Australian Bureau of Meteorology Pre-Phase A Mission Study Report

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Concurrent Design Facility

Australian Bureau of Meteorology

Pre-Phase A Mission Study Report

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1 Executive brief

This report presents the findings of a Pre-Phase A study which was conducted by the Australian National Concurrent Design Facility (ANCDF) and involved a total of 27 personnel from the Australian Bureau of Meteorology (The Bureau), UNSW Canberra Space, the Australian Space Agency, and Geoscience Australia.

- This study was conducted during four two-hour CDF sessions over the course of three weeks in March and April 2021.

- The study examined the feasibility of developing dedicated satellite missions to fulfil future Bureau operational needs. Three meteorological instruments with the potential to meet a key set of the Bureau's future needs for satellite data were selected from a set of ten possible instruments. For each of these the Bureau provided a rough outline of the performance specifications (e.g., accuracy, spatial resolution, frequency bands). The instruments selected for analysis in the study are;

    - **a lightning sensor** to support severe storm forecasts and warnings and climate studies,

    - **a synthetic aperture radar (SAR)** for use over the Antarctic to support ice monitoring and,

    - **a hyperspectral microwave sounder** to provide atmospheric temperature and water vapour information for assimilation into numerical weather prediction (NWP) models.

- For each instrument a follow-up 30-minute requirements refinement meeting was held after Session 4 of the CDF study.

- Australia has a nascent space industry. The pathway to trusted and reliable operational sensors will require development of pathfinder or demonstration payloads as a first step. This study focused on sensor configurations that can be developed over the next 5-10 years, by primarily Australian industry, with mentoring from international partners where needed.

- The study provided an:

    - assessment of the current global technical capability and cost estimates for each of the three instruments,

    - estimation of the capacity of Australian industry to deliver instruments with similar capability as those currently deployed and/or pathfinder missions that would provide reduced capability but useful data to the Bureau within a 5-year time window and,

    - recommendation to proceed to a Phase A study to develop baseline conceptual designs for a pathfinder version of each mission.

- This study does not consider technical solutions or Australian technical capability for real time data transmission which would include the need for ground station capabilities and processing of data, but this capability would be essential for operational missions that support the Bureau's forecast and warning services.

- This study also presents the results of a survey conducted by Earth Observation Australia (EOA) that identifies Australian missions and/or projects that may be considered as candidates for a meteorological satellite mission. This study assesses the potential value of these missions in supporting weather services.

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5 Executive summary

The Bureau of Meteorology depends heavily on Earth Observations (EO) from satellites to predict the weather. Australia does not own or operate EO satellites and relies on foreign owned satellites for these observations. The Bureau commissioned this study to explore the feasibility of Australian designed and built meteorological satellites that could meet specific Australian needs for weather and climate observations.

As set out in the Australian Civil Space Strategy (the Strategy) the Australian Space Agency is working with partners across Government to develop technology roadmaps for each of the National Civil Space Priority Areas identified in the Strategy.

Three studies have been conducted by the UNSW ANCDF to inform the development of the roadmap for Earth Observation from Space. The three studies include: 1) a Pre-Phase A study for the AquaWatch mission sponsored by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2) a Phase A study for an Australian Satellite Cross-Calibration Radiometer (SCR) series sponsored by Geoscience Australia (GA) as a potential part of the USGS/NASA (United States Geological Survey) Sustainable Land Imaging Initiative, and 3) this study commissioned by the Australian Bureau of Meteorology (the Bureau) to identify key missions/instruments to support metrological forecasting and disaster monitoring and mitigation.

The objectives of this study were to identify three meteorological instruments from a set of ten possible instruments, identified by the Bureau, which have the potential to meet not only the Bureau's future needs for satellite data but to provide a data generation capability to the global meteorological community. For each of the instruments, the Bureau provided an outline of the performance specifications (e.g., accuracy, spatial resolution, frequency bands). The instruments are required to meet one or more of the following criteria:

a) satisfy the Bureau's NWP (Numerical Weather Prediction) and Nowcasting requirements, preferably with a focus on disaster resilience;
b) address gaps in the global observing system, as defined by the WMO's (World Meteorological Organisation) 'Rolling Review of Requirements' (https://community.wmo.int/rolling-review-requirements-process), and CGMS (Coordination Group on Meteorological Satellites) High Level Priority Plan (https://www.cgms-info.org/documents/CGMS_HIGH_LEVEL_PRIORITY_PLAN.pdf);
c) strengthen key partnerships with international satellite data providers, to ensure ongoing access to critical satellite data streams;
d) data assurance to support critical services by building a sovereign satellite industry capability;
e) have a secondary impact on the Bureau's data needs and business functions.

The Bureau selected ten possible instruments for consideration and presented an overview of each mission during the first CDF session. The instruments were discussed in detail among the study team, Bureau scientists and stakeholders. A poll was then conducted where the Bureau's personnel (Table 25) ranked, in order of importance, the major requirements that each sensor must achieve. The ten instrument options were then evaluated in terms of their capability to fulfil these requirements as well as their importance in providing modalities to enhance the working arrangements between the Bureau and international meteorological agencies/organisations.

This study does not consider technical solutions or Australian capability for real time data transmission, but this capability would be essential for operational missions that support the Bureau's forecast and warning services.

Three instruments were selected for analysis in this study:

- **a lightning sensor** to support severe storm forecasts and warnings and climate studies,
- **a SAR instrument** for ice monitoring, and
- **a hyperspectral microwave sounder** for atmospheric temperature and humidity profiling.

An analysis was performed by the UNSW team to investigate the feasibility of developing such sensors in Australia based on the technical, programmatic, and industry capacity as well as cost implications by comparison with the current and planned capabilities pursued by international space agencies and the wider global space industry.

Based on the NASA EO Instrument Cost Model and the Bureau's preliminary requirements, the rough order of magnitude costs are AUD $86 million for a 100kg lightning payload, AUD $13 million for a 4kg microwave pathfinder, and AUD $17 million for an 85kg SAR pathfinder. Costs for the platform, testing, launch and operation are not included in these estimates.

Most of the satellite data currently used by the Bureau are from operational missions with continuity. With the Australian space industry in an early developmental phase, there is effort required to build the infrastructure and skills necessary to manufacture any of the identified missions to a fully operational capacity within the next 5 years. The pathway to operational, reliable and trusted missions is through the development of demonstration or pathfinder missions.

Australian industry developed pathfinder missions could include sovereign instrument designs, spacecraft subsystems and data processing capabilities which could serve as a pathway to longer-term operational systems as the industry matures, whilst simultaneously providing improved data products to the Bureau and its partners in the short-term. In doing so, it would build Australian space heritage and increase the Technology Readiness Levels (TRL) of the Australian space sector. The result would be an increase of skills in Australia across the supply chain and within all related sectors.

For each mission it was concluded that a Phase A investigation is warranted. Outcomes from these studies could be a further down-selection to consider development of one or two missions, a refined profile for each mission, a restructuring of project goals, investment in key domestic technology areas and establishing working relationships with international partners (both industrial and governmental) for mission development.

This study also presents the results of a survey conducted by Earth Observation Australia (EOA) that identifies Australian missions and/or projects that may be considered as candidates for a meteorological satellite mission. This study assesses the potential value of these missions in supporting weather services.

6 Study context

The Bureau has been a substantial user of Earth observations from space for several decades, and this continues to grow at a significant pace. The Bureau currently assimilates data from over 30 satellites[1] into weather, ocean and hydrology prediction and visualisation systems every day. This is crucial for the provision of weather forecasts and warnings across Australia and beyond, to support national commitments for safety and security specified in the *Meteorology Act 1955*.

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

Over the next decade, volumes of data used by the Bureau are predicted to increase by a factor of 30 – 50 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 are much reduced and unevenly distributed.

The value of satellite observations to the Bureau and the broader economy was described in the Deloitte *Economic study into an Australian continuous launch small satellite program for Earth observation*[2]. It found that the Bureau's services, which are largely underpinned by satellite data, contribute a significant proportion of the direct value added by the EO sector.

The Bureau's *Research and Development Plan 2020-2030* articulates a number of initiatives within its 10-year vision for improving weather forecasts, including "*substantial increases in data assimilated, and much greater variety of traditional and non-traditional data sources used in our systems*". This includes using observations from conventional large science-grade satellite missions and new sources like SmallSats.

This Pre-Phase A study is concerned with identifying possible missions so that the Bureau can improve its weather forecasting, nowcasting and environmental monitoring objectives.

In general, the study has used the NASA project lifecycle approach for conducting a Pre-Phase A space mission study. Table 1 provides a summary of the formulation undertaken in this study[3].

Table 1 NASA Project Lifecycle Pre Phase A formulation

Pre-Phase A Definition	Concept Studies
Purpose	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected.
Approach	A study or proposal team analyses a broad range of mission concepts that can fall within technical, cost, and schedule constraints and that contribute to program and Mission Directorate goals and objectives. Pre-Phase A effort could include focused examinations on high-risk or high technology development areas.

[1] http://www.bom.gov.au/australia/charts/bulletins/nmoc_bulletin.shtml
[2] https://www2.deloitte.com/au/en/pages/economics/articles/economics-earth-observation.html
[3] https://www.nasa.gov/seh/3-project-life-cycle

Typical outcomes	Together the study team, customers, and other potential stakeholders, help the team to identify promising mission concept(s). The key stakeholders (including the customer) are identified and expectations for the project are gathered from them. If feasible concepts can be found, one or more may be selected to go into Phase A for further development.

7 Acknowledgments

This study was undertaken by the following study participants:

space UNSW CANBERRA — Australian Government Bureau of Meteorology — Australian Government Geoscience Australia — Australian Space Agency

A full list of study participants can be found in Appendix A: Study participants.

8 Study methodology and objectives

The study was conducted during four CDF sessions and in outside work conducted by UNSW Canberra Space engineering personnel over a period depicted in Figure 1. Sessions 1 and 2 were geared to defining the Bureau's top ten meteorological space missions and down-selecting to three key missions for further investigation. Sessions 3 and 4 presented the findings of the study team, further interaction with the Bureau's scientists and data users and a discussion of results and conclusions.

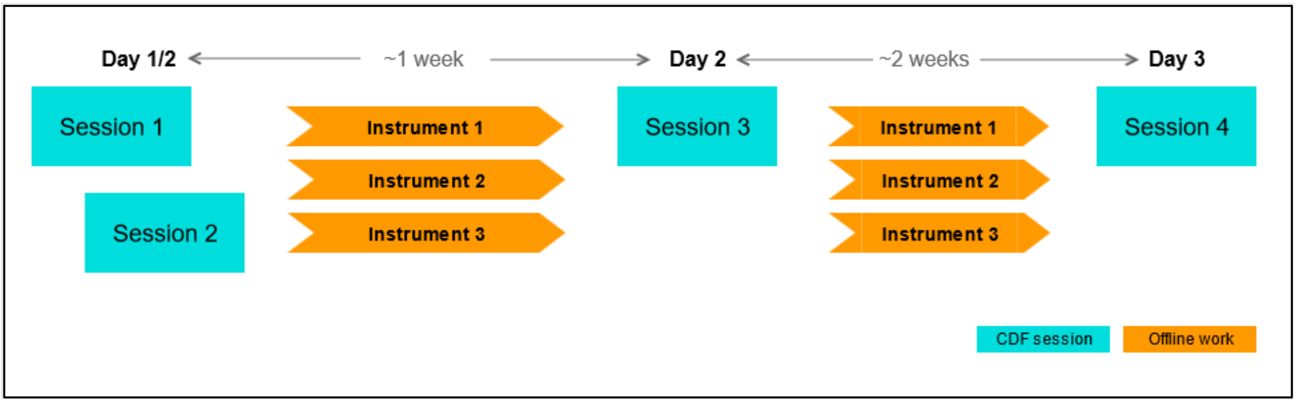


Figure 1 Study workflow

The following methodology was used to fulfil the study objectives for each of the three missions;

a) assess the current global capability and technical feasibility of each instrument type,
b) construct a set of preliminary mission and performance requirements for each instrument,
c) assess the technical and programmatic feasibility to develop each instrument,
d) identify constraints, limitations, technology gaps or non-feasible elements to develop each instrument type within the context of the current state of the Australian space industry,
e) define a preliminary development approach considering areas of mission risk and,
f) determine the features, size and cost of these missions which can include scoping of international partnership options,
g) recommend those missions which have sufficient technical feasibility to merit further investigation in Phase A study where an initial instrument design baseline and mission concept, as well as a codified system-level requirements document, needed system technology developments, and program/project technical management plans would be created.[4]

Australia has a nascent space industry, and so the pathway to trusted and reliable operational sensors will require development of pathfinder or demonstration payloads as a first step. This study focused on sensor configurations that can be developed over the next 5-10 years, by primarily Australian industry, with mentoring from international partners where needed.

[4] Australian Government Commonwealth Contract-Services, ID 225-3030-21 (2021)

9 Bureau mission options

The Bureau presented an overview of ten meteorological satellite capabilities that if developed would provide a sovereign contribution to the meteorological data used by the Bureau and international partners. This section presents a summary of each of the capabilities which formed the basis for a down-selection exercise to explore in greater detail the feasibility of developing the top three missions deemed most important to the Bureau.

9.1 Option 1 – Real-time vertical Infrared (IR) soundings

Operational requirement: IR sounders are sensitive to temperature and moisture profiles at different heights in the atmosphere. Current hyperspectral instruments deliver temperature information with a vertical resolution of around 1 K per km, humidity information with a resolution of 10% per km, and an Instantaneous Field of View (IFOV) of around 12 km. Coupled with advances in computing and processing, these observations have been one of the greatest contributions from meteorological satellites to weather forecasting. They have shown consistently that they improve forecast accuracy and consequently assist in the early prediction of severe weather events. At the Bureau, IR soundings from the IASI instrument have the greatest impact on the Bureau's Numerical Weather Prediction (NWP) system, and account for 20% of the impact on forecast accuracy on the Bureau's global scale model.

Over the next decade the Bureau's NWP system will continue to improve, with expected improvement in spatial resolutions and better modelling of error correlations. The global model will approach convection-resolving resolution and regional models will approach sub kilometre resolutions. Currently, data is thinned to reduce error correlations between measurements, but in the future this will be overcome by directly accounting for these correlations, using better forward operators and using observations with smaller footprints. These improvements, together with expected innovations in computing and assimilation techniques will allow the Bureau to assimilate greater volumes of satellite observations which will result in improvements to the Bureau's forecasts[5].

IR soundings used at the Bureau are mostly from satellites in Low Earth Orbit (LEO). Data is received over the internet and from the Bureau's ground stations. Locally received data is delivered within 20 minutes of the observation time, to meet the Bureau's low latency requirements for rapid update city-scale modelling. The Bureau does not currently have access to hyperspectral IR sounding observations from geostationary orbit. Such observations could be of great benefit to the small domain, high resolution weather models over the most populated regions of Australia, as they would provide more frequent observations at lower latency, creating more opportunities for cloud-free observations. The China Meteorological Administration (CMA) operate the GIIRS instrument over the China region, and EUMETSAT will launch a hyperspectral IR sounder on their Meteosat Third Generation (MTG) mission in 2023.

Similar operational sensor: IASI, CrIS

Future hyperspectral sounders: IASI-NG, MTG-IRS

Similar CubeSat: MISTIC WINDS

[5] http://www.bom.gov.au/inside/Research_and_Development_Plan_2020-2030.pdf

Continuity: Ultimately the Bureau requires operational missions with continuity. The Bureau recognises that the pathway to operational, reliable and trusted missions is through the development of demonstration or pathfinder missions.

9.2 Option 2 –Hyperspectral microwave soundings and radiances

Operational requirements: Microwave sounders provide global all-weather temperature and moisture information from the Earth's surface to top of the atmosphere. The temperature soundings mainly exploit the oxygen band between 50 and 60 GHz, while the water vapour lines at 22.235 and 183.31 GHz are used for water vapour detection and profile retrieval.

According to the World Meteorological Organisation (WMO), observations from microwave sounders have been the single most important source of observational information for global NWP over the past 20 years. The low vertical and horizontal resolution of current microwave sounders compared with IR sounders makes them more suited to large scale events, however their use has shown significant impact on weather forecasts, particularly because of their ability to 'see' though clouds. In the Bureau, microwave observations from the AMSU sensor have the third greatest impact on NWP (after IASI and satellite-derived upper atmosphere winds) and make a significant contribution to the forecast accuracy on the global model. International weather agencies with more advanced "all-sky" assimilation find that microwave sounders have the greatest impact on weather forecasts in their systems.

