	4	3.9
Power (solar arrays, batteries, EPS)	17	16.5
TT&C	4	3.9
CD&H	3	2.9
AOCS	6	5.8
Propulsion	7	6.8
Other (balance, launch, etc.)	3	2.9
TOTAL, Dry Mass		***96.9***
Propellant (incl. 10% margin)		46
TOTAL, Wet Mass		**142.9**

[1] Space Mission Engineering: The New SMAD, Table 14-18 'Average Mass by Subsystem as a Percentage of Dry Mass for 4 Types of Spacecraft'

Appendix C – Preliminary Link Budget for LEO Mid-Inclination Orbit

This appendix shows payload downlink radiocommunications link analysis for the LEO pathfinder in the nominal 550 km mid-inclination orbit. Table 42 shows the link budget for the best-case scenario of the orbit where the satellite flies directly overhead a ground station. Table 43 shows a coarse analysis of the different data-rates attainable, considering 100 km ranges of slant range.

Table 42: Payload downlink radiocommunications link budget for the 550 km mid-inclination orbit at the best case.

System Specifics			**Source / Rationale**
Transmitter			
Frequency	8.4	GHz	Top of band of interest (worst case)
Transmit Output Power level (Pt)	33.0	dBm	As per the reference transmitter.
TX Cable Loss	1.0	dB	Assumed reasonable value
TX Antenna Gain (Gt)	6	dBi	EnduroSat X-Band Patch Array (single)
Transmitter EIRP	38.0	dBm	*= Pt – Cable Loss + Gt*
Path			
Slant Range	550	km	Orbit altitude = Best-case value
TX Pointing Loss (Lpt)	0.0	dB	Best-case value
Polarisation Mismatch (Lpol)	3.0	dB	Worst case for a circular polarised system to linear, chosen to account for any variation due to implementation
RX Pointing Loss (Lpr)	0.5	dB	Assumed reasonable value
Atmospheric loss (Latm)	0.0	dB	Not used—applied later
Wavelength	*0.036*	*m*	
Free Space Path Loss (Lfs)	*165.74*	*dB*	
Total Path Losses	*166.24*	*dB*	*= Lpt + Lpol + Lpr + Latm + Lfs*
Receiver Parameters			
RX Antenna Gain (Gr)	50.5	dBi	Nominal 5.4 m dish value—55% efficiency at 8 GHz
RX Cable Loss	1.00	dB	Assumed reasonable value
System Temperature	300	K	Typical ambient temperature
Noise Power Density N0	*-173.8*	*dBm/Hz*	*Calculated from system temperature*

Power at Receiver	*-81.74*	*dBm*	= *EIRP – Total Path Losses + Gr – Cable Loss*
Modulation & Coding			
Modulation & Coding Scheme	DVB-S2 VCM SRRC(0.35)		DVB-S2 standard, as widely supported, designed for satellites, and fairly Shannon-efficient
Symbol rate	25	MBd	See Table 32
User Bits/Symbol	Varies	bit/symbol	
Symbol occupied bandwidth	1.17	Hz/Bd	Derived from modulation & coding for square-root-raised-cosine filter with roll off of 0.35
Spectral bandwidth	*29*	*MHz*	= *Symbol rate* × Symbol occupied bandwidth
Minimum Eb/N0	Varies	dB	
User data rate	Varies	Mbps	
Receiver Performance			
Symbol Energy (Es) at Receiver	***-155.7***	*dBm/Hz*	
Es/N0	***18.1***	*dB*	
Desired Link Margin	3.0	dB	See CDF-R-LD-31. The lower limit of 3 dB is was chosen, noting that the example design can be improved.

Table 43: Attainable communications modes and data rates for the 550 km mid-inclination orbit.

Slant Range (km)	Max Path Angle off Nadir (°)	Min Elevation Angle (°)	FSPL Variation (dB)	Min Es/N0 (dB)	Max Pointing Loss (est.) (dB)	Max Atm Loss (dB)	Total Extra Losses (dB)	Min Es/N0 with extra losses and margin (dB)	Best usable VCM Mode	User Data Rate (Mbps)
500 – 600	22.5	65.4	0.8	17.4	3.0	0.36	3.4	11.0	8PSK 9/10	67.0
600 – 700	36.4	49.9	2.1	16.0	3.0	0.41	3.4	9.6	8PSK 5/6	62.0
700 – 800	44.1	40.9	3.3	14.9	6.0	0.47	6.5	5.4	QPSK 5/6	41.4
800 – 900	49.3	34.5	4.3	13.8	10.0	0.54	10.5	0.3	QPSK 2/5	19.7
900 – 1000	53.1	29.7	5.2	12.9	10.0	0.61	10.6	-0.7	QPSK 1/3	16.4