Microwave radiances are also important for climate monitoring applications due to the heritage of the temperature records from microwave sensors as far back as 1979. They are important for long-range climate projections that require consistent and systematic high-quality observations.

The Bureau receives microwave sounding data from the US and Europe via the internet and from the Bureau's ground stations in near real time, to meet the low latency requirements of NWP.

SmallSat constellations of microwave sensors offer opportunities as a complementary data type to the main missions in early-morning, mid-morning and mid-afternoon LEO orbit. The ability to launch larger numbers of these smaller and cheaper sensors means that they have the potential to fill spatial and temporal gaps in global coverage with higher spatial resolution.

The Bureau is interested in exploring the feasibility of a hyperspectral instrument of ~100 channels, allowing it to better depict the temperature and moisture fields in the vertical. Combined with an appropriate antenna, it will also importantly provide critical all-weather sounding data around and over Australia at a resolution appropriate to current operational numerical weather prediction models. This high resolution observational data is anticipated to improve numerical analysis, for example in the case of severe weather and to provide an improved basis for subsequent forecasts. More sophisticated use of water-vapour sensitive channels is expected to have a high impact on precipitation forecasting, and imagery from microwave instruments can be generated for use in extreme weather nowcasting.

Similar operational sensors:

- AMSU-A on the NOAA and Metop satellites, provide only temperature soundings.
- MHS on the NOAA and Metop satellites (AMSU-B on older missions) are used together with AMSU-A to provide humidity soundings.
- ATMS on the SNPP and JPSS satellites, provides both temperature and humidity soundings.

- MWHS-2 and MWTS –2 on China's FY-3, separately provide humidity and temperature soundings.
- The Metop-Second Generation Microwave Sounder, will be launched by EUMETSAT in 2024. Compared with AMSU-A and MHS it will have two additional temperature channels and three humidity sounding channels.

Similar CubeSats :

- TEMPEST-D, measures water vapour in five channels from 89 to 182 GHz.
- TROPICS, provides temperature profiles in 7 channels near the 118.75 GHz oxygen absorption line, water vapour profiles using 3 channels near the 183 GHz water vapour absorption line, imagery in a single channel near 90 GHz for precipitation measurements, and a single channel at 206 GHz for cloud ice measurements.
- IOD GEMS, 3D temperature and moisture atmospheric profiles. Follow-on mission is GEM-STORM, with 48 low-earth orbiting 6U passive microwave CubeSat satellites with sounding and imaging channels.

Continuity: Ultimately the Bureau requires operational missions with continuity. The Bureau recognises that the pathway to operational, reliable and trusted missions is through the development of demonstration or pathfinder missions.

9.3 Option 3 – Real-time weather imaging

Operational requirements: The Bureau relies on real time, high temporal frequency, visible and infrared satellite observations to support operational weather services including for:

- Volcanic ash – for warnings and alerts for the aviation industry.
- Tropical cyclones – for monitoring the formation and track of cyclones.
- Bushfires – for hotspot detection, monitoring of smoke and wind changes.
- Solar insolation – used to understand how much sunshine is available to fuel solar cells, a variable and increasing part of Australia's energy mix.
- General situational awareness – for monitoring the development, position, moving direction and speed of high impact weather events such as thunderstorms.

The Bureau's needs for real time weather imaging are currently met by JMA's Himawari-8 satellite, located at 140.7 deg E, and also Korea's Geo-Kompsat-2A. Since the launch of Himawari-8 in 2015, the Bureau has benefited from full disk imagery, every 10 minutes, with a latency of around 7 minutes. In addition to the routine 10-minute images, the Bureau also has access to rapid scan data every 2.5 minutes (from Himawari) and every 2 minutes from Korea's satellite by request. The rapid scan imagery is valuable for fast moving high impact events such as volcanic ash, tropical cyclones and bushfires, and was used during the Black Summer fires in 2019/20.

There are currently no sounder or lightning observations from geostationary orbit over Australia, except for China's FY-4 satellites which provide lightning data over parts of Western Australia for part of the year.

Similar sensors/ missions:

- Himawari-8/9, AHI (Japan)

- GeoKompsat-2A, AMI (South Korea)
- FY-4B, AGRI (China)
- GOES-16, -17, ABI (US)

Continuity: The Bureau is reliant on international agencies (JMA, KMA and CMA) for geostationary satellite coverage over the Australian region.

9.4 Option 4 – Extended observations of the Antarctic using Synthetic Aperture RADAR (SAR)

Operational requirement: High resolution coverage of the Antarctic sea ice zone is needed for monitoring of near-real-time operations and for use in numerical weather prediction models.

Sea ice can threaten marine operations and present a hazard for ocean vessels and installations. The Bureau's ice monitoring service delivers a daily sea-ice edge service and weekly ice bulletin for mariners, which requires routine near real time SAR observations for measuring and inferring ice parameters like surface roughness, ice type, concentration, and drift speed.

The Bureau is moving away from weather and seasonal models that retain a static sea ice through the modelling timescale. The new generation of models will simulate earth processes through fully coupled systems that include the modelling of sea ice – on both a global scale and higher resolution regional Antarctic models. It is expected that such models will not only benefit regional Antarctic forecasting but will also provide an increase in performance over mid and lower latitudes, including Australia. Observations over the Antarctic sea ice zone are sparse and mostly lacking. Satellite data are also more difficult to interpret over this region due to, for example, little optical contrast between the surface and atmosphere (Brunet et al., 2015). SAR observations are required to provide initial conditions for the models.

L and C band SAR are complementary and the preferred technologies, however X-band SAR is also useful. The Bureau currently relies on the two Sentinel-1 missions to meet operational needs. Together these satellites provide coverage of the Antarctic region every three to five days. To meet operational needs, daily SAR observations would be ideal. When there are gaps in coverage the Bureau supplements these observations with commercial SAR data from Radarsat-2 and TerraSAR-X, as well as visible imagery from Landsat, Sentinel-2/3 and MODIS however these are less useful as there are few cloud-free days per week. Passive microwave radiometers such as SSMI-S and AMSR-2 are also useful as a backup.

SAR data is also useful for detecting crevasses and sastrugi, which are hazards for aircraft landing in the Antarctic.

An Australian SAR mission could provide a secondary benefit of on-demand imaging of the continental surface, providing observations useful in soil moisture analysis.

Orbit options: elliptical orbit or constellation of LEOs

Similar sensors/ missions:

- Sentinel 1A (C Band)
- Sentinel 1B (C Band)
- Radarsat-2 (C band)
- RCM-1 (C-band)
- ALOS PALSAR-2 (L band)

- ICEYE (X band)
- COSMO SkyMed (X band)
- ROSE-L (L band - planned for 2028)
- NI-SAR (L Band – planned for 2022)
- ALOS 4 (L-band – planned for 2022)

Continuity: The Bureau requires operational missions with continuity. The Bureau recognises that the pathway to operational, reliable, and trusted missions is through the development of demonstration or pathfinder missions.

9.5 Option 5 – Lightning sensor

Operational requirement: It is estimated that there are 5–10 deaths per year from lightning strikes in Australia, and more than 100 serious injuries. Lightning also ignites bushfires, causes damage to electrical infrastructure and the storms associated with lightning also cause damage.

At the Bureau, lightning data is used in a number of applications. Real time lightning observations (intra cloud and cloud-to-ground) are critical for monitoring the formation, development, tracking and classification of thunderstorms, and can serve as a very clear indicator of the strength and extent of storm cells. Monitoring the total flash rates and the rate changes makes it possible to identify lightning cells with the potential to produce severe weather.

Lightning data are also used to better understand climate variability. Lightning is one of the Global Climate Observing System's (GCOS) list of Essential Climate Variables (ECVs), required to understand and predict the evolution of climate.

The Bureau has developed automated procedures for thunderstorm cell tracking and monitoring lightning strike density which are used by forecasters to diagnose, forecast and warn of thunderstorms more accurately and efficiently. These help the Bureau improve safety for the Australian community and for stakeholders in sectors including aviation and defence. Currently the Bureau uses in-situ lightning observations from commercial companies to support these services.

Satellite based lightning observations provide an opportunity for a different but complementary dataset for the Bureau's forecasters. The Bureau does not currently have access to satellite-based lightning observations for the Australian region, though the China Meteorological Agency (CMA) provides data from their demonstrator FY-4A mission for parts of Western Australia for some of the year. Satellite based lightning is capable of detecting total lightning activity during both day and night, over land and sea, potentially filling in data gaps where ground-based lightning detection networks offer low detection resolution. It could be useful for tropical cyclone modelling away from the land surface, and could provide support to small Pacific nations.

The Coordination Group on Meteorological Satellites (CGMS, 2021) recommends the advancement of new generation of geostationary satellites, including those with advanced lightning mapping. Such a mission could potentially be hosted on an international satellite, providing opportunities for partnership.

Similar sensors/missions:

- GLM (GOES-16, 17) - US region coverage.

- LMI (FY-4 series) - limited Australian region coverage
- LIS (ISS)
- LM (Electro M N1) - planned for 2025

Orbit options: Geostationary orbit required to meet the Bureau's requirements for continuous real-time observations.

9.6 Option 6 – 3D wind-field horizontal component

Operational requirement: Wind observations at all levels of the atmosphere are one of the key elements required for global NWP. Wind profiles are listed as the highest priority critical atmospheric variable that is not adequately measured by current or planned observing systems according to the World Meteorological Organisation (WMO) Rolling Review of Requirements (WMO, 2018). Observations from in-situ networks such as radiosondes, wind profilers and radars provide high quality but poor coverage of wind speed and direction, whereas satellite observations such as those derived from geostationary satellites and scatterometers provide good global coverage but limited vertical coverage. Despite the limitations, satellite derived upper-atmosphere winds have an extremely high impact on forecast accuracy.

Satellite based Doppler wind lidar technology is being developed to provide 3D winds of acceptable coverage and vertical resolution, but thick cloud will provide limitations. Satellite Doppler wind LIDAR has the potential to provide a breakthrough in tropical wind profiling. The very small footprint of the high frequency LIDAR gives wind measurements in scattered cloud conditions. Preliminary impact studies of the Aeolus instrument, the first satellite-based Doppler Wind LIDAR, have shown significant positive impact in weather forecasts, particularly on tropical winds (Rennie and Isaksen, 2020).

Similar sensors/missions:
- Aeolus

9.7 Option 7 – Precipitation and clouds

Operational requirement: The Bureau operates a network of rain gauges and weather radars in order to meet its requirements for real time precipitation observations. These in-situ observations are of high quality but there are gaps in spatial coverage, particularly over oceans, and these networks only provide information near and at the Earth's surface.

Passive microwave and infrared sounders are sensitive to cloud and precipitation and can be used to provide information on these quantities to NWP, particularly with "all-sky" assimilation systems. In the near future the Bureau will assimilate cloud information derived from Himawari-8 radiances into the Bureau's city-scale models and the National Analysis System (NAS). In the future satellite observations from EarthCARE will be investigated.

Active sensors such as lidar and radar provide more direct information, however there are not many missions with these types of capabilities, so the observations are temporally sparse with respect to the typical scales of weather phenomena. Different frequencies, antenna types and transceiver technologies are used, however the main frequencies used are the Ku, Ka, and W bands.

Space-based cloud and precipitation radars enhance the ability to monitor and study cloud and precipitation processes on a global scale. Climatology of global precipitation observations are used to identify shifts in precipitation and to assess drought and other risks to communities and the environment. Real time observations are used in nowcasting to monitor and provide forecasters with guidance on floods and other high impact weather events. Cloud observations have also been used in global NWP (Fielding and Janiskova, 2020; Janiskova and Fielding, 2020) where they have demonstrated positive impact on forecast accuracy. Products from GMI and CloudSat are used extensively in model validation and verification.

Similar sensors/missions:

- TRMM (1997-2015)
- CloudSat (2006 – 2020)
- RainCube (2018 – 2020)
- GPM (2014 – present)
- EarthCARE (2022 – future)

9.8 Option 8 – Wave height, direction, and period

Operational requirement: Altimeter data are essential for the Bureau's ocean model and for ocean forecasting. The Bureau operates a global ocean forecasting system with high horizontal resolution around the Australian region and coarser resolution outside the Australian region. The system can resolve mesoscale eddies and major current systems to high vertical resolution to resolve the mixed layer and thermocline. The system provides daily analyses and forecasts of ocean temperature, salinity, sea level and currents out to 7 days lead time. Key users of the Bureau's ocean services include the Australian Defence Force and the fisheries industry.

The Bureau's ocean model uses various satellite and in-situ observations, including data from four altimeter instruments (Cryosat2, Jason-3, SARAL, Sentinel 3A). The average accepted number of altimetry observations from these four satellites is currently around 200,000 per day. Altimeters provide information on sea level, ocean topography, significant wave height, near surface wind speed. CGMS reports that ocean altimetry currently has poor coverage, no afternoon orbit and poor polar coverage. There is a need for more large-swath instruments, to increase geographical altimetry coverage, for example through wide-swath altimetry.

Similar missions:

- Cryosat2
- Jason
- SARAL
- Sentinel 3A
- SWOT (to be launched in 2022) will provide much improved resolution altimetry compared with current technology.

9.9 Option 9 – Day and night capability

Operational requirement: The Bureau currently uses data from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument onboard the Suomi National Polar Partnership (NPP) mission. The VIIRS day/night band in the spectral range of 0.5–0.9 μm provides visible imagery at night, mainly from illumination from the moon.

The Day/Night band can be used in nowcasting applications to track fog at night, for monitoring warm low-level cloud, and to track air quality and visibility hazards such as smoke and dust at night.

Himawari-8 does not have a day/night band, but the Bureau uses an RGB product (referred to as the Night Microphysics RGB product) derived from three Himawari-8 channels. This product is used for fog and low cloud detection at night, providing forecasters with information on the atmosphere 24/7.

Current sensors/missions:

- VIIRS (SNPP and NOAA-20)
- FY-3E (MERSI-LL)

9.10 Option 10 – Real-time data dissemination of large data volumes from space

Operational requirement: Over 95% of observations used in the Bureau's weather models are from satellites. Satellite data contributes to 70% of the forecast error reduction (on the Bureau's 24 hour global domain), and 61% over the Australian verification domain. In the Bureau, the forecast impact of satellite data is more than double the impact of convectional in-situ data. It is critical that satellite data are received in near real time, to ensure that forecasters receive high quality model outputs.

The WMO defines the latency requirements of global NWP and high-resolution NWP for atmospheric temperature, humidity profiles and wind vector at sea surface as 30 minutes. In practice however the latency of these observations is longer than the recommended 30 mins. There are a number of factors that can affect the latency of satellite data, including transmission speed to the ground station, the number of ground stations, the number of satellites that can be observed at a ground station, and data pre-processing.

To meet NWP requirements for low latency satellite observations, the Bureau operates a network of ground stations that receive data from several LEO satellites. The Bureau is also a member of the Direct Broadcast Network (DBNet), a worldwide network of local, Direct Broadcast receiving stations that enable the delivery of satellite data to the global user community. The use of these systems maximises the benefits of LEO satellite data to NWP.

It is essential that any operational satellite missions developed for meteorological applications have the capability to transmit data in near real time, preferably with a latency of <30 mins.

10 Australian Community Mission Options

In addition to the mission options presented by the Bureau, the EO community was invited to submit details on any current Australian missions and/or projects that may be considered as candidates for a meteorological satellite mission that could support high impact weather events such as bushfires and severe storms, or sensors that support numerical weather prediction. The survey was conducted by Earth Observation Australia (EOA).

The EO community proposals cover a wide range of technologies and missions which would be valuable for weather forecasting. A detailed list of all the missions is presented in Appendix B, and a summary of the capabilities and their potential benefits for meteorology and mitigating the impacts of high impact weather events is provided below.

Table 2 EO Community missions and benefits to meteorology and disaster resilience

Missions	How the mission capabilities would benefit meteorology and disaster resilience
AIRES Nighthawk **Satellite Cross-Calibration Radiometers (SCR)** **CSIROSat-1** **Skyris** **SmartSat CRC / Uni of Adelaide SMIRF** **OzFuel** **WildfireSat**	High spatial resolution imagery is useful for high resolution weather models for urban areas, fuel load monitoring in support of bushfires, bushfire detection, and sea-ice monitoring (when cloud-free). High resolution imagery are also used for land use monitoring, agriculture, resource exploration, and water security. Satellites with Infrared (IR) capability can measure forest fuel load and vegetation moisture levels, which are essential datasets for bushfire management.
Uni of Newcastle CubeSat GPS meteorology experiment **ASCER GNSS** **Skykraft GNSS RO** **SPIRE GSMM**	GNSS related observations are becoming increasingly important for both terrestrial weather and space weather applications. GNSS Radio Occultation and GNSS to ground observations are assimilated operationally into the Bureau's NWP system and have significant impact on improving forecast accuracy. GNSS reflectometry is a new technique that has the potential to provide useful surface information relevant to meteorological and disaster resilience, including for estimating soil moisture, flood/wetlands mapping, ocean surface winds, and sea ice height.
NovaSAR-1	SAR observations are used by the Bureau for ice monitoring, estimating wind speeds during tropical cyclone events, and monitoring flood extent. Although there are increasing numbers of SAR satellites in orbit, temporal coverage is still limited.
University of Melbourne SpIRIT	Gamma ray technology offers a potentially exciting new capability for improving our understanding of lightning, including how lightning is initiated, and the lifecycle of thunderstorms.
ANU CHICO (Cubesat	Hyperspectral observations for coastal regions and oceans at high resolution (~30m) would provide valuable information for monitoring

Hyperspectral Imager for the Coastal Oceans)	water quality which is vital for fisheries, coral reef health, and defence applications.
Space Edge Computing	On board computing technologies that enable fast (near real time) access to EO data will become increasingly important with expected growing volumes of data from large missions, and the growing interest in SmallSat meteorological sensors

11 Mission down-selection

A poll was conducted using the Menti on-line survey tool where the Bureau's personnel ranked, in order of importance, the five major requirements that each sensor must achieve. The results are summarised in Table 3.

Table 3 Bureau mission requirements for meteorological instruments

Bureau requirements	Ranking value (%)
Meet the Bureau's NWP and Nowcasting requirements, preferably with a focus on disaster resilience.	31.11
Strengthen key international partnerships, to ensure ongoing access to critical satellite data streams.	21.67
Data assurance through building a sovereign satellite industry capability.	21.39
Address gaps in the global observing system, as defined by WMO and CGMS.	17.22
Have a secondary impact on the Bureau's data needs and business functions.	8.61

During the CDF study a survey was conducted to rank 10 of the most critical meteorological satellite capabilities currently used at the Bureau. Bureau personnel ranked the missions in order of importance in meeting several important Bureau charter services. The summary is presented in Table 4.

Table 4 Ranking survey of 10 of the most critical meteorological satellite capabilities used at the Bureau

Mission / Instrument	Ranking	Notes
Temperature and Humidity measurement / Vertical IR Sounder	8	Support Bureau's NWP capability e.g. Mistic Winds smallsat
Temperature and Humidity measurement / Hyperspectral Microwave Sounder	4	Support Bureau's NWP capability e.g. TEMPEST smallsat
Real-time Weather Imaging	9	Support Bureau's operational weather services. Reliance on JMA Himawari data
Synthetic Aperture Radar / Antarctic sea ice monitoring	2	Support Bureau's monitoring of near-real-time operations and for use in numerical weather prediction models
Lightning Detection	3	Support Bureau's continuous real time observations

3D Wind-field monitoring / Doppler LIDAR	5	Support Bureau's global NWP mission.
Precipitation and cloud measurement / LIDAR and RADAR instruments	6	Supports Bureau's global NWP and nowcasting
Wave height, direction and period measurement/ Altimeter	7	Supports Bureau's ocean services
Day and night imaging capability / VIS – IR imager	10	Supports Bureau's nowcasting mission
Real-time satellite data dissemination to support NWP	(1)*	Improve latency in NWP data. ***Excluded from study due to likelihood of provision by other agencies**

The ten instrument options were then ranked using the weighted average summarised in Table 3 in terms of their capability to fulfil the Bureau's requirements. The detail survey results are included in Appendix D.

The results indicated that the top three instruments chosen for investigation were:

- a lightning detection sensor,
- a microwave sounder and
- a SAR instrument for ice monitoring.

12 Mission concepts

This section provides a description of each instrument for the three identified missions.

12.1 Mission concept 1 – Lightning sensor

12.1.1 Objectives and requirements

The primary objective of a lightning sensor "is to add complimentary information to the existing ground lightning detection systems, with the benefit to provide a much wider coverage, including poorly populated areas, and a reference to correlate different ground systems and networks. Additional objectives of the mission are contribution to climate and atmospheric chemistry monitoring through observation of distribution and long-term effects of lightning."[6]

Lightning mapping from geostationary orbit improves severe storm analysis, lightning hazard detection, hurricane intensity prediction, wildfire response, and precipitation estimation, and mitigates aviation hazards.

Operational requirements (provided by the Bureau):

- Real time data dissemination (i.e., less than 1min)
- Geostationary positioning over Australia and the western Pacific for persistent coverage

Table 5 provides a summary of WMO (colour coded bold-black), and Bureau first order performance requirements (colour coded blue) for a lightning sensor. The Bureau's requirements are based on capabilities specified for the US NSOSA study (NOAA, 2019) and may change in the future based on user needs and expectations as well as further analysis of industry capability. These requirements were compiled by the Bureau and delivered at the study kick-off.

Table 5 Lightning sensor requirements summary

Requirement	Threshold	Baseline	Objective
Coverage: Full disk, Australian region and surrounding oceans			
Availability of service (e.g. 98%)	(90%)	(93%)	(95%)
Total number of detected flashes in the corresponding time interval and the space unit. The space unit (grid box) should be equal to the horizontal resolution and the accumulation time to the observing cycle			
Timeliness	**30 min** (1 min)	**5 min** (30 sec)	**30 sec** (20 sec)
Horizontal resolution	**15 km** (10km)	**3 km** (8km)	**1 km** (2km)
Sampling frequency	**15 min** (1 sec)	**5 min** (2 msec)	**30 sec** (1 msec)
Accuracy (Minimum instantaneous probability of correct detection of flashes over 24hours)	(50%)	(70%)	(80%)
Number of detected **cloud-to-ground flashes** in the corresponding time interval and the space unit. The space unit (grid box) should be equal to the horizontal resolution and the accumulation time to the observing cycle.			
Timeliness	**30 min** (1 min)	**5 min** (30 sec)	**30 sec** (20 sec)
Horizontal resolution	**15 km** (10km)	**3 km** (8km)	**1 km (2km)**
Sampling frequency	**15 min** (1 sec)	**5 min** (2 msec)	**30 secs** (1 msec)

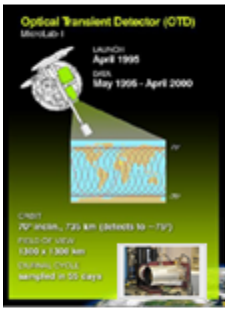
[6] Tommasi, L., "Design and performance of the lightning imager for the Meteosat third generation", Proc. Vol. 10567, SPIE International Conference on Space Optics – ICSO 2006 https://doi.org/10.1117/12.2308053

12.1.2 Related missions

International meteorological agencies have developed a number of space-based electro-optical imaging sensors that continuously observe lightning pulses in the atmosphere. This section presents an overview of past, present and future lightning imaging missions.

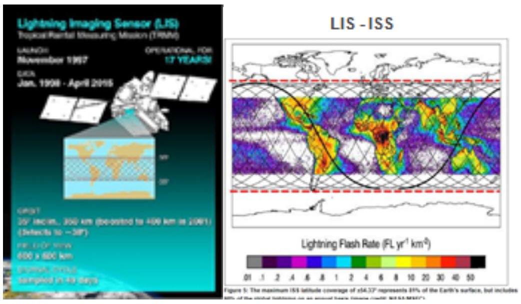
Instrument performance and design data were taken from open sources. However, not all data was available for every sensor.[7],[8]

12.1.2.1 Optical Transient Detector (OTD)



The OTD was developed by NASA-Marshall and was launched on the MicroLab-1 spacecraft in 1995. OTD was in LEO at a nominal altitude of 740 km and an inclination angle of 70 degrees. It provided a spatial resolution of 10 km and covers a swath of ~ 1300 x 1300 km. It had a flash detection capability of between 40-50% depending on acquisition geometry using a 2 msec integration period.

12.1.2.2 Lightning Imaging Sensor (LIS)



The LIS was developed by NASA-Marshall Space Flight Centre in partnership with JAXA and has been flown on both the Tropical Rainfall Meteorological Mission (TRMM) and the International Space Station (ISS). The TRMM-LIS was in service from 1997-2015. It was in LEO at a nominal altitude of 350-405 km and an inclination of 35 degrees. LIS provided a spatial resolution of 3-6 km (depending on the altitude during the mission lifetime) and covered a swath of ~ 600 x 600 km. It provided an average flash detection capability of 80% using a 1 msec integration period.9

The ISS-LIS has been in service since 2017. It is in LEO at a nominal altitude of 410 km and an inclination of 51.6 degrees. It provides a spatial resolution of 4-8 km. It provides a flash detection capability of 80% using a 1 msec integration period.

LIS has a mass of ~ 100 kg and consumes ~35 W during operation. The downlink processed data rate is ~ 8kbps.

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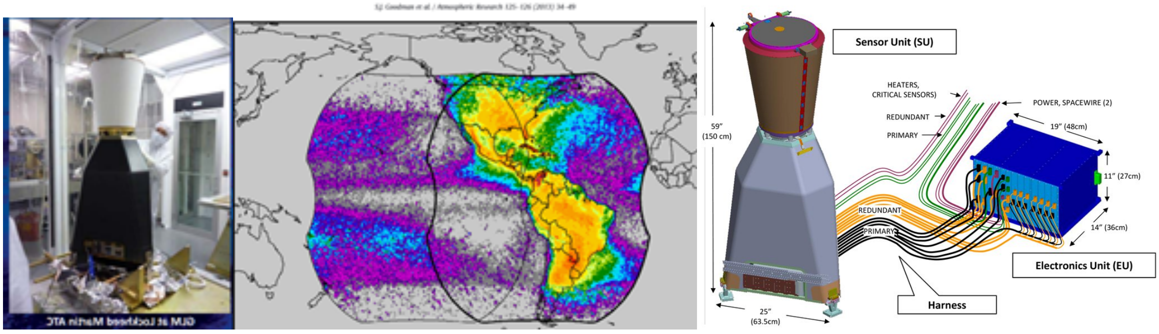
[7] eoportal.org
[8] https://ghrc.nsstc.nasa.gov/lightning
[9] https://gpm.nasa.gov/missions

12.1.2.3 Geostationary Lightning Mapper (GLM)[10]



The GLM was developed by NOAA and Lockheed and was launched on the GOES-16 spacecraft in 2017 and the GOES-17 spacecraft in 2018. GLM covers latitudes between 66 deg. North and 66 deg. South. GLM is located at 141 deg. West on GOES-16 and 8 deg. East on GOES-17.11

GLM provides a spatial resolution of 8-14 km and provides a flash detection capability of 80% depending on acquisition geometry using a 2 msec integration period.12

GLM has a mass of ~ 125 kg and consumes ~290 W during operation. The downlink processed data rate is around 7.7Mbps which is much higher than OTD or LIS.13

12.1.2.4 Lightning Imager (LI)

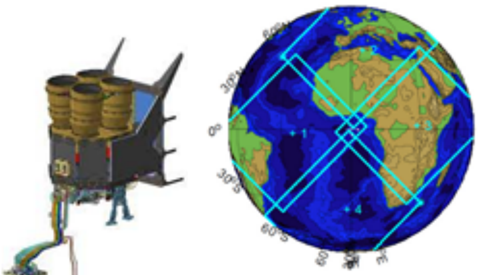


Figure 2: LI geographical coverage area on the Earth. The 4 rectangles represent the coverage of the detectors in the 4 optical cameras.

The LI is being developed by EUMETSAT with industry partners Thales (FR) and Leonardo (IT). The LI will launch in 2022 on board MTG-I1 and will be located in geostationary orbit to cover latitudes 75 deg. North to 75 deg. South and longitudes 65 deg. West to 65 deg. East. LI will provide a spatial resolution of 4.5 km and a flash detection efficiency of 80% using a 2 msec integration period. Updates from LI occur every 30 seconds.14

LI has a mass of ~ 106 kg and consumes ~195 W during operation. The downlink processed data rate is ~ 17Mbps.

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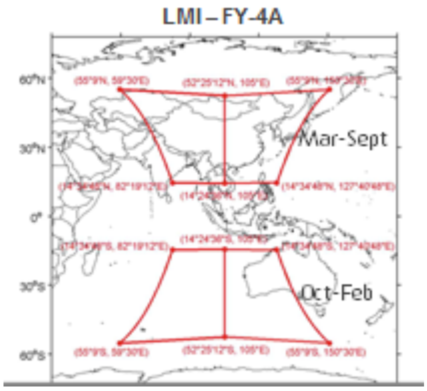
[10] https://www.goes-r.gov/resources/docs.html
[11] NOAA/NASA Program Office, GOES-R Data Book, (2018) https://www.goes-r.gov/resources/docs.html
[12] S. J. Goodman et al., "The GOES-R Geostationary Lightning Mapper (GLM)", Atmospheric Research, Vol. 125–126 (May 2013), pp. 34-49. doi: 10.1016/j.atmosres.2013.01.006
[13] S. Edgington, et al., "Design, Calibration, and On-Orbit Testing of the Geostationary Lightning Mapper on the GOES-R Series Weather Satellite", Proc. of SPIE Vol. 11180 1118040-3, International Conference on Space Optics — ICSO 2018 (Nov 2018) doi: 10.1117/12.2536063
[14] S. Lorenzini, et al., "Optical design of the Lightning Imager for MTG", Proc. of SPIE Vol. 10564 1056406-11 International Conference on Space Optics — ICSO 2012 (Oct. 2018) doi: 10.1117/12.2309091

12.1.2.5 Lightning Mapper Imager (LMI)[15]



LMI was developed by the Chinese Meteorological Agency (CMA) and was launched into geostationary orbit in 2016 on board FY-4A, and 2021 on board FY-4B.

LMI covers a region between ~56 deg N/59 deg E and 150 deg E to 14 deg N/82 deg E and 127 deg E in the March-September period. During the October – February period the coverage is a region between ~ 56 deg S/59 deg E and 150 deg E to ~ 14 deg S/82 deg E and 127 deg E.

LMI provides a spatial resolution of 8 km and a flash detection efficiency of 90% using a 2 msec integration period. Updates from LMI occur every 60 seconds.

12.1.2.6 Related missions performance summary

Table 6 presents a summary of the performance data for the lightning sensors described in the previous section.

Table 6 Current lightning sensor performance summary

System Parameters	OTD	TRMM-LIS	ISS-LIS	GLM	Lightning Imager	LMI
Mission sponsor	NASA	NASA/JAXA	NASA	NOAA	Eumetsat	CMA
Instrument developer	MASA-Marshall	NASA-Marshall	NASA-Marshall	Lockheed	Thales(FR)+ Leonardo(IT)	
Spacecraft	MicroLab-1	TRMM	ISS	GOES-16 / GOES-17	MTG-I	FY-4A
Service dates	1995-	1997-2015	2017 -	2017 - / 2018 -	2022-	2016
Orbit	LEO (incl. 70°)	LEO (incl. 35°)	LEO (incl. 51.6°)	**GEO**	**GEO**	**GEO**
Altitude (km)	740	~ 350 → 405 ('01)	~ 410	35,786 (longitude loc.75.2° W)	35,786 (longitude loc. 0°)	35,786 (longitude loc. 145°E)

[15] Hui, W., "Characteristics of lightning signals over the Tibetan Plateau and the capability of FY-4A LMI lightning detection in the Plateau", Int J. Remote Sensing, 41(12), 2020

Sensor spatial coverage						
➔Latitude		~ 38°N / 38°S	~ 55°N / 55°S	~ 66°N / °66 S	~ 75°N / 75°S	
➔Longitude	-	-	-	~ 141°W / 8°E	~ 65°W / 65° E	
Spatial resolution (km)	10	3-6	4-8	8-14	4.5	8
Sensor swath (km)	1300 x 1300	600 x 600				
Integration time (msec)	2	1	1	2		**2**
Flash detection efficiency (%)	40-50	80	80	80	80	90
Timeliness - updates (min)					0.5	1.0
Instrument form factor (mm)	Sensor unit: ~Dia: 200 mm x L: 350 mm Electronics box: ~	Sensor unit: ~Dia: 200 mm x L: 350 mm Electronics box: ~	Sensor unit: ~Dia: 200 mm x L: 350 mm Electronics box: ~	Sensor unit: ~Dia: 635 x L: 1500 Electronics box: ~ 480 x 270 x 360	Sensor unit: ~75 x 1100 x 1200 Electronics box: ~300 x 240 x 160	
Total mass(kg) – optics + electronics		101	101	125	106	
Power (W) – approx.. operating		35	35	290	195	
Downlink processed data rate		8 kbps	8 kbps	7.7 Mbps	17 Mbps	

12.1.3 Instrument discussion

The emission spectrum of lightning events has very pronounced spectral features with a predominant atomic oxygen emission centred at 777.4 nm. Photons emitted by a lightning event are scattered (redirected) many times before leaving the cloud and illuminate an area of tens of kilometres in diameter. The instruments in existence today are designed around an imaging spectrometer that disperses the incoming flux and uses a narrow band filter (NBF) centred on 777 nm to eliminate flux outside of this band and signal coming from the cloud background. The sensors also have spatial resolution capability of < 10 km and detect events in both day and night conditions.