Appendix D - Pre-Phase A Customer Requirements Cross-Reference

Req. No.	Description	LEO	GEO
PRG-1	The mission shall deliver capability into the Australian space industry.	Section 5	Section 4
PRG-2	The mission shall store all data from the mission in Australia.	Section 10, more specifically Section 10.3.2	Section 10, more specifically Section 10.3.2
PRG-3	The mission shall consider the possibility of locating the Mission Operations Centre (MOC) and its staff in Australia or sharing MOC with an international partner.	Section 10.1.2	Section 10.1.2, Section 4.5
PRG-4	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 10.1.1 and Section 10.1.2	Section 10.1.1 and Section 10.1.2
PRG-5	The mission imagery, products and services shall be made freely available.	Section 10.3.3	Section 10.3.3
PRG-6	The mission shall leverage existing National Space Program and Sub-Program governance, procurement strategy and ground segment wherever viable.	Section 4.5	Section 4.5
PRG-7	The costings should include design, build and launch and commissioning of the payload.	Appendix H	Appendix H
PRG-8	The mission shall align with the Bureau strategy.	Section 1.7, Section 1.9, Section 2.1, Section 2.5	Section 1.7, Section 1.9, Section 2.1, Section 2.5
PRG-9	The mission shall undergo space segment Assembly, Integration and Testing in Australia as much as possible.	See Section 7.2	See Section 7.2
PRG-10	The mission shall consider ground segment requirements. The CDF should consider using an external provider to operate the ground segment component. The CDF report should include a costing of a commercial solution to the Ground Segment, including an option for 24/7 monitoring, if this is required.	Section 10.1.1, Section 10.4.1	Section 10.1.1, Section 10.4.1

Req. No.	Description	LEO	GEO
MIS-1	The mission will add complementary information to the existing ground lightning detection systems, with the benefit to provide much wider coverage, over ocean and including poorly populated areas.	Section 5.5.1, Section 5.5.2, Section 5.5.3	Section 4.4.1
MIS-2	The mission shall strengthen key partnerships with international satellite data providers, to ensure ongoing access to critical satellite data streams.	Section 1.9, Section 4.2, Section 10.2.3	Section 1.9, Section 4.2, Section 10.2.3
MIS-3	The mission shall archive and make freely available L0 to L2 data.	Section 10.3	Section 10.3
MIS-4	The mission shall provide L2 data in Near Real Time <20s.	In Section 5.4	In Section 6.8.1 and 11.3.9
MIS-5	The mission shall generate data and products which are commensurate with the measurements from existing geostationary lightning images.	Section 5.5.1, Section 11.4	Section 11.4
MIS-6	Each space segment shall have an in-orbit operational life of no less than 5 years following commissioning.	Assumed initial point of failure is inability for ADCS system to provide pointing accuracy. Thus, an ADCS subsystem derived pointing requirement in Section 5.9.1	Assumed initial point of failure to be propulsion fuel levels. Thus, a propulsion subsystem requirement in Section 6.4
MIS-7	Should a pathfinder pathway be appropriate the pathfinder space segment shall complete in-orbit commissioning within 4 years of the kick-off of the implementation phase.	Section 5.4.5, Section 13.3.1	N/A
MIS-8	The first geostationary space segment shall complete in-orbit commissioning within 8-12 years of the kick-off of the implementation phase.	N/A	Repeated as a propulsion subsystem requirement in Section 6.4
MIS-9	The mission shall contribute to global efforts in mapping and monitoring lightning, complementing existing geostationary lightning coverage.	See Section 2.5, Section 4.1, Section 4.2, Section 5.5.1	Section 1.7, Section 1.8, Section 1.9, Section 2.5, Section 4.1, Section 4.2, Section 4.5
MIS-10	The mission shall have the capability to be programmed to change data acquisition depending on the filtering required to maximise the detection efficiency and minimise the false alarm rate.	Section 5.4.3, Section 7.3	Section 5.4.3, Section 7.3