Lightning sensors generate a large amount of data (in Gbps) and require on-board event data processing that performs thresholding of each frame compared to a running average of the background. Reporting of events on an exception/threshold basis helps to reduce the amount of data that must be managed. In addition, some form of data storage is required, and this can add complexity and mass to the instrument if, for example, a solid-state data recorder must be used.

12.1.3.1 Performance design drivers

The space segment of the mission includes the instrument payload and all the other subsystems hosted on the spacecraft bus such as on-board computer, power and communications systems and avionics.

- Orbit:
  - A geostationary orbit is preferred to meet observation persistence and event timeliness requirements for an operational system. A sun-synchronous LEO placement could provide data for research purposes especially where coverage over areas of the world's oceans is missing with the present sensors. A LEO placement would however result in a low revisit rate (e.g., 1-3 days depending on the number of spacecraft). Regardless of spacecraft mass, the launch costs associated with getting a spacecraft into geostationary orbit will be higher than LEO.

- Payload size, weight and power (SWaP):
  - A sensor with performance levels equal to current sensors implies an instrument weighing ~ 100 kg, contained within a volume of ~1 m^3 and consuming ~ 200 W during operations which would require a small-sat bus to host the imager and other spacecraft subsystems. The development of a science grade instrument for the global user community would necessarily imply that the spacecraft is designed for low fault, reliable operations over a multi-year mission life. The development of such a system is beyond the current capacity of the Australian space industry especially if all or most of the spacecraft content is required to be 'home-grown'.

12.1.3.2 Critical technology development areas

Electro-optical sensors require careful development, design, and integration. The sensor would require narrow-band pass filters centred on the oxygen triplet at 777nm, low noise focal plane readout electronics and diffraction limited optical subsystems. These are areas that would require in-country development. However, all subsystems and components for existing lightning sensors have achieved TRL 9 and would not require development to achieve mission outcomes especially if these are procured from overseas vendors.

Development of a lightning sensor is not beyond the reach of current Australian space industry participants for a Pathfinder mission. Although several subsystems (e.g., optical front end, narrow band filter) may not be easily developed in-country and would need to be procured from overseas suppliers, the design of these subsystems could be performed within Australia. Other subsystems such as avionics subsystems could be developed in-country depending on the size of the instrument and the spacecraft.

12.1.3.3 Sovereign capability

The selection of a suitable spacecraft platform is an iterative approach and requires detailed knowledge of the payload instrument's specifications. The available platform resources, in turn, place constraints on achievable payload performance and overall mission design.

The capability to develop microsatellite buses and associated avionics including power and communications subsystems, positioning and control subsystems and on-board computers and flight software exists in-country. The capability to integrate and test these components as well as environmental test facilities also exists in Australia.

12.1.3.4 Potential overseas partners

An Australian lightning sensor mission might be developed sooner if partnerships with organisations that have previously developed these sensors could be formed. Partnering with other meteorological agencies could potentially lead to a joint mission development program with significant Australian contribution. An instrument developed by Australian industry could also be hosted on a partner organisation's satellite.

12.1.4 Implementation options

Although a system such as Lightning Imager or GLM cannot be developed within the present Australian industry context, a reduced capability sensor could be designed, developed, and hosted on a large CubeSat. The space segment performance capability would need to be defined considering end-user needs for meaningful data products and the Bureau's requirements for such a sensor.

A smaller sensor with reduced capability hosted on a large CubeSat(s), which could serve as a Pathfinder for future lightning sensor development, is within the reach of current MAIT (manufacturing, alignment, integration, test) capability in Australia. However, a mission life of 1-2 years rather than 5-7 years would need to be considered. Reduced capability compared to the current fleet of lightning sensors could mean a lower event detection efficiency with higher false alarm rates, poorer spatial resolution and/or a narrower field of view / coverage area. Further investigations under a Phase A study could consider the threshold where a reduced capability sensor is no longer of value for meteorological applications. Depending on the chosen development pathway a hosted or dedicated platform can be considered with international partners or organisations.

Other technology development areas include event-based or phenomenon/active vision sensors (EBS) which differ from conventional frame cameras. Instead of capturing images at a fixed rate, they asynchronously measure per-pixel brightness changes. In contrast to standard cameras, which acquire full images at a rate specified by an external clock (e.g., 30 fps), event cameras, respond to brightness changes in the scene asynchronously and independently for every pixel. The output of an event camera is a variable data-rate sequence of digital events, with each event representing a change of brightness of predefined magnitude at a pixel at a particular time. This technology area could be explored for its application to lightning detection.

An EBS is part of the UNSW Canberra Space M2 spacecraft and commissioning of this sensor is underway in Q2 –Q3 2021. The EBS camera was integrated at UNSW Canberra Space and is based on a Davis 240 sensor and focal plane electronics/image processing algorithms developed by Western Sydney University and an optical lens assembly designed by UNSW Canberra Space.

Further investigations could be undertaken in a Phase A study to achieve these aims and develop a concept of operations, launch and platform configurations as well as exploring mission operations, ground segment data acquisition, processing and dissemination tasks and interoperability with existing Australian and international infrastructure.

12.1.5 Cost estimate

The cost estimate for a lightning detection mission would be comprised of estimates for the instrument, spacecraft, launch, and operations. The instrument development cost estimates are based on several assumptions as described while using cost models and publicly available data for similar sensors. Development costs for the spacecraft and its subsystems are not included because the mission requirements are not fully developed in this pre Phase A study. Launch costs are included based on publicly available data from LSPs for various spacecraft.

Spacecraft level MAIT and operations cost estimates for a Cubesat mission based on the experience of the UNSW Canberra Space M2 program is given only as an example.

Several cost estimates were provided for a full-capability lightning detection instrument by way of comparison to similar or currently deployed systems. Table 7 provides a summary of the estimated instrument cost only based on analogy, published information and the NASA instrument cost model.

Table 7 Lightning sensor cost estimate summary

Cost Estimate	MAUD (2020 $ adjusted for inflation)
Analogy with similar systems such as Lightning Imager	80 - 95
Published data for the Lockheed contract for two GLM sensors (2007)[16]	75 - 80
NASA EO Instrument Cost Model (NICM) for a 100 kg/ 200 W instrument[17], [18].	86

Launch costs would depend on the LSP rates and can be examined in Section 15. Operational and ground segment costs are not included.

12.1.6 Open points and questions

Several open points remain when considering the development of a Pathfinder of full operation capability (FOC) lightning sensor.

- Trade-off of LEO constellation vs geostationary orbit to deliver an instrument(s) providing global coverage. However, the Bureau indicated that a sensor in geostationary orbit is preferable for persistent coverage over Australia.
- Pathfinder approach to consider a set of reduced mission requirements to develop sovereign capability.
- Consider leveraging advances in spacecraft subsystems development within Australia and pursue existing lightning detection imaging system development by overseas groups.
- Given the state of optical fabrication capability for space optics in Australia what domestic organisations are best placed to manufacture the optical system?
- Query LSPs regarding placement of CubeSats/MicroSats into geostationary orbit.

[16] https://news.lockheedmartin.com/2007-12-19-Lockheed-Martin-Awarded-Contract-for-GOES-R-Geostationary-Lightning-Mapper
[17] Mrozinski, J., et al., "Latest NASA instrument cost model (NICM): Version VI", AIAA SPACE 2014 Conference and Exposition (Aug 2014
[18] Mrozinski, J., "NASA Instrument Cost Model: NICM 8.5", 2019 NASA Cost and Schedule Symposium (August 13-15, 2018, Houston, TX)

12.2 Mission concept 2 – Extended observations of the Antarctic using Synthetic Aperture RADAR (SAR)

12.2.1 Objectives and requirements

The Bureau's ice monitoring service requires daily observations (preferably SAR with capability similar to Sentinel-1) for measuring geophysical ice parameters such as surface roughness, type, concentration, and drift speed. The Bureau is developing a regional Antarctic model which will require real time observations of sea ice concentration.

- There is a need for more all-season, all-weather observations of ice parameters (daily, 30 m resolution)
- Coverage: Australian region (Met Area Ten[19]), possibly whole Antarctic region.
- Should still cover latitudes > 75° S.
- Assimilation of data for NWP
- There is a strong desire for sovereign capability, as many instruments are not operated throughout their entire orbit (with the exception of the Sentinels).

A refinement of these baseline requirements was undertaken during the study. Table 8 presents a summary of these requirements plus general requirements for a SAR instrument for ice monitoring applications[20].

Table 8 General observation requirements for sea ice concentration and motion measurements using SAR

	Sea Ice Concentration	**Sea Ice Motion**
Requirement	**Objective**	**Objective**
Repeat Cycle	• At least daily • Every 6 hours to capture diurnal and tidal effects. • < 6 hours in cases to capture small scale events.	• Daily, or every 3 days if combined with PMR. • Every 6 hours in cases to capture diurnal and tidal effects.
Resolution	≤ 25m	- 10m in marginal ice zones - 25-50m elsewhere
Coverage Area	Met Area 10	Met Area 10
Frequency	• C band • Potentially L band for sea ice thickness	• C band or X band during freezing season • L band during melting season
Polarisation	HH+HV; HH+VV at shallow incidence angles	HH; HH+HV
Incidence angle	20° - 50°	20° - 50°
Seasonality	Year-round	Year-round
Latency	< 4 hours	TBC

[19] http://www.bom.gov.au/marine/maps/metarea-10.shtml
[20] Falkingham, J.C., " Global Satellite Observation Requirements for Floating Ice - Focusing on Synthetic Aperture Radar"

A SAR mission could have secondary benefits if it could also be operated over the Australian continent, as the observations are also important for hydrology and land surface models where they can provide information on soil moisture.

12.2.2 Related missions

This section presents an overview of operational SAR imaging missions that are relevant to this mission concept for sea ice concentration and sea ice motion measurements. Although there are many SAR missions for biospheric monitoring that are currently deployed[21].

12.2.2.1 Sentinel-1

The Sentinel-1 mission consists currently of a constellation of two polar orbiting satellites (Sentinel-1A and Sentinel-1B) providing C-band Synthetic Aperture Radar (SAR) imaging capability for continuous radar mapping of the earth. Primary mission objectives include land monitoring of forests, water, soil and agriculture, maritime environment, sea ice and iceberg monitoring, emergency mapping support, sea vessel detection, and climate change monitoring. The two spacecraft are operating in the same orbital plane in a 693 km sun-synchronous orbit (SSO), near polar (98.18 deg.) orbit with a 12-day repeat cycle and 175 orbits per cycle. Four imaging modes are available with resolution down to 5m and swath of up to 400 km. Each satellite has dual polarisation capability and precise measurement of spacecraft position and attitude are available for each observation[22]. Sentinel-1C and -1D are planned for launch in 2022 and 2023 respectively.

12.2.2.2 RADARSAT2

RADARSAT-2 is a follow-on mission of RADARSAT-1 hosting a C-band phased array SAR antenna with the aim to continue the RADARSAT program and provide data continuity to RADARSAT-1 users. The mission objective is to provide continuous monitoring of environmental changes and deliver observational SAR data to both commercial and scientific users across a range of fields, including agriculture, forestry, geology, hydrology, oceanography, coastal monitoring, and ice studies. RADARSAT-2 is orbiting in a 798 km SSO dawn-dusk polar orbit with a repeat cycle of 24 days. Five imaging modes are available with resolution ranging between 3m and 100m and swath widths ranging between 20km and 170km.[23]

12.2.2.3 RADARSAT Constellation Mission (RCM)

RCM is a successor mission to RADARSAT-2 which includes three spacecraft each hosting a C-band phased array antenna. The main mission objectives are maritime surveillance, including sea ice and iceberg monitoring, marine winds, oil pollution monitoring and response, ship detection, and resource management. The three spacecraft are in a 600 km SSO dawn-dusk orbit and are spaced apart in the same orbital plane. The RCM constellation provides a repeat cycle of 179 orbits every 12 days and offers an improvement of sea-ice monitoring capability from 2–3-day coverage at 100 m resolution for RADARSAT-2 to daily coverage at 50 m resolution with an image swath of 350 km.

[21] Peak, S., at al., "Small-satellite synthetic aperture radar for continuous global biospheric monitoring: a review", Remote Sens. **2020**, 12, 2546 (2020)
[22] https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-1-sar/sar-instrument
[23] https://earth.esa.int/web/eoportal/satellite-missions/r/radarsat-2

12.2.2.4 ICEYE

The ICEYE constellation currently comprises 10 small satellites (average satellite mass 85 kg) in LEO. The aim of the constellation is to provide SAR imagery (both spotlight and strip map) with high revisit rate and short time from request to delivery of the images. The satellites are placed in a sun-synchronous orbit between 560 to 580 km, which is at inclination 97.7 degrees, thus providing 15 orbits per day. Each satellite carries an X-band SAR payload with a VV polarisation, giving sub-metre resolution. The communications link is implemented at X-band with a rate of 140 Mbits/s. The relevant applications for the constellation include wave height and wind estimation, sea-ice monitoring, iceberg monitoring, and global flood monitoring[24].

Each radar pulse produced by the ICEYE SAR instrument can be digitally programmed to modulate over a bandwidth between 37.6 and 300 MHz centred on the X-band (9.65 GHz) part of the spectrum. The pulse repetition frequency (PRF) can be selected between 2 and 10 kHz and the peak transmitted power can be as much as 3.2 kW.

The active phased array antenna can provide electronic beam steering. This is used in addition to the satellite's mechanical agility to point a radar beam precisely onto the Earth's surface. This agility also allows the beam to be directed towards the right or left side of the satellite track[25].

The instrument's nominal operating parameters are detailed in Table 9.

Table 9 ICEYE SAR operating parameters

Parameters	Value
Carrier frequency	9.65 GHz (X-band)
Look direction	both LEFT and RIGHT
Antenna size	3.2 m (along-track) x 0.4 m
PRF	2-10 kHz
Range Bandwidth	37.6-300 MHz
Peak Radiated Power	3.2 kW
Polarization	V V
Incidence angle range	15-35 (mode dependent)
Mass	85 kg
Communication (radar payload data downlink)	X-band 140 Mbits/s

The flexibility of the satellites facilitates imaging modes to be constantly evolved. Currently, the satellites operate in two primary modes called 'Spotlight Mode' and 'Stripmap Mode' with each mode providing different output imaging capabilities depending on tasking and exploitation requirements, as detailed in Table 10.

[24] https://directory.eoportal.org/web/eoportal/satellite-missions/i/iceye-constellation
[25] Ignatenko, V., "ICEYE microsatellite SAT constellation status update: evaluation of first commercial imaging modes, IEEE Intl. Geoscience and Remote Sensing Symposium IGARSS 2020.

Table 10 Summary of ICEYE imaging modes

Parameters	Stripmap	Spotlight
Nominal swath width (km)	30	5
Nominal product length (km)	50	5
Incidence angle (scene centre)	15-30°	20-35°
NESZ (dBm2/m2)	-21.5 to -20	-18 to -15
AASR (dB)& RASR (dB)	-15 & -20	-15 & -20
Slant range resolution (m)	0.5 to 2.5	0.5
Slant azimuth resolution (m)	3	0.25
Slant range spacing (m)	0.4 to 2.4	0.4
Slant azimuth spacing (m)	1.6	0.2
Ground range resolution (m)	3	1
Ground azimuth resolution (m)	3	1
Ground range spacing (m)	2.5	0.5
Ground azimuth spacing (m)	2.5	0.5
Range looks	1 to 2	4
Azimuth looks	3	1
ESA Copernicus Contributing Mission (CCM) Resolution Class (6)	VHR2	VHR1
Polarization	VV	VV

Table 11 presents a side-by side comparison of the size, mass, and power (SWaP) specifications for Sentinel, Radarsat-2 and RCM. The metrics represent major cost drivers which place constraints on the required spacecraft bus size, launch vehicle selection, number and size of solar arrays, and orbit selection. An estimation of spacecraft and mission costs for a new SAR imaging spacecraft must be performed in the context of specific mission/user requirements and requires detailed mission analyses that are typical of a Phase A investigation.

Table 11 SWaP comparison for Sentinel-1, Radarsat-2 and Radarsat-RCM

Parameter	Sentinel 1A&1B	RADARSAT-2	RCM
Total Instrument Mass	945 kg	750 kg	670 kg
Total Launch Mass	2300 kg	2200 kg	1430 kg
SAR Antenna Size	0.821m x 12.3m	1.37m x 15m	1.37m x 6.88m
Spacecraft bus size	3.9m x 2.6m x 2.5m	3.7m (height) x 1.36m (dia.)	3.6m x 1.1m x 1.7m
Solar Array Power	4800 W (EOL)	3400 W (BOL)	22W (avg.)

		2400 W (EOL)	1600 W (Peak)
Payload/Transmitter Peak Power	4368 W	1650 W (normal mode) 2280 W (ultra-fine mode)	1600 W
Data Downlink	X-Band: 2x 260Mbit/s	X-Band: 2x 105Mbit/s	X-Band: 2x 150Mbit/s
Mission cost (estimated)	EUR 280 M [26] (2014) ~ AUD 490M (2020)	TBD	CAD 600 M[27] (2010) ~ AUD 780 M (2020) (full constellation, including launch and ground infrastructure upgrade)

12.2.3 Instrument discussion

SAR images the earth by RF illumination and sensing the reflections. Typical instruments contain an illuminator and detector. In radar, the resolution that is obtained is directly related to the size (or aperture) of the antenna. SAR uses the motion of a small antenna to synthesise a large aperture, hence the name synthetic aperture radar. In addition to this approach, which is also referred to as active SAR, passive SAR utilizes RF illuminations from other sources, such as other spacecraft or GNSS to implement the imaging[28].

12.2.3.1 Performance design drivers

Space-based synthetic aperture radar is challenging, especially when the goal is to place it on a small spacecraft. The orbit dictates a range of parameters, including the revisit times, areas that can be mapped, and the resolution that can be achieved. As seen in the case of ICEYE, the orbit of choice is a sun-synchronous one, likely due to advantages in power generation and thermal control. The altitude of the satellite affects both the field of view for a particular antenna beamwidth as well as the actual power required at the transmitter. This has flow-on effects on the size of the antenna, size of the power amplifier, and input power required (solar panels and batteries). Another consideration that is related to the orbit is need for orbital maintenance. Orbits change over time due to various perturbations. A lower orbit will also experience more significant atmospheric drag, which will lead to gradual orbital decay. Orbital maintenance is performed using propulsion, which then mandates a propulsion subsystem be included in the spacecraft, which adds weight and takes up volume. Additionally, orbital maintenance sets a limit on the lifetime of the SAR spacecraft that is determined by the available propellant and frequency of orbital manoeuvres.

Having a single satellite would only provide sparse revisit times in the order of days apart. To ensure more frequent revisit times, a constellation of satellites need to be used. Key choices in this respect are the number of satellites and their distribution around the constellation. With close international coordination, an Australian SAR system could be designed to complement existing international missions to maximise coverage of the polar regions.

[26]https://spaceflightnow.com/soyuz/vs07/140402preview/#:~:text=Levrini%20said%20the%20Sentinel%201A,million%2C%20under%20current%20economic%20conditions.
[27] https://spacenews.com/canadian-radarsat-constellation-get-374-million-cash-infusion
[28] https://ieeexplore.ieee.org/document/9104353

12.2.3.2 Critical technology areas

All the subsystems needed for a Smallsat SAR have reached TRL 9. The challenging development and engineering challenges relate to the size and configuration/steering of the antenna, the power needed which will drive the size and weight of the power subsystem and the configuration of the spacecraft bus.

A hosted payload vs. a dedicated platform can be examined but a hosted payload option is probably not feasible for SAR due to the large antenna required for a full operational capability mission.

12.2.3.3 Sovereign capability

Further investigation of the on-shore SAR capability for a Cubesat or Smallsat mission would need to be undertaken during a Phase A study.

12.2.3.4 Potential overseas partners

An Australian SAR mission might be developed sooner if partnerships with organisations that have previously developed these sensors could be formed. Partnering with international companies such as Thales Alenia Space and EADS Astrium (Sentinel-1 manufacturers), ICEYE Ltd[29] , Capella Space[30] , SSTL[31] and others could potentially lead to a joint mission development program with significant Australian contribution.

12.2.4 Implementation options

The spacecraft platform hosts all the necessary subsystems required to support the payload during launch and on-orbit operation. The selection of a suitable spacecraft platform is an iterative approach and requires detailed knowledge of the payload instrument's specifications. The available platform resources, in turn, place constraints on achievable payload performance and overall mission design. Allowable payload mass, available power and physical dimensions, attitude control and downlink data rate capability impose fundamental limitations on the attainable performance of a SAR imaging payload.

A pathfinder approach to build small/micro satellites that provide a testbed to develop key subsystems would be the most advantageous means to realise a SAR capability within the Australian context. A follow-on Phase A study would be required to determine the feasibility of such an approach.

The capability to develop microsatellite buses and associated avionics including power and communications subsystems, positioning and control subsystems and on-board computers and flight software exists in-country. However, the development of a small satellite bus ~ 100 kg is currently beyond Australian manufacturing capability. The capability to integrate and test these components as well as environmental test facilities does exist in Australia.

The SAR instrument could be designed in Australia and developed in partnership with international contributions.

12.2.5 Cost estimate

The cost estimate for a SAR mission would be comprised of estimates for the instrument, spacecraft, launch, and operations. The instrument development cost estimates are based on several assumptions as described while using cost models and publicly available data for similar sensors.

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[29] https://www.iceye.com/systems/national-sar-missions
[30] https://www.capellaspace.com/
[31] https://www.sstl.co.uk/

Development costs for the spacecraft and its subsystems are not included because the mission requirements are not fully developed in this Pre–Phase A study. Launch costs are included based on publicly available data from LSPs for various spacecraft.

Spacecraft level MAIT and operations cost estimates for a Cubesat mission based on the experience of the UNSW Canberra Space M2 program is given only as an example.

A rough order of magnitude (ROM) cost estimate for a SAR payload may be obtained by analogy to previous missions using the NASA Instrument Cost Model (NICM)[32]. Total cost for such a mission is

Total Instrument Cost = 1.244 * TotalMass^0.36 * TotalMaxPower^0.5.

Mass and power requirements of the instrument are the biggest cost drivers. For example, an 85 kg payload producing 4kW of power during operations (e.g. ICEYE) would cost ~ AUD17 million based on the above NICM approach.

Published estimates by Filippazzo and Dinand[33] provide an estimate of the ICEYE development cost for the spacecraft and instrument including launch at 75,000€ / kg. At 85 kg this would equate to €6.74 million or AUD8.9 million.

SSTL published an estimate for the DMC-SAR system, which is an X-Band, 200 kg SAR instrument integrated to the SSTL 6000 bus at AUD50 million[34].

Table 12 SAR sensor cost estimate summary

Cost Estimate	MAUD
NASA NICM model assuming 85 kg payload, 4kW (e.g. ICEYE)	17 (instrument only)
Filippazzo and Dinand estimate of the ICEYE development cost for the spacecraft and instrument including launch at 75,000€ / kg, for 85 kg payload	8.9 (Instrument, spacecraft + launch)
SSTL estimate for the DMC-SAR, X-Band, 200 kg SAR instrument integrated to the SSTL 6000 bus	50 (instrument + spacecraft)

A better cost estimate may be obtained via a parametric cost model. However, this approach requires more accurate instrument information derived from detailed mission analyses considering specific mission requirements. This approach is recommended as part of a subsequent Phase-A study.

12.2.6 Open points and questions

As for the other instruments that were considered in this study several questions and feasibility related analyses would need to be conducted in a subsequent Phase A study. These include;

- Assessment of the feasibility of integrating C and L Band SAR Payload on SmallSat or MicroSat.

[32] https://www.nasa.gov/sites/default/files/files/14_NICM_VII_for_2015_NASA_Cost_SymposiumFinal_tagged.pdf
[33] Filipazzo, G., and Dinand, S., "The potential impact of small satellite radar constellations on traditional space systems", 5th Federated and Fractionated Satellite systems Workshop, ISAE SUPAERO, Toulouse, France, 2-3 November 2017
[34] Baker, A., "Affordable SAR constellations to support homeland security", 23rd Annual AIAA/USU Conference on Small Satellites, SSC09-III-3 (2009).

- Trade-off of LEO constellation vs HEO constellation. Could interferometric synthetic aperture microwave sounding instruments be developed and used in LEO as a steppingstone for their application to HEO?
- Investigate pathfinder approach with reduced mission requirements to develop sovereign SmallSat/MicroSat capability and leverage and advance already existing SAR imaging system development and radar signal processing capability.
- Perform a detailed survey of organisations in Australia that could provide SAR imaging system critical components.

12.3 Mission concept 3 –Hyperspectral microwave sounder

12.3.1 Objectives and requirements

The following list of requirements and mission objectives was provided by the Bureau in the mission overview presentation and during discussions throughout the study:

- Microwave radiometers (e.g. AMSU-A+MHS, ATMS) are found by many weather agencies to provide of the highest impact of any observations in global NWP. Humidity sounders are becoming increasingly important as data assimilation techniques improve
- A Forecast Sensitivity to Observations (FSO) study looking at the impact of microwave radiances on the Australian region forecasts showed greatest impact off the North-west coast of Queensland (where tropical cyclone impact is significant). In this region, most impact is from mid-tropospheric temperature channels AMSUA-6, and ATMS-7.
- MW Sounders provide nearly global all-weather temperature information from surface to 100 km and can carry additional channels (frequencies) sensitive to tropospheric and lower stratospheric water vapour and ice particles. However, their spatial resolution (both vertical and horizontal) can be lower than that of the IR instruments.
- This instrument when launched could be the first ultraspectral microwave sounder in orbit and would be expected to provide improved microwave sounding capability. Associated with an appropriate antenna, it could provide resolutions up to 4km, providing at appropriate resolution for current high-resolution NWP.
- Some frequencies can be used to deliver ice cloud information, important for aviation safety.
- Observations from geostationary orbit could be more useful for high resolution NWP due to frequency of observations (but represent a development challenge.
- Continuity: The Bureau requires operational missions with continuity. The Bureau recognises that the pathway to operational, reliable and trusted missions and sensors is through the development of demonstration or pathfinder missions.
- Timing: There may be an opportunity to host a payload on a LEO satellite by 2026. A longer time constraint for a geostationary mission. This microwave hyperspectral program could be a candidate for Moon to Mars application and funding as the microwave bands covered by the instrument are those of significance to Martian remote sensing.
- Bands of interest:
    - 50-60, 118, 183GHz bands with 100 channels or more grouped around these for hyperspectral capability.
    - A smaller number of window/hydrometeor detection channels..

Table 13. Requirements for Microwave Sounder

Requirement Level		Baseline		Objective	
Organisation*		**WMO**	**Bureau**	**WMO**	**Bureau**
Coverage					
Temperature (and humidity)	Horizontal Resolution (km)	2 - 100	15 - 25	0.5 - 50	5 - 10
	Vertical resolution (km)	0.25 - 1.5	2.5	0.1 - 1	1.5
	Temperature Accuracy (K)	1	1	0.5	0.5
Humidity	Horizontal resolution	5 - 50	16	0.5 - 15	5 - 10
	Vertical resolution (km)	0.2 - 1	2	0.1 - 0.5	1
	Accuracy	5%	10%	2%	5%
Channels	Number of channels		Hyperspectral, ~112 channels in total		3 primary bands, with 112 channels (hyperspectral) in total
	Frequencies		From 20 to 205 GHz. Including 60, 120, 183 GHz bands plus window'/hydro. channels		From 20 to 205GHz Including 60, 120, 183 bands and window / hyrdro. chans
	Other options		Potentially with tuneable channels		Potentially with tuneable channels (Ultraspectral option)
Latency			~20 min		~20 min
Timeliness			Direct readout over Australia		Direct readout over Australia
Availability of service (e.g. 98%)			98%		98%

12.3.2 Related missions

This section presents an overview of operational microwave sounder missions that are relevant to this mission concept.

12.3.2.1 Similar large satellites

- **AMSU-A**, a cross-track sounder measures temperature in 15 discrete frequency channels (23-90 GHz), window channels at 23.8, 31.4 and 89 GHz provide information on surface temperature and emissivity. The AMSU-A instruments were launched with a partner 5-channel humidity sounder (AMSU-B on older satellites followed by MHS on later ones) with three channels at 183GHz to provide humidity information.
- **ATMS** is similar to AMSU-A/MHS and has 22 channels including the 54GHz band for temperature sounding and five channels in the 183 GHz band for moisture sounding.
- **SSMI/S** is a 24-channel conical sounder with additional capability for stratospheric temperature sounding, surface imaging and integrated water vapour retrieval.

12.3.2.2 Planned instruments in LEO orbit

- **Metop-SG-A and B**, are EUMETSAT weather satellites featuring the MWS instrument, a 24-channel 23.8 - 229 GHz microwave sounder. Expected launch is in 2021-22.
- **Arctic Weather Satellite (AWS)** a small satellite (120 kg) in sun-synchronous orbit aimed at improving Arctic and global weather forecasts. It will feature a cross-track scanning microwave (MW) radiometer with temperature and humidity sounding capabilities.

12.3.2.3 Similar CubeSat sensors (LEO orbit)

- **TEMPEST-D**, measures water vapour in 5 channels from 89 to 182 GHz.
- **TROPICS**, provides temperature profiles in 7 channels near the 118.75 GHz oxygen absorption line, water vapour profiles using 3 channels near the 183 GHz water vapour absorption line, imagery in a single channel near 90 GHz for precipitation measurements, and a single channel at 206 GHz for cloud ice measurements.
- **IOD-GEMS**, 3D temperature and moisture atmospheric profiles. Follow-on mission GEM-STORM, with 48 low-earth orbiting 6U passive microwave CubeSat satellites with sounding and imaging channels.
- **Polarcube**, A student-built CubeSat with a (low-cost)118.75 GHz sounder. 0-18 km altitude, 8 channel filter bank.

Table 14 provides a summary of CubeSat hosted microwave sounders in LEO.

Table 14. LEO CubeSat Microwave Sounding Missions

Mission		MicroMas[35]	MicroMas-2[36]	MiRaTa[37]	EON-MW[38],[39]	TROPICS[40],[41]	TEMPEST-D[42]
Cost				USD 3.6M		USD 32.2M	
Launch Date		2014	2018	2017		2021	2018
Satellite Platform		3U CubeSat	3U CubeSat	3U CubeSat	12U CubeSat	3U CubeSat	6U CubeSat
Orbit			500 km, SSO	450 km perigee, 810 km apogee, SSO	<550 km, SSO	550 km, 30-degree incl.	400 km
Instrument	Size		1 U	~1.5U 10x10x18 cm	220 mm x 220 mm x 340 mm	1U	4U
	Mass (kg)			0.905	4		3.8
	Power (W)		2	5.5	22.7	2	6.5
	Channels		89 GHz 114.9 - 118.6 GHz 183.3±1 GHz 183.3±3 GHz 183.3±7 GHz 207 GHz	50.3 - 55.5 GHz 183.3±3 GHz 183.3±7 GHz 204.8 GHz	23.8 GHz 22ch 31.4 GHz 50.3 - 55.5 GHz 88.2 GHz 183.3 - 191.3 GHz	90 GHz 114.5 - 118.6 GHz 184.4 - 190.3 GHz 206 GHz	87 GHz 164 GHz 174 GHz 178 GHz 181 GHz
	NEdT (K) @ 300K		0.1-0.6	0.1 K at 55 GHz, 0.3/0.2/0.15 K at 183 ± 1/3/7 GHz,	0.7-3.6	0.6-0.95	0.13-0.7

[35] https://directory.eoportal.org/web/eoportal/satellite-missions/m/micromas-1
[36] https://directory.eoportal.org/web/eoportal/satellite-missions/m/micromas-2
[37] https://directory.eoportal.org/web/eoportal/satellite-missions/m/mirata
[38] doi:10.1080/16000870.2020.1857143
[39] https://digitalcommons.usu.edu/SmallSat/2017/all2017/40/
[40] https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/tropics
[41] https://tropics.ll.mit.edu/CMS/tropics/pdf/nasaTropicsFactSheet.pdf
[42] https://www.jpl.nasa.gov/CubeSat/missions/tempest-d.php

				and 0.25 K at 207 GHz			
	Swath Width (km)					50.7 km @ 90 GHz 41.2 km @ 118 GHz 27.5 km @ 183 GHz 26 km @ 205 GHz	1550 km
	Spatial Resolution (km)					29.6 km @ 90 GHz 24.1 km @ 118 GHz 16.1 km @ 183 GHz 15.2 km @ 205 GHz	13 km @ 181 GHz 25 km @ 87 GHz
	Vertical Resolution (km)			3 – 5 (2 K uncertainty)	"Similar to ATMS"		

12.3.3 Instrument discussion

A microwave sounder is a multi-channel passive radiometer with sensitive receivers that can measure thermally emitted electromagnetic radiation in a variety of frequency bands. An example of measured opacity for water and oxygen is shown in Figure 2.[43] The channels marked are from the AMSU-A sounder.