Appendix E - Pre-Phase A Derived Requirements Summary

ID	Type	Requirement	Threshold	Breakthrough	Objective
CDF-R-LD-1	**Spatial**	Spatial resolution – GSD (km) at SSP	As per MTG-LI	≤ 2	≤ 1
CDF-R-LD-2	**Temporal**	L1 (ms) L2 Data latency (minutes)	2 <5	2 <2	1 <1
CDF-R-LD-3	**Coverage**	Geographical Coverage/orbit	Australia	Himawari disk	Himawari disk
CDF-R-LD-4	**Other Instrument specs**	SNR, sensitivity, temporal resolution, location accuracy, spacecraft lifetime, product latency	As per GLM	As per MTG-LI	To meet temporal and spatial without loss of detection efficiency and sensitivity
CDF-R-LD-5	**Detection efficiency**	of total lightning	>80%	>90%	>90%
CDF-R-LD-6	**False Alarm Rate**	of total lightning	<5%	<5%	<5%
CDF-R-LD-7	**Spatial**	Spatial resolution – GSD (km) at SSP	As per MTG-LI	≤ 4	≤ 1
CDF-R-LD-8	**Temporal**	Data latency (minutes)	<5	<2	<2
CDF-R-LD-9	**Detection efficiency**	of total lightning	>70%	>80%	>90%
CDF-R-LD-10	**Spatial**	Spatial resolution – GSD (km)	3-6	≤ 2	≤ 1
CDF-R-LD-11	**Swath**	Swath Width (km)	600	>600	1000
CDF-R-LD-12	**Temporal**	Data latency	-	-	-

ID	Type	Requirement	Threshold	Breakthrough	Objective
CDF-R-LD-13	**Coverage**	Geographical Coverage/orbit	±35°	±55°	global
CDF-R-LD-14	**Instrument specs**	SNR, sensitivity, temporal resolution	As per GLM	As per MTG-LI	>MTG-LI

ID	Requirement	Upstream
CDF-R-LD-15	The GEO spacecraft must be placed in the desired operational GEO slot in less than 8-12 years	MIS-8
CDF-R-LD-16	The GEO spacecraft must be able to support no less than 5 years of operational manoeuvres including station-keeping.	MIS-6
CDF-R-LD-17	The propulsion subsystem of the GEO spacecraft must be able to place the spacecraft into an appropriate disposal orbit after no less than 5 years of operations has been completed.	MIS-6
CDF-R-LD-18	During abnormal operations, the mission shall operate for up to four days without the ability to downlink data, without loss of any data. *Rationale: Whilst untimely data cannot be used for real-time lightning strike reporting, the event data may still be useful in the context of providing a continuous/uninterrupted time-series data product. Four days is a generally recommended timespan that balances the possible length of an operational outage with a need to store excessive amounts of data.*	
CDF-R-LD-19	During normal operations, payload data shall reach the ground segment at most 20 seconds after the data was created.	MIS-04
CDF-R-LD-20	The communications system shall have an in-orbit operational life of at least five years post-commissioning.	MIS-06

ID	Requirement	Upstream
CDF-R-LD-21	The orbit shall facilitate vacation of the LEO protected region within 25 years after the end of the nominal mission.	PRG-4, relating to the responsible use of space.
CDF-R-LD-22	The orbit shall enable lightning observations over the entire Australian continent and its coastal waters with no gaps.	MIS-1
CDF-R-LD-23	The orbit shall enable lightning observations over regions of the Earth with significant lightning activity.	MIS-5, MIS-9
CDF-R-LD-24 (optional)	The orbit shall enable lightning observations over the entire globe. *Rationale: no lightning detector has provided global coverage since the OTD sensor on Microlab-1, which ceased operations in March 2000.*	Objective user requirements for climate monitoring and cross-calibration, Table 5.
CDF-R-LD-25 (optional)	The orbit shall enable lightning observations above fixed locations on the Earth with consistent mean solar time. *Rationale: continental lightning exhibits a strong diurnal variation; continental lightning activity peaks in the late afternoon, between 15:00 and 17:00. The LD LEO pathfinder orbit could fix the local time of observations to one of peak lightning activity.*	
CDF-R-LD-26	The space and ground segments shall be operated in accordance with the ITU Radio Regulations, and any applicable national regulations where the downlink system is to be operated.	PRG-04
CDF-R-LD-27	During normal operations, payload data shall reach the ground segment at most 24 hours after the data was created. *Rationale: Whilst there is no explicit upstream requirement, setting a reasonable and non-restrictive data latency requirement assists in constraining the solution space.*	PRG-02, MIS-03
CDF-R-LD-28	During abnormal operations, the mission shall operate for up to four days without the ability to downlink data, without loss of any data.	