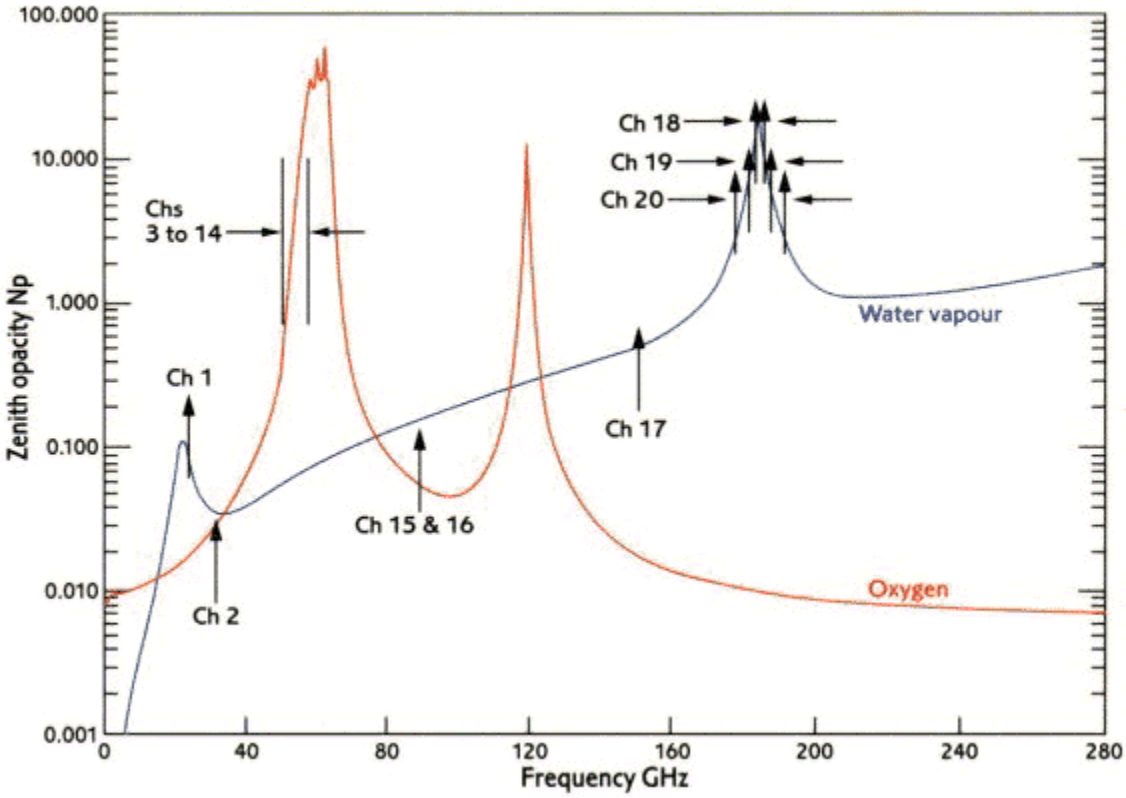

Figure 2 Zenith opacity due to oxygen and water vapour in the microwave frequency range.

On LEO satellites the radiometer contains a hot calibration source and uses the deep space background radiation as a cold calibration source. Generally, two scanning methods are used. Typically, cross-track scanning has been used, since this requires a smaller antenna aperture, allows longer integration times per pixel, but is more affected by polarization variation across the swath width and features low spatial resolution. The second scanning option is conical scanning, which provides constant pixel resolution and polarization across the swath but needs larger apertures to support the same swath width compared to cross track scanning. A depiction of the scanning techniques is shown in Figure 3.[44]

[43] [John, Viju. (2005). Analysis of upper tropospheric humidity measurements by microwave sounders and radiosondes
[44] J.E.Charlton, U.Klein, Sula Systems Ltd, ESTEC -- NEXT GENERATION MICROWAVE RADIOMETRY MISSIONS FOR METEOROLOGY IN LOW EARTH ORBITS

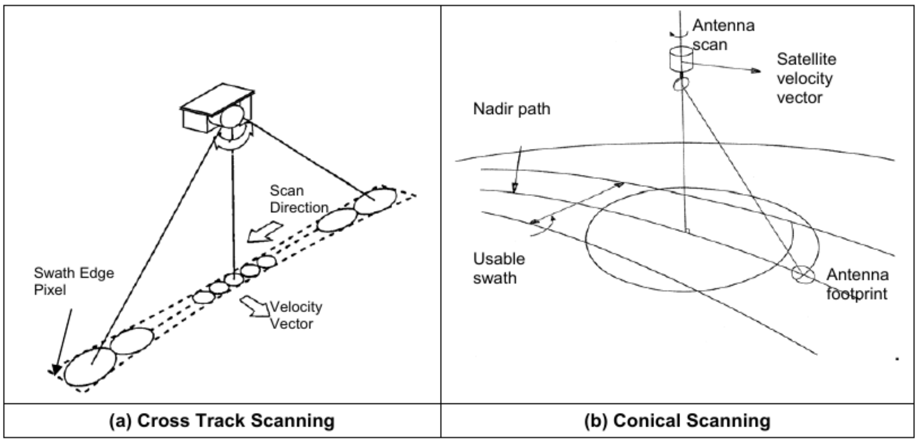

Figure 3 Radiometer tracking.

The radiometer traditionally consists of a reflector, a scanning mechanism, RF frontend with filter banks, low noise amplifiers, heterodynes and digitizers. The scanning operation is typically performed using a mechanically operated director or a rotator/spinner. The radiometer alternates between scanning and pointing at hot and cold calibration sources. Research studies[45] have suggested phased array radiometers, which remove the need for mechanically operated directors and rotators, at the cost of increased signal processing complexity.

12.3.3.1 Performance drivers

The key areas contributing to the performance of the microwave sounder are the radiometric sensitivity and spatial resolution, which are dictated by the aperture size and frontend sensitivity. Under certain conditions spatial resolution and radiometric sensitivity can be traded off by using spatial smoothing, averaging of over-sampled footprints, or spatial resolution can be enhanced at the expense of radiometric resolution by decreasing integration times in the sensors.

The main contributor to the instrument size is the reflector. The reflector size is dictated by the lowest frequency band that needs to be monitored and the gain that is needed. Traditional LEO radiometers utilize dish-shaped reflectors with mechanically operated directors for cross-path tracking or rotators/spinners for conical tracking. Most cube satellites, such as the MicroMAS-2 3U CubeSat only scan channels above 90 GHz due to the limited aperture size, whereas the 12U EON-MW supports channels down to 23 GHz due to the larger aperture. Some research studies proposed phased array sounders, which perform digital beam steering and thereby omit the need for mechanically steered reflectors and rotators. However, an increased amount of RF frontend hardware, signal processing and calibrations is required.

The number of channels is driven by the physical space requirements of the filter banks, local oscillators and processing hardware. Recent advances in the miniaturization of filter banks increases the number of channels that can be utilized on SmallSats from a few channels to tens of channels[46].

[45] B. H. Lambrigtsen, S. T. Brown, S. J. Dinardo, P. P. Kangaslahti, A. B. Tanner, W. J. Wilson, "Progress in developing GeoSTAR: a microwave sounder for GOES-R," Proc. SPIE 5882, Earth Observing Systems X, 58820L (22 August 2005); https://doi.org/10.1117/12.615269
[46] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6496895

Power consumption is highly dependent on the number of channels used and actuation mechanism. The numbers range from 2 W for the 3U MicroMAS-2 and TROPICS to 22.7 W for the 12U EON-MW. The larger form factor satellite and solar array surface area, the larger the power budget for the instrument. The power draw varies significantly from instrument to instrument. While the power draw breakdown for the instruments used for previous missions is not available, it is fair to assume that the RF chain for each channel utilizes 100 – 500 mW for conventional sounders. Hyperspectral sounders can potentially utilize parts of the active RF chain across multiple channels. The mechanisms operating the director or rotator contribute to the power consumption as well. A hot calibration source needs electricity to maintain a set temperature, though alternate methods are possible.

Physical components such as the main reflector and direction mechanism as well as housing for the RF components and interference mitigation will contribute to the mass of the radiometer. Most sounder instruments generate only low amounts of data (10s of kb/sample), for which UHF / Sband communications are sufficient to downlink.

12.3.3.2 Key technology development areas

High frequency RF frontends require careful development, design and integration. Some of this is in common for other instruments such as radar and satellite communications and expertise of individuals and businesses in these domains can be utilized. Signal processing knowledge is required to develop and design the algorithms for detection and calibration.

12.3.3.3 Sovereign capability

Multiple Defence subcontractors have experience designing and building RF equipment for radar applications, communications etc. This could be utilized for sounding equipment.

Several sovereign universities and businesses have test facilities for RF equipment. It is unknown whether these cover the desired frequency ranges for the sounder.

The following Australian organisations listed in Table 15 have been identified as having either experience in developing microwave sounders, or experience in developing systems similar to that used in microwave sounders.

Table 15 Australian organisations with experience in technologies applicable to developing a microwave sounder

Organisation	Technology	Experience
CEA technologies	RF frontends and signal processing solutions for tracking and surveillance	Phased array radar solutions for the navy, Coastal surveillance system
E and S	Met Radar signal processing. Sat. Data reception and processing Environmental Monitoring	Met radar manufacture, data processing Satellite data reception and application systems
Vaisala	Atmospheric sounders	Ground based

12.3.3.4 Potential overseas partners

Several companies or organisations could serve as potential partners including MIT Lincoln Labs that developed the microwave sounder for the Joint Polar Satellite System, OHB-Italia that developed the sounder for the ESA MetOp missions and SSTL.

12.3.4 Implementation options

It is suggested to utilize one or multiple pathfinder missions to develop and increase the TRL of the radiometer. The first pathfinder versions of the instrument can be flown as payload on high-altitude balloons or aircraft prior to launching a SmallSat mission. Since the instrument size is one of the main design drivers, it is suggested to focus on the higher frequencies, allowing smaller aperture sizes. Internationally there is also some significant development work now going ahead on a 2m deployable antenna.

It is suggested to take advantage of the recent advances in the miniaturization of filter banks, allowing a large number of filters to be compacted in small physical areas. This allows hyperspectral sounding on instruments that can fit on small satellites[47].

The choice of channels and their bandwidth should be heavily weighted on their contribution and impact to improving the models and predictions. This allows a pathfinder mission to be utilized as a technology demonstrator mission while contributing with valuable data to the national and international community and improve the accuracy of climate predictions. This pathfinder can be followed by a small-sat scale mission with a larger power budget and physical size, allowing larger apertures and more signal processing equipment.

The sounder instrument can be developed independent of satellite missions. Prototypes can be tested on high altitude balloons or from ground sites to increase the TRL of the instrument before integration in a spacecraft. Form factors, mass and power budgets have to be taken into account during this phase, such that minimal changes are required when designing the space mission.

Geostationary missions have been proposed but have never been developed. Conventional passive measurement methods do not work due to the increased distance to the earth. Interferometric methods have to be used instead[48]. Further research is required for the development of the instrumentation required for geostationary sounding. Due to the increased cost of the development and launch of a geostationary spacecraft, the cost and benefits over a constellation of LEO spacecraft should be investigated in further detail. It is suggested to focus on lower risk LEO pathfinder missions and identify shortcomings in the data and resolution prior to considering geostationary missions.

12.3.5 Cost estimate

The cost estimate for a microwave sounder mission would be comprised of estimates for the instrument, spacecraft, launch, and operations. The instrument development cost estimates are based on several assumptions as described while using cost models and publicly available data for similar sensors. Development costs for the spacecraft and its subsystems are not included because

[47] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6496895
[48] [https://ieeexplore.ieee.org/abstract/document/6050010

the mission requirements are not fully developed in this pre–Phase A study. Launch costs are included based on publicly available data from LSPs for various spacecraft.

Spacecraft level MAIT and operations cost estimates for a Cubesat mission based on the experience of the UNSW Canberra Space M2 program is given only as an example.

The estimated cost of the microwave sounding instrument can be approximated using the following equation from the NASA Instrument Cost Model (NICM), version 7:

$$Total\ \ Instrument\ Cost = 1664\ \times Total\ Mass^{0.38}\ \times Total\ Max.Power^{0.4}$$

Table 16 MW mission cost estimate summary

Cost Estimate	MAUD (2021 $ adjusted for inflation)
NASA EO Instrument Cost Model (NICM) for a 1 kg/ 5 W instrument[49], [50]	4.100
NASA EO Instrument Cost Model (NICM) for a 4 kg/ 25 W instrument[51], [52].	13

Launch costs for a MicroSat or SmallSat platforms are specified in Section 15.

12.3.6 Open points and questions

As for the other instruments that were considered in this study several questions and feasibility related analyses would need to be conducted in a subsequent Phase A study. These include;

- Assessment of pathfinder missions to gradually build expertise in the development and operation of microwave sounders.
- Consider development of ground based or airborne instrument to build expertise and reduce the risk of a SmallSat pathfinder.
- Is it worth to investigate and develop phased array sounders?
- Conduct a detailed survey of Australia based RF testing facilities that may be needed.

12.4 Additional estimated costs for a Pathfinder Cubesat mission

All three instrument mission options could be developed using an iterative capability development approach which would include Pathfinder missions. These Pathfinders would carry a reduced capacity payload which would allow Australian development of capabilities needed to achieve a fully operational capability in the future.

Although a 6U-24U Cubesat platform and subsystem cost cannot be developed without specific mission requirements there are other costs that can be estimated. These include spacecraft level AIT, environmental testing, and operations. However, the operational scenario is also better left to

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[49] Mrozinski, J., et al., "Latest NASA instrument cost model (NICM): Version VI", AIAA SPACE 2014 Conference and Exposition (Aug 2014

[50] Mrozinski, J., "NASA Instrument Cost Model: NICM 8.5", 2019 NASA Cost and Schedule Symposium (August 13-15, 2018, Houston, TX)

[51] Mrozinski, J., et al., "Latest NASA instrument cost model (NICM): Version VI", AIAA SPACE 2014 Conference and Exposition (Aug 2014

[52] Mrozinski, J., "NASA Instrument Cost Model: NICM 8.5", 2019 NASA Cost and Schedule Symposium (August 13-15, 2018, Houston, TX)

Phase A study where infrastructure options for the mission operations centre and ground segment networks are defined.

12.4.1 Spacecraft level AIT

The number of staff required for AIT activities will be dependent on the instrument design & the required spacecraft platform. Based on prior experience at UNSW Canberra Space in the development of the M2 and M2PF spacecraft (6U and 3U CubeSats, respectively) the following estimates for instrument and spacecraft level AIT activities are provided in Table 17.

Table 17 Estimated spacecraft level AIT costs (CubeSat)

Personnel / Role	Number of Personnel (1 year @ 200KAUD)
AIT engineer	2
Electrical subsystems engineer	1
Mechanical/thermal engineer	1
Payload engineer	1
Software engineer	1
Program manager	1
TOTAL (for 1 years)	**7 personnel (~$1,400k)**

12.4.2 Environmental qualification

Mission environmental qualification tests at spacecraft level could incur a facility charge (e.g., performed at ANU NTSF) which does not include prototyping and development tests costs. However, this estimate is program and facility usage dependent.

12.4.3 Operations

Estimated operations costs for a pathfinder cubesat mission are listed in Table 18 and based on the perceived personnel required to operate and maintain the mission. These costs are estimated based on an AUD 200k annual salary cost (includes superannuation, overheads, etc.) per person, with roles and number of personnel detailed as follows:

Table 18 Estimated operations cost (Cubesat)

Personnel / Role	Number of Personnel (1 year @ $200k)
Project Manager	1
Operations Engineers	2
Flight Software Engineers	1
RF engineer	1
Payload engineer	1
Ground Station Engineer	1
Thermal Engineer	6 months

Electrical Engineer	6 months
TOTAL (for 1 years)	**8 personnel (~$1,600k)**

13 Satellite platforms

A number of satellite platforms are possible for each mission. This section provides a non-exhaustive summary of commercial offshore and Australian platform providers including the platform class/size, allowable payload mass, size, and power as well as indicative cost and TRL levels where available.

13.1 Offshore platform providers

A list of offshore platform providers is included in Table 19.

Table 19 Partial list of offshore platform providers

Platform					Comments
Company	**Name**	**Class/size**	**Payload Accommodation**	**Cost**	
ISISpace		6U			
		12U/16U			
Nanoavionics[53],[54],[55]	M6P	6U			
	M12P	12U	17.5 kg 11U		
	MP42	MicroSat 115 kg	1.2 x 1.2 x 0.81 m		
Clydespace[56]	EPIC 6U	6U			
	EPIC 12U	12U	9U 240 W (peak)		
Tyvak[57]	Trestles 6U	6U	180 W (peak)	>USD 500k	
	Trestles 12U	12U	180 W (peak)	>USD 1M	
	Mavericks	MicroSat	2 kW (peak)	>USD 2M	
Blue Canyon[58]	XB6	6U	4U		
	XB12	12U	8U		
	X-Sat, Mercury	MicroSat	355 x 432 x 432 mm		
	X-Sat, Venus	MicroSat	432 x 416 x 685 mm		

[53] https://nanoavionics.com/small-satellite-buses/6u-nanosatellite-bus-m6p/
[54] https://nanoavionics.com/small-satellite-buses/12u-nanosatellite-bus-m12p-m12p-r/
[55] https://nanoavionics.com/small-satellite-buses/2613-2
[56] https://www.aac-clyde.space/epic-spacecraft
[57] https://www.tyvak.com/platforms
[58] https://www.bluecanyontech.com/spacecraft

	X-Sat, Saturn	SmallSat	200 kg (max.) 762 x 762 x 1016 mm		
Berlin Space Technologies[59],[60]	LEOS-50	MicroSat 75 kg	30 kg 550 x 550 x 400 mm 25 W / 250 W (peak)		
	LEOS-100	SmallSat 150 kg	75 kg 600 x 600 x 600 mm 300 W / 2 kW (peak)		
SSTL[61],[62]	SSTL-CUBE	12U			
	SSTL-MICRO	MicroSat	30 kg - 65 kg 450 x 340 x 340 mm 63 W / 200 W (peak)		
York Space Systems[63]	S-CLASS	SmallSat 200 kg (max.)	65 - 115 kg 800 W (peak)		TRL 7/8
Momentus[64]	Vigoride		300 kg (max.) 1.25 m^3 600 W (max.)	USD 4.8M	TRL 7/8

13.2 Australian platform providers

A list of Australian platform providers is included in Table 20.

Table 20 Partial list of Australian platform providers

	Platform				Comments
Company	Name	Class/size	Payload Accommodation	Cost	
Inovor[65]	6U Apogee	6U 10 kg			TRL 7/8
	12U Apogee	12U 20 kg	1000 W (peak)		TRL 7/8
UNSW Canberra Space	Custom CubeSat	26.7kg (max.)			TRL 9

[59] https://www.berlin-space-tech.com/portfolio/leos-50
[60] https://www.berlin-space-tech.com/portfolio/leos-100
[61] https://www.sstl.co.uk/getmedia/cb0d738d-bbf5-4a0a-9c81-4dd91f0f239f/SSTL-CUBE.pdf
[62] https://www.sstl.co.uk/getmedia/78c3ae88-0f17-40a1-9448-8c3c7e9f6944/SSTL-MICRO.pdf
[63] https://www.yorkspacesystems.com/s-class
[64] https://momentus.space
[65] https://www.inovor.com.au/space-technology/bus-platform

14 Spacecraft level Australian AIT and qualification infrastructure

Environmental qualification testing forms part of an overarching effort to provide total mission assurance, i.e. establish the highest level of confidence possible that the fully integrated system (spacecraft bus + payload) would operate correctly on-orbit resulting in a successful mission. Detailed environmental qualification requirements depend on the specific mission requirements, the launch service provider (LSP) and launch vehicle (LV) selected to deliver the system to orbit. The relevant environmental qualification tests to be conducted are listed below (where model type and tests required depend on the design, development and verification approach taken):

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

Environmental qualification testing is a critical part of the project workflow and requires suitable facilities and appropriately trained personnel to ensure a successful environmental qualification test campaign. The National Space Test Facility (NSTF) at the Australian National University (ANU) at Mt Stromlo in Canberra can provide the full range of testing services required for environmental qualification of CubeSats and small MicroSats listed above.[66] Shock and vibration test services can be provided by additional test houses such as VIPAC in Melbourne and Austest in Sydney. NSTF personnel have the relevant experience to perform spacecraft environmental qualification testing and have the necessary ESD and contamination control procedures in place. Other test houses may not be familiar with the particularly strict handling requirements of space system hardware. This is of particular importance for handling spacecraft hosting imaging payload systems.

The existing spacecraft environmental qualification test infrastructure in Australia is appropriate to support CubeSat (1kg to 50kg) and MicroSat (50kg to 100kg) mission. However, there is a capability gap for larger spacecraft (>150kg). Smaller spacecraft programs often must satisfy less stringent environmental qualification test requirements compared with larger spacecraft.

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

15 Launch segment

Due to the conceptual nature of this study, the exact launch details for each mission cannot yet be determined. However, a range of launch services and costs are outlined below to provide indicative options so that each mission cost can be estimated. Launch services were limited to CubeSats, MicroSats, and SmallSats.

15.1 Offshore launch service providers

An abbreviated list of launch service providers for the mission are described in this section;

15.1.1 RocketLab

RocketLab is a USA company with a New Zealand subsidiary that offers launch services for CubeSats, MicroSats, and SmallSats on their Electron rocket which operates out of their launch site in Mahia, New Zealand.

Quoted prices for launches on-board their Electron rocket were as of 19th of September 2019 are:

- USD 4.9M for dedicated launch, with maximum of 300 kg to 500 km at 39° inclination, or ~200 kg to 550 km SSO.
- USD ~1.0M for a 12U CubeSat (20 kg) to LEO
- USD ~0.5M for a 6U CubeSat (10 kg) to LEO

More options and details on RocketLab's Electron launch service can be found within their user's guide (https://www.rocketlabusa.com/assets/Uploads/Payload-User-Guide-LAUNCH-V6.6.pdf)

15.1.2 Space Exploration Technologies (SpaceX)

SpaceX is a USA based launch service and high-speed internet provider that offers SmallSat rideshare launch services on-board their Falcon 9 rockets. SpaceX's rideshare program offer launches into LEO, SSO, and polar orbits, and costs begin at USD 1M for 200 kg, and USD 5k each additional kilogram. Details on SpaceX's rideshare program can be found within their user's guide (https://storage.googleapis.com/rideshare-static/Rideshare_Payload_Users_Guide.pdf)

15.1.3 Antrix

Antrix is an Indian launch service provider that operate their Polar Satellite Launch Vehicle (PSLV) from the Satish Dhawan Space Centre, India. Their PSLV is designed to accommodate SmallSats, MicroSats, and CubeSats in various configurations, with a capacity to place satellites up to 500 kg at 500 km LEO.

Current PSLV launch costs are:

- EUR 17k per kilogram for CubeSats
- ~EUR 10-12k per kilogram for MicroSats and SmallSats.

15.1.4 Momentus

Momentus is a USA company that plans to begin providing launch, custom orbit insertion, and hosted payload services in mid-2021. Momentus plan to fly their Vigoride 'space-tug' on-board SpaceX's Falcon 9, and either deliver small, micro, or CubeSats to custom orbits or provide hosted payload services. Momentus launch service pricing is listed in Table 21.

Table 21 Momentus launch service pricing summary

Orbit	3U	6U	12U	50 kg	>50 kg
SSO	USD 120k – 170k	USD 230k – 330k	USD 430k – 640k	USD 540k – 800k	Inquire with Momentus
LEO	USD 170k – 260k	USD 330k – 500k	USD 640k – 960k	USD 800k – 1.2M	

Additional details on Momentus' services can be found via their website (https://momentus.space)

15.1.5 Spaceflight Industries

Spaceflight Industries is a launch service and mission management provider located in Seattle, USA. providing launch services by brokering launch slots from multiple vendors. Spaceflight launch service pricing is listed in Table 22.

Table 22 Spaceflight launch service pricing summary

Payload Type	6U	12U	50 kg	100 kg	200 kg	300 kg
Mass (kg)	10	20	50	100	200	300
Price to LEO	USD 295k	USD 595k	USD 895k	USD 975k	USD 1.35M	USD 1.85M

Additional details can be found via their website (https://spaceflight.com).

15.2 Australian launch service providers

The provision of launch services within Australia is limited at present. However, several organisations are advancing their capabilities. These include;

15.2.1 Black Sky Aerospace

Black Sky Aerospace is a Queensland based company who are developing a launch vehicle capable of placing small satellites into LEO or SSO orbits. Their expected first launch date is in 2024. No indicative launch costs are currently available.[67]

15.2.2 Gilmour Space Technologies

Gilmour Space Technologies[68] is a start-up company based in Queensland who are developing their small satellite launcher called 'Eris'. The currently available projected capability of the Eris launch vehicle is as follows:

- 215 kg payload to 500 km SSO
- 305 kg payload to 500 km equatorial orbit

and is targeting its first launch in 2022. Currently, there are no indicative launch costs available.

[67] https://bsaero.space/
[68] https://www.gspacetech.com

16 Orbits

Due to the nature of this study as a pre-phase A study, orbits have not been defined for the three selected mission concepts. The orbit selection process requires selection of a specific payload instrument and detailed analyses of the imaging system performance for the selected orbit geometry. This process is then facilitated though clear user requirements that are flowed down to specific mission requirements, which was beyond the scope of this current study. Nevertheless, this section discusses some general considerations with regards to orbit selection and propulsion requirements.

Low Earth Orbiting (LEO) spacecraft and spacecraft constellations for meteorological and earth observation missions are typically placed in sun-synchronous polar orbits. This has the advantages of achieving global coverage daily or within a small number of days depending on the precise orbital parameters, repeating ground tracks, and a fixed orbit plane relative to the solar illumination vector, resulting in optimal solar array illumination conditions for fixed solar arrays. A spacecraft in a sun-synchronous orbit passes over any given point on the earth at the same local time, governed by the local time of the ascending node (LTAN) of the specific orbit, ensuring constant solar illumination conditions for repeat observations. As an example, a dawn/dusk orbit with LTAN of 6am provides minimum eclipse periods and therefore constant solar panel illumination conditions, which is ideal for power generation. This type of orbit would be a desirable choice for a radar imaging spacecraft as it does not require solar illumination of the scene to be imaged, whereas a spacecraft employing an optical (visible) imaging system may perform better in a noon/midnight orbit with an LTAN of 12pm.

Highly Elliptical Orbits (HEO) offer the potential of increased spacecraft pass duration at high elevation. Historically, the Molniya orbit, with a critical orbit inclination of 63.5° and apogee over the northern hemisphere, has been of particular interest for high latitude communication spacecraft in the northern hemisphere. It can provide continuous, high latitude coverage for approximately 8 hours out of a 12-hour orbital period, with minimal drift of the orbit, i.e., the argument of perigee, over time.

Three spacecraft in different orbital planes would be required for 24-hour continuous coverage. Other HEOs with different inclinations and with apogee over the southern hemisphere are possible, however, propulsion is required to compensate for the drift in the argument of perigee over time. HEO altitudes typically range from upper LEO/low MEO altitudes at perigee to high MEO, geostationary or higher than geostationary altitudes at apogee. As a result, spacecraft experience increased radiation exposure (highly energetic electrons and protons) as they are travelling through the inner and outer radiation belts. Depending on the precise orbital parameters, exposure can be higher than in geostationary and significantly higher than in LEO, except for spacecraft passing through the polar regions, impacting the overall mission lifetime.[69] Non-constant altitude and changing solar illumination conditions need to be considered for imaging system performance evaluations and in any operational planning activities.

Spacecraft in geostationary orbit offer the advantage that a spacecraft's position remains fixed at a selected longitude. This provides the advantage of continuous coverage of the visible part of the planet and a fixed 24-hour communication link. Owing to the significantly higher altitude compared with LEO, larger swath widths are generally achievable for earth observation spacecraft in geostationary orbit compared to LEO orbiting spacecraft, albeit at the expense of ground resolution, increased complexity, size, mass, and power consumption. Despite being geo-synchronous and free from aerodynamic drag, active station keeping is still necessary in geostationary orbit due to luni-solar perturbations, Earth's tri-axiality (specifically the equatorial bulge) and solar radiation pressure.

[69] Trischenko et al. 2019; Advances in Space Research 63(2019) 3761-3767

The need for on-board propulsion may be driven by several operational needs:

- Compliance with space debris mitigation standards, notably the need to vacate the LEO protected region within 25 years after the end of the nominal mission.
- End-of-life disposal into graveyard orbit for MEO, geostationary spacecraft.
- Station acquisition and station keeping needs in a formation flying scenario.
- General station keeping needs and collision avoidance manoeuvres.

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

Station acquisition may become important in the case the spacecraft is launched as a secondary payload and ejected into a non-optimal orbit; in which case it may be required to be manoeuvred to its final orbit via its own on-board propulsion system.

Station keeping may be required to compensate for a loss in altitude or a drift in any of the other orbital parameters over time due to aerodynamic drag and/or other perturbations due to the sun and moon, Earth’s tri-axiality, and solar radiation pressure. In this case, on-board propulsion would be needed in regular intervals to maintain a constant altitude and guarantee continuous imaging performance.

The ability to manoeuvre a spacecraft in response to a conjunction warning to reduce the probability of colliding with orbital debris or another operational spacecraft shall also be considered.

17 Ground stations

Ground station requirements were not assessed in this study but would be considered in a follow-up Phase A study. There could be several options for providing ground stations for uploading and downloading data to the spacecraft. There are several ground station operators offering uplink telemetry and commanding services, S-Band and X-Band downlink as well as cloud-based secure data and image processing services. Table 23 provides a partial list of commercial ground station service providers.

Table 23 Commercial ground station providers

Capricorn Space (AUS)	https://capricornspace.com.au/
Cingulan Space (AUS)	http://www.cingulanspace.com.au/
Amazon Web Services (US)	https://aws.amazon.com/ground-station/
Viasat (US)	https://www.viasat.com/business-and-commercial/space-and-networking-technology/ground-network
KSat (Norway)	https://www.ksat.no/
Nova Systems (AUS)	https://www.novasystems.com/

There may also be the possibility of using both Australian government and international partner agency ground station infrastructure (TBC).

Although beyond the scope of this study, options and costs for providing a ground segment and a mission control function can be investigated in future studies.

18 Conclusions and Recommendations

The study makes the following recommendations;

- Phase A investigation is warranted for each of the three missions. Pathfinder missions for a CubeSat hosting any of the imagers seem feasible within the next 5 years given adequate investment, industry/government coordination and implementation. These instruments, although having a descoped set of requirements compared to state-of-the-art systems, could contain a high percentage of Australian hardware and software. The design of the mission and space segment would ideally be Australian but some partnerships with international entities might be necessary.

- It will be important to define the stakeholders, technical teams, and data users to help ensure the mission goals and operational concepts are aligned with the EO Roadmap before development beyond Phase A.

During the study, a set of technology gaps/observations were identified during the analysis of each mission. These included;

Lightning detection:

- The optical design of the instrument could be undertaken in Australia.
- Depending on the design of the optical system, the manufacturing of the lenses/mirrors could prove difficult in Australia given the current domestic optical fabrication capability.
- Optical system AIT capability within Australian industry was not apparent to the study team but the ANU NSTF does provide the capability to integrate and test space-based optical systems.
- Integration of optical system(s) and detectors/focal plane subsystem(s) could be undertaken at NSTF.
- All spacecraft subsystems except the optics for the instrument could be developed within Australia where components are procured from international and domestic suppliers.
- Environmental testing at subsystem and spacecraft level is available within Australia (e.g., NSTF)

SAR:

- Further investigations into the SAR capabilities in Australia should be performed, especially for the design of the antenna and signal processing hardware/software.

Microwave sounder:

- Further investigations into the RF capabilities in Australia should be performed, especially for the design of the high frequency hyperspectral equipment. Given access to currently available components design, development and testing of this instrument can be done in Australia.
- Interferometric sounders for geostationary satellite applications have so far not been developed and tested. Australia can take a lead in this.