ID	Requirement	Upstream
	Rationale: This duration balances the need for a backup ground segment with the desire to maintain continuity in the science data.	
CDF-R-LD-29	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-LD-30	The spacecraft shall be capable of transferring payload data to the ground segment in a nadir pointing configuration. *Rationale: As the system should operate the lightning detector continuously, this implies the satellite must always nadir point.*	
CDF-R-LD-31	All communication links shall be designed with a nominal link margin of at least 3 dB. *Rationale: A 3 dB link margin is considered typical for LEO communication systems, with 6 dB link margin desirable where possible.*	
CDF-R-LD-32	The attitude determination and control system architecture for the lightning detector sensor must provide a 10 km or less ground plane resolution for a LEO orbit at 550 to 600 km and at 35 788 km for a GEO orbit.	
CDF-R-LD-33	In support of both the LEO and GEO ADCS, the spacecraft must be able to support no less than 5 years of operational manoeuvres including station-keeping.	

Appendix F - Pre-Phase A Derived Specifications Summary

ID	Specification	Value	Derivation
CDF-S-LD-1	Mass (kg)	32	MTG-LI weighs 93 kg. A third of this mass was assumed for a single optical head.
CDF-S-LD-2	Volume (mm^3)	400 x 400 x 1200	MTG-LI has a 718 mm x 1200 mm x 1456 mm volume envelope. The volume was scaled down by about a fourth.
CDF-S-LD-3	Power (W)	100	MTG-LI consumes 300 W[50]. A third of this power was assumed for a single optical head.
CDF-S-LD-4	Data rate (Mbps)	7.5	MTG-LI operates at 30 Mbps with four optical heads. The proposed concept uses one optical head, hence will generate data at 7.5 Mbps.
CDF-S-LD-5	Pointing knowledge (arc min)	0.2	Derived from the requirement to geolocate within half a GSD from the GEO altitude as proposed during the study (half of 4.5 km[50] from 35,786 km).
CDF-S-LD-6	Duty cycle	100%	The lightning detector must be operating constantly as per the concept of operations.

ID	Manoeuvre	Assumption	Delta-V (m/s)
CDF-S-LD-7	**Orbit-raise from GTO**	Launch vehicle inserts satellite into highly elliptical Geostationary Transfer Orbit (GTO) at a LEO altitude. Perform a thruster burn at GTO apogee to correct inclination and circularise into desired GEO altitude. Circularising when the spacecraft is at GTO apogee (at GEO altitude) is assumed to lead to lower delta-V and monetary costs when compared to direct launch into GEO or Hohmann transfer from a LEO insertion.	1496

ID	Manoeuvre	Assumption	Delta-V (m/s)
CDF-S-LD-8	**Station-keeping**	Preliminary calculations indicate that station keeping for a 5-year mission, consisting of East-West and North-South burns, requires 235 m/s. This delta-V figure has been rounded up to 250 m/s to add margin that accounts for 46 – 50 m/s estimates found in existing literature.	250
CDF-S-LD-9	**GEO Disposal**	A circular GEO graveyard orbit is assumed, so a Hohmann transfer with a total perigee change of 302 km is targeted.	277
CDF-S-LD-10	**Total**	Add 2% delta-V to running total to account for errors such as launcher injection, thruster pointing inaccuracies.	2063
CDF-S-LD-11	**Hohmann transfer to mission GEO slot from above-GEO Graveyard orbit**	After the launch vehicle inserts satellite 300 km above GEO, return spacecraft to desired GEO slot as a circular-to-circular Hohmann transfer.	277
CDF-S-LD-12	**Station-keeping**	Preliminary calculations indicate that station keeping for a 5-year mission, consisting of East-West and North-South burns, requires 235 m/s. This delta-V figure has been rounded up to 250 m/s to add margin that accounts for 46 – 50 m/s estimates found in existing literature.	250
CDF-S-LD-13	**GEO Disposal**	At the end of the mission, return the spacecraft to a circular GEO graveyard orbit 300 km above GEO.	277
CDF-S-LD-14	**Total**	Add 2% delta-V to running total to account for errors such as launcher injection, thruster pointing inaccuracies.	814

ID	Specification	Value	Derivation
CDF-S-LD-15	On-board data storage (Gbit)	2531	Four days of data collection from the payload, which is generating data at 7.5 Mbps (CDF-S-LD-4).

ID	Parameter	Value
CDF-S-LD-16	Payload Output Data Rate (Mbps)	7.5
	Derivation	
CDF-S-LD-17	Packeting Overhead (%)	**10%**
CDF-S-LD-18	Required Data Downlink Rate (Mbps)	**8.25**

ID	Requirement	Threshold	Breakthrough	Objective	Assumed
CDF-S-LD-19*	Spatial resolution – GSD (km) **	3-6	3	3	**3**
CDF-S-LD-20*	Swath Width (km)	600	> 600	1000	**600**
CDF-S-LD-21*	L1 (ms) L2 Data latency	2 -	2 -	1 -	**2** **-**
CDF-S-LD-21*	Data latency	**No constraint (climate applications only)**			
CDF-S-LD-22*	Geographical Coverage (Latitude Range)	±35°	±55°	Full Globe	**±55°**
CDF-S-LD-23*	SNR, sensitivity, temporal resolution	As per GLM	As per MTG-LI	>MTG-LI	**Not evaluated**
CDF-S-LD-24*	Detection efficiency of total lightning	>70%	>80%	>90%	**Adjustable threshold**
CDF-S-LD-25*	False Alarm Rate	<5%	<5%	<5%	**<5%**

*** A 3km GSD would provide a new research baseline that does not presently exist; anything smaller will degrade performance*

ID	Specification	Value
CDF-S-LD-26	Mass (kg)	< 10

CDF-S-LD-27	Volume	< 3U
CDF-S-LD-28	Power (W)	< 12
CDF-S-LD-29	Data rate (kbps)	< 50

ID	Specification	Value	Notes
CDF-S-LD-30	F/#	2	Assumption.
CDF-S-LD-31	Pixel pitch (μm)	24	Assumption.
CDF-S-LD-32	Optical aperture (mm)	1.7	Derived from F/# = 2 and focal length f = 3.3 mm.
CDF-S-LD-33	Focal length (mm)	3.3	Derived from orbit altitude, GSD, and pixel pitch.
CDF-S-LD-34	Field of view (deg)	+/- 28.30	Derived using orbit altitude and swath width.
CDF-S-LD-35	Instantaneous field of view (deg)	0.41	Derived from orbit altitude GSD.

ID	Specification	GLIS Value	LD Value	Notes for LD
CDF-S-LD-36*	Mass (kg)	< 10	10	Conservative upper bound based on the GLIS design.
CDF-S-LD-37*	Volume	< 3U	4U	Conservative upper bound based on UNSW Canberra Space's experience with the M2 mission.
CDF-S-LD-38*	Power (W)	< 12	12	Conservative upper bound based on the GLIS design.
CDF-S-LD-39	Data rate (kbps)	< 50	100	See section 5.4.4.

ID	Specification	GLIS Value	LD Value	Notes for LD
CDF-S-LD-40*	Pointing knowledge (deg)	*Unspecified*	0.2	Half a pixel, as per LIS requirement.

ID	Baseline Orbit Parameter	Value
CDF-S-LD-41	Altitude [km]	550
CDF-S-LD-42	Inclination [deg]	45
CDF-S-LD-43	Period [minutes]	95.65

ID	SSO Orbit Parameter	Value
CDF-S-LD-44	Altitude [km]	605.52
CDF-S-LD-45	Inclination [deg]	97.83
CDF-S-LD-46	Period [minutes]	96.92
CDF-S-LD-47	Repeat Cycle [days]	7
CDF-S-LD-48	Recurrence Grid Interval [km]	385.34
CDF-S-LD-49	Mean Local Time at Equator	16:00

ID	Parameter	Value
CDF-S-LD-50	Acquisition Time (min/orbit)	95.65 (CDF-S-LD-42)
CDF-S-LD-51	Payload Output Data Rate (Kbps)	100 (CDF-S-LD-38)

	Derivation	
CDF-S-LD-52	Payload Data Generated (Gb/day)	**8.24**
CDF-S-LD-53	Packeting Overhead (%)	**10%**
CDF-S-LD-54	Required Data Downlink (Gb/day)	**9.06**

ID	Parameter	Value	Unit	Rationale
CDF-S-LD-55	Frequency Band	8025 – 8400	MHz	Supported by the reference transmitter. See also the discussion under the sub-heading Architecture in section 11.3.8.
CDF-S-LD-56	Output Power	2	W	As per the reference transmitter.
CDF-S-LD-57	Symbol Rate	25	MBd	Assumed reasonable, representative, modest value, noting that higher bandwidths may increase difficulty and complexity of radiocommunications licencing. Appears to be supported by a number of available off-the-shelf CubeSat platforms[122].
CDF-S-LD-58	Satellite Antenna Gain	6	dBi	As per reference antenna.
CDF-S-LD-59	Antenna Beamwidth (half power)	74	°	As per reference antenna.
CDF-S-LD-60	Acceptable Bit Error Rate (approximate)	10^{-7}	bits/bit	Reasonable value supported by DVB-S2[32].

[122] For example, the EnduroSat 6U Cubesat Platform and larger models - https://www.endurosat.com/cubesat-store/cubesat-platforms/6u-cubesat-platform/

ID	Parameter	Value	Unit	Rationale
CDF-S-LD-61	Ground Station Antenna Gain	50.5	dBi	5.4 m dish, 55% efficiency, assumed representative of the minimum of a commercial provider[123].

[123] As an example, 5.4 m dishes or larger are available at all of ViaSat's ground stations - https://www.viasat.com/space-innovation/space-and-networking-technology/ground-network/.

Appendix G – Instrument Specifications for Current and Previous Lightning Detector Missions

This data has been taken from Reference Document 10 (see Reference Document list on page 18): Bureau Of Meteorology – Draft Satellite Lightning Sensor Mission description and requirements document (14 October 2022).

Note that the information in these tables has been compiled using the open literature. In some cases, the specifications may have changed closer to the launch of the instrument. For the latest specifications, contact the mission sponsor.

Lightning Imaging Sensor (LIS):

Note that the specifications differ for ISS-LIS

Specification	Value
Mission Sponsor	NASA/JAXA
Principal investigator	Hugh Christian (University of Alabama)
Orbit	inclination 35°
Altitude (km)	350-405
Spectral filter (nm)	777.4 (0.3nm)
Swath (km)	600x600
Imager type	CCD 128x128
Horizontal resolution (km)	3(nadir)-6(limb)
Temporal resolution (ms)	2
Mass (kg)	20 (15??)
lens focal length (mm)	200
Diameter (mm)	100
Lens aperture (mm) how different from diameter?	33
f Lens f number	2
Minimum energy/threshold	4.7 µJ/m2 sr
Volume (height, width, depth)	:~Dia: 200mm x L 350 mm
Power (W)	30 (25)
FOV (degree/km)	80x80/8
IFOV (degree/km) &	0.7
Flash detection efficiency	>90% (not met due to telemetry)
False alarm rate	<10%
Product latency	
Signal to noise	6
Detection threshold	4.7 µJ m-2 sr-1
Temporal resolution	500 frames/sec

Specification	Value
Telemetry/Format (kb/s)	8 PCM (Pulse Code Modulation) 12 bits
Spatial Coverage	N: 38.0, S: -38.0, E: 180.0, W: -180.0 (Tropics)
Temporal Coverage	January 1, 1998 – April 8, 2015
Location accuracy	1 pixel
Dynamic range	>100 defined as the variation in event energy incident on a detector from minimum to maximum
Intensity accuracy	10%
Quantum efficiency of CCD	0.6
Operating temperature (Celsius)	-25 to 40
Parameter	Lightning, lightning density

NOAA Global Lightning Mapper (GLM):

Specification	Value
Mission Sponsor	NASA
Principal investigator (no PI for operational instruments)	Hugh Christian (University of Alabama)
Contractor	Lockheed-Martin Advanced Technology Corp (LM ATC), Palo Alto, CA
Orbit	Geostationary ±0.5
Spectral filter (nm)	777.4 (1nm resolution) 30 nm solar rejection filter 3 nm solar blocking filter
Lens focal length (mm)	134
Lens f number	1.22
Imager type	CCD array with 1372 x 1300 pixels, pixel size (variable)
Horizontal resolution (km)	8 (nadir)-14 (limb)
Pixel size (um)	30x30

Specification	Value
Location accuracy	within a half a pixel.
Well depth of CCD	~2 million electrons
Aperture Diameter (mm)	120
Lens field of view	+- 8deg
Temporal resolution	2ms
Mass total (kg)	125
Mass sensor unit (kg)	67
Mass electronics unit (kg)	41
Volume (height, width, depth)	149 cm × 63.5 cm × 65.8 cm
Power (W)	405 (total) (290 payload)
Data rate/Telemetry	7.7 Mbit/s; modulation: PCM; quantization = 14 bit
FOV (degree)	±8
Flash detection efficiency	>80% (24 hours) > 70% (day)>90% (night)
False alarm rate	<5%
Product latency	<20 s
Signal to noise ??	6 > 100
Onboard Digital video data	12.5 Gbps
ADC resolution	14bits
Event rate	>1e^{5} sec^{-1} (after filtering?)
Operating life	>10 years
Sensitivity	10µJ/sr/m^{2} calibration is measured in Joules in space, the on ground calibration is in Watts https://slidetodoc.com/glm-performance-review-and-post-launch-test-results/
Navigation performance	.5 pixel https://slidetodoc.com/glm-performance-review-and-post-launch-test-results/

Meteosat Third Generation – Lightning Imager (MTG-LI):

Specification	Value
Mission Sponsor	EUMETSAT
Principal investigator	Bartolomeo Viticchiè
Orbit	Geostationary
Spectral filter (nm)	777.4 ±.17nm (1.9nm band with Bart) (1.6 according to Leonardo talk)
Lens focal length (mm)	190.8
Lens f number	1.73
Imager type	CMOS 1000 x 1170 pixels (per camera), 24 µm pitch
Horizontal resolution (km)	< 10 Km @ Latitude 45° and Subsatellite Longitude targeted GSD of 4.5 Km at Sub Satellite Point – SSP
Location accuracy	
LI Optical Head Envelope	718 x 1200 x 1456 mm^3
Lens field of view	
Temporal resolution	1000 frame per second; 1ms
Mass total (kg)	130 Leonardo
Mass sensor unit (kg)	102 Leonardo
Mass electronics unit (kg)	12 Leonardo
Power (W)	60(detector only) < 320W (total) 110W optical head 95W electronics
Data rate/Telemetry	30Mbitsps https://slidetodoc.com/mtg-lightning-imager-proxy-data-presentation-to-the/
Telemetry	Ka band
FOV (degree)	16° diameter shifted northward or 84% of visible Earth disk, including all Eumetsat member states
Flash detection efficiency	>70% (24 hours) >90% (night)
False alarm rate	<5%
Product latency	<20 s
Signal to noise	4 (day) 12 (night)
Onboard Digital video data	6 Gb/s download to 4MB/s mission data (Leonardo) differs from 30 above
ADC resolution	12 bit

Specification	Value
Event rate	500 kbps
Operating life	≥2023-02 to ≥2030
Reliability	4% maximum outages over one year
Dynamic range of Earth background	0 to 296.5 W/m²/µm/sr
Optical pulse dynamic range (LLp)	6.7 to 670 mW/m²/sr
Optical pulse size (can be much smaller and much larger)	10 Km to 100 Km circular pulse diameter
Maximum number of optical pulses in the FOV	25 in 1 millisecond 800 in 1 second
Sensitivity	7.0 mW/m²/sr (day) 17.0 mW/m²/sr (night) Dobber paper (High sensitivity (detection of lightning pulses up to 4µJ/(m2sr) Leornardo specifications
Dynamic range	4.0 -400 mW/m²/sr
Instrument Average detection probability	90% for latitude 45 deg 70% as average over the FOV 40% over EUMETSAT member
Calibration accuracy	10%

Key Differences Between GLM and MTG-LI:

Key design feature	LI*	GLM
Detector	1000x1170 (x4) pixels CMOS	1372x1300 pixels CCD
Spatial resolution	4.5 km at Nadir (variable within the FOV; about 8 km over Europe)	8 km (nearly constant; 14 km at FOV edge)
Coverage	Up to 80 degrees North	Up to 52 degrees North
Spectral band	777.4 nm with 1.9 nm bandwidth	777.4 nm with 1 nm bandwidth
Integration time (frame rate)	1 ms	2 ms
On-board processing	Lightning detection and data filtering	Lightning detection
Bandwidth	30 Mbps (3x3 pixel window for each detection)	7.7 Mbps
Latency (timeliness)	1 min	20 sec
Detection efficiency	70-90% flash detection efficiency (expected)	70-90% flash detection efficiency

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