19 List of acronyms and abbreviations

Table 24 Abbreviations and acronyms

Abbreviation	Description
AHI	Advanced Himawari Imager
AIT	Assembly, Integration, and Test
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
ANCDF	Australian National Concurrent Design Facility
ANU	Australian National University
ATMS	Advanced Technology Microwave Sounder
AUD	Australian dollar
avg.	average
BOL	Beginning of Life
Bureau	Bureau of Meteorology
CDF	Concurrent Design Facility
btw	between
CAD	Canadian dollar
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group on Meteorological Satellites
CIMR	Copernicus Imaging Microwave Radiometer
CMA	Chinese Meteorological Agency
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Deg.	degree
Dia.	diameter
EBS	Event based sensor
EMC	Electromagnetic compatibility
EO	Earth Observation
EOL	End of Life
EON-MW	Earth Observing Nanosatellite-Microwave
Metop-SG	Meteorological operational satellite-Second Generation
ESD	Electro-static Discharge
etc.	etcetera
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FOC	Full Operational Capability
fps	Frames per second
FTE	Full-Time Equivalent
GA	Geoscience Australia
Gbps	Gigabits per second
GEMS	Geostationary Environment Monitoring Spectrometer
GHz	Gigahertz
GIMS	Geodetic Integrated Monitoring system
GLM	Geostationary Lightning Mapper
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System

Abbreviation	Description
GSD	Ground sampling distance
GSE	Ground support equipment
HEO	Highly elliptical orbit
HH	Horizontal transmit / Horizontal receive
HV	Horizontal transmit / Vertical receive
ICI	Ice Cloud Imager
IR	Infrared
ISS	International Space Station
JAXA	Japanese Aerospace Exploration Agency
JMA	Japan Meteorological Agency
JPL	Jet Propulsion Laboratory
K	Degrees Kelvin
kbps	Kilobits per second
kg	kilogram
km	Kilometre
LEO	Low Earth Orbit
LGN	Landsat Ground Network
LI	Lightning Imager
LIDAR	Light Detection and Ranging
LIS	Lightning Imaging Sensor
LMI	Lightning Mapper Imager
LSP	Launch service provider
LTAN	Local time ascending node
LV	Launch Vehicle
m	metre
m^3	Cubic metre
MAIT	Manufacturing, assembly, integration and test
Mbps	Megabits per second
MEO	Medium Earth Orbit
MetOp-SG	Meteorological Operational Satellite- Second Generation
MHz	Megahertz
MicroMAS	Micro-sized Microwave Atmospheric Satellite
MiRaTa	Microwave Radiometer Technology Acceleration
MIT	Massachusetts Institute of Technology
msec	millisecond
mW	milliwatt
MW	Microwave
MWI	Microwave Imager
MWS	Microwave Sounder
NASA	National Aeronautics and Space Administration
NBF	Narrow band filter
NEdT	Noise equivalent delta temperature
NICM	NASA Instrument Cost Model
nm	nanometre
NOAA	National Oceanic and Atmospheric Administration
NSTF	National Space Test Facility

Abbreviation	Description
NWP	National Weather Prediction
OSCAR	Observing Systems Capability Analysis and Review Tool
OTD	Optical Transient Detector
PF	Pathfinder
PMR	Power-to-Mean Ratio
PSLV	Polar satellite launch vehicle
RCM	Radarsat Constellation Mission
RF	Radio frequency
RO	Radio occultation
ROM	Rough order of magnitude
S/C	Spacecraft
SAR	Synthetic Aperture Radar
SCR	Satellite Cross-calibration Radiometer
SNR	Signal-to-noise ration
SSMIS	Special Sensor Microwave-Imager/Sounder
SSO	Sun-synchronous orbit
SSTL	Surrey Satellite Technology Ltd.
SWaP	Size, weight and power
SWIR	Short-Wave Infrared
SWOT	Surface Water and Ocean Topography
TBC	To be confirmed
TBD	To be determined
TEMPEST	Temporal Experiment for Storms and Tropical Systems
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Meteorological Mission
TROPICS	Time Resolved Observations of Precipitations Structure and Storm Intensity with a Constellation of SmallSats
UNSW	University of New South Wales
USD	US dollar
USGS	US Geological Survey
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS/IR	Visible/Infrared
W	Watt
WMO	World Meteorological Organisation

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21 Appendix A: Study participants

The list of personnel involved in or consulted as part of the study is presented in Table 25.

Table 25 List of personnel

Organisation	Person	Role / contacted for
Bureau of Meteorology	Agnes Lane Fiona Smith John Le Marshall Beth Ebert Peter Steinle Chris Tingwell Alain Protat Leon Majewski Alessandra Monerris Chris Lucas Vincent Villani Pallavi Govekar Aruna Gillkum David Gooding Andrew Dowdy Jan Lieser Caroline Poulsen	Meteorological Earth Observations experts
UNSW Canberra Space	Denis Naughton Philippe Laniakea Jai Vennik Clint Therakam Edwin Peters Elias Aboutanios Jan-Christian Meyer	Mission design and domain engineering expertise
Geoscience Australia	David Hudson	Remote sensing expertise
Australian Space Agency	Reece Biddiscombe Arvind Ramana	Programmatic guidance

22 Appendix B: EOA survey results

Name of mission	Mission purpose	Development Phase	Project Partners
Nighthawk	To demonstrate the market need and gap for 24 hr (especially nighttime) high-spatial resolution infrared imagery. Orbit configuration will be optimised for the Australasian region with wildfires, volcanic eruptions, dust storms, extreme convective storms and flooding of prime importance. Data can also be used in precision farming applications (land surface temperature), fisheries (see surface temperature) and urban heat island assessments.	Pre-Phase A	AIRES Pty Ltd. with partners: Dr Fred Prata, AIRES Pty Ltd and Prof. Mervyn Lynch, Curtin University
Space Edge Computing	Spiral Blue is building the Space Edge Computer - an onboard computing system that will give Earth observation satellites the ability to process images captured on the satellite itself. This enables a reduction in size of downlinked data by a factor of 20 to 1000x, depending on the nature of the processing algorithm. This data reduction greatly increases the effective coverage and revisit rate of the host satellite. Space Edge Computing also enables faster turnaround times, greater flexibility, and easier development of onboard data processing applications. We anticipate this will enable a more capable and affordable Meteorological and Disaster Resilience Mission.	Phase D	Spiral Blue with partners: SatRevolution, Space Machines Company, Modularity Space, Esper Satellites, ANU, AAO, Saber Astronautics, and others
CubeSat GPS meteorology experiment	This is a scientific satellite mission with a 2U-sized CubeSat to perform multiple GPS radar remote sensing experiments for geodesy, meteorology, space weather, and environment. The technical objective is to demonstrate CubeSat-compatible patch antennas and receivers for measuring precise dual frequency GPS tracking data (pseudorange and carrier phase). The CubeSat GPS data will be processed to (1) determine precise orbit at the accuracy of 10 cm, (2) retrieve neutral density (“drag force”) within the thermosphere, (3) estimate vertical profiles of refractive index, temperature and humidity variations within the troposphere and stratosphere from refracted radio signals (“occultation”), (4) measure electron contents within the ionosphere (“space weather”) from combination of dual frequency radio signals, (5) demonstrate feasibility of surface reflected radio signals for mapping inundated area, land surface moisture, sea surface roughness.	Phase B	University of Newcastle with partners

	These science experiments were conducted with full-sized antennas and GPS receivers on regular spacecraft (for example, COSMIC, CHAMP, and GRACE), microsatellite like CyGNSS, and more recently, Spire Global's 3U CubeSat. This proposed mission is to develop the Australian capability of building and operating nanosatellite-based science mission and processing science measurements useful to meteorology, space weather, geodesy, and space situational awareness.		
Satellite Cross-Calibration Radiometers (SCR)	The Australian Satellite Cross-Calibration Radiometer (SCR) series aims to directly improve the calibration of optical satellites increasingly used in the commercial Earth observation sector to deliver more interoperable data. A small 50-100kg Low Earth Orbit 'cross-calibration' satellites would collect a type of data that addresses both of these issues, known as 'hyperspectral' data. We have determined that the development of such missions is feasible for Australian industry. We have also determined that the cost is comparatively low at approximately $36m per satellite, with a minimum of two satellites required initially, and two new satellites launched every two years after that. More information can be found at: https://unsw.adfa.edu.au/space-research/sites/space/files/uploads/GA_ASA_SCR_Public.pdf	Phase A by 30 June 2021	Geoscience Australia with partners: ASA, CSIRO and partner land imaging programs
CSIROSat-1	CSIROSAT-1 is an Australian-designed and built precursor testbed 3U satellite for evaluating use of short-wave IR imaging satellites to characterise fuel condition and other key land-cover characteristics as input to fire fish assessments. Other potential applications include cloud characterisation, flood mapping and fire detection.	Phase-D (launch late 2021 or early 2022)	CSIRO, Inovor
GNSS-R payload	ACSER is developing a GNSS receiver for space application. Earlier GNSS models have been used in GNSS-R instruments and this receiver could also. GNSS-R can be used to monitor sea state, water extent (e.g. floods) and other weather-related indicators.		ACSER/UNSW
Skykraft Air Traffic Management Constellation	Opportunity to leverage 210 small spacecraft from 2022/23	Currently Phase C/D	Skykraft
GNSS Radio Occultation	Implement GNSS-RO for multi-constellation, tri-band, all-in-view on a 210 satellite constellation	Bus/Constellation is Phase C/D	Skykraft (leveraging Air Traffic Management constellation)

Troposphere and Ionosphere Sensing using Emitters of Opportunity	Improve density of radio observations by leveraging terrestrial emitters where dispersion can be measured from space	Bus is Phase C/D, Receiver is C/D, Processing is A	Skykraft
Skyris	Skyris is a "smart Earth Imaging" mission comprising a constellation of small satellites. The satellites have an on-board edge compute module enabling them to not only collect images, as a typical remote sensing satellite, but to perform higher level functions. These higher level functions include damage detection and object search, among others, using on-board Machine Learning algorithms. It is envisaged that the spacecraft will cover a variety of spectral bands, to suit a range of different applications, with different spacecraft in the constellation potentially carrying different instruments. The SASAT1 mission currently under development is a SMARTSAT-Myriota-Inovor collaboration mission that will carry a Near Infra-Red (NIR) and Thermal Infra-Red (TIR) spectral band instrument and a high compute module for on-board edge computing. This mission will be used for a number of applications, one of which is a technology demonstrator for the Skyris mission. This technology demonstrator may suite bushfire detection and other disaster relief applications.	Pre-Phase A for the Full Skyris Mission, but Phase D for the partial demonstration	SMARTSAT and Myriota
NovaSAR-1	CSIRO operate a 10% share of the tasking capability of the Synthetic Aperture Radar (SAR) satellite, NovaSAR-1, under an agreement with UK-based SSTL. An additional 10% share of the satellite capacity is available for purchase. All NovaSAR-1 data collected by CSIRO is to be made available free and open-access to users and downlink of the data is soon to occur via an Australian-based ground station. SAR can see through clouds associated with floods/storms and smoke associated with bushfires. NovaSAR-1 and other SAR sensors are therefore key EO datasets for use in disaster response, with application to meteorological (storms, floods, fires) and geological/geomorphological hazards (landslides, erosion, earthquakes, mining etc). NovaSAR-1 is not currently operated specifically for disaster response (e.g. staff are not on call 24/7 to task images) but the imagery has already been used to make observations of bushfires and flood events in Australia on a best-efforts basis.		CSIRO; satellite operated by Surrey Satellite Technology Ltd (UK); other capacity share partners include ISRO (India), DOST (Phillippines) and UKSA (UK)

	Experience gained through NovaSAR-1 operations and establishing of the ground segment are valuable for the operation of future Australian national missions.		
Super resolution Mosaic Infrared Focal (SMIRF) Sensor	The Project is around developing a low-cost, high resolution Thermal Infrared Sensor for a small satellite	Pre-Phase A	SITAEL with partners: SmartSat CRC / University of Adelaide IPAS
Disaster Avoidance and Resilience Activation & Automation [DARAA]	Disaster Response systems can be enhanced to provide automated damage detection and assessment via distributed IoT sensor systems (eg. bridge monitoring systems etc) which also need standardized formats. Automated Disaster Resilience requires automated activation of Regenerative Technology systems (via standardized formats). EnGen Institute has internationally recognized expertise in Regenerative Technology systems science, architecture and engineering. The proposed project to DEMONSTRATE these capabilities and STANDARDIZE these data formats will greatly enhance the usefulness of BoM (Bureau) and EOA data. The Principal Investigator has participated in ISO Standards development and advised the Australian DoD on implementation of engineering standards. New standards will empower industry to produce Disaster Response technology.	Phase C	EnGen Institute
OzFuel	OzFuel (Australian Forest Fuel Monitoring from Space) is a bushfire mitigation satellite mission aimed at delivering fuel hazard remote sensing data for downstream Earth Observation data analytics services, with the goal of improving Australia's pre-fire monitoring, prediction, preparation, response and resilience. OzFuel will acquire spatial data on fuel conditions such as load and moisture content, tuned specifically to Australia's Eucalypt-dominant forests, capturing vegetation moisture metrics at 10-30 m spatial resolution and 5 nm spectral resolution. Operational data will be tested within data services such as the Australian Flammability Monitoring System (AFMS) that produces near real time landscape flammability indices continent-wide. In the longer term, OzFuel is envisioned to complement a host of planned satellite systems aimed at active fire detection. Pre Phase A study available here: https://inspace.anu.edu.au/activity/missions/ozfuel	Pre-Phase A is complete.	Australian National University, Geoscience Australia, CSIRO

CHICO (Cubesat Hyperspectral Imager for the Coastal Oceans)	CHICO is a visible light hyperspectral imager focused on the littoral environment (the land/water boundary in rivers/lakes and the ocean), designed for defence, civil and research applications. For defence it provides a standoff detection capability for denied areas (e.g. beach approaches and submerged structure classification, disaster management). CHICO's water quality monitoring capabilities are relevant to aquaculture, in-land agriculture, and coral reef health, providing insight to wider monitoring of the Australian marine environment (agricultural run-off, sedimentation). The project is focused on a 12U microsat formfactor, and is also compatible with a first-generation option deployed to the ISS within 2 years. The program is funded to deliver a preliminary design in June 2021, with funding for fabrication and deployment currently under negotiation. The imager will be self-calibrated through direct imagery and initially designed to monitor aquatic ecosystems at sufficient spectral resolution (~1-10 nm). Spatial resolution of ~30 m is achieved from LEO. There is an option to extend the visible light sensor to the shortwave infrared. The program shares many aspects of its design goals with the SmartSat-CSIRO AquaWatch initiative. Active development of CHICO would allow early field trials to inform the detailed design of the more extensive AquaWatch system.	Phase B	Australian National University, SatDek, Defence Materials and Technology Centre, CSIRO (including independent consultant Deakin University), Skykraft
Marine extreme detection and warning system	Marine heatwaves, tropical cyclones, storm surges, extreme ocean currents are becoming more frequent or extreme in a warming climate. High resolution sea surface temperature (microwave), surface winds (scatterometer), ocean current, and sea level measurements are crucial to detect these extreme events and to mitigate their impacts.		CSIRO with partners
SpIRIT CubeSat	SpIRIT is a 6U (~10kg) nano-satellite being developed in Australia through funding from the International Space Investment - Expand Capability scheme of the Australian Space Agency. SpIRIT, expected to be launched in 2022 and currently undergoing critical design (phase C), will carry on board a gamma and x-ray instrument provided by the Italian Space Agency which is similar in capabilities to NASA's Fermi Gamma Burst Monitor (GBM). While both SpIRIT and Fermi are primarily astrophysics missions, Fermi's GBM has been used innovatively by scientists to study terrestrial gamma-ray flashes associated to thunderstorms, shedding some light on a class of atmospheric events that are still poorly understood. The progress in miniaturisation technology, and the rapid timescale for nanosatellite development presents the opportunity to demonstrate in-orbit capabilities of SpIRIT for atmospheric science, and then to follow-up with a customised	Phase C	University of Melbourne, Inovor Technologies, Sitael Australia, Neumann Space, Nova Systems, Italian Space Agency

	future version of one or more low-cost nanosatellites hosting a multiple sensors for lighting and terrestrial gamma-ray flashes detection, including a gamma ray detector customised and optimised for Earth observations. This approach leverages existing R&D funding by the Australian Space Agency and offers novel opportunities to study weather events over large bodies of water surrounding Australia, where ground sensor coverage is more challenging.		
WildFireSat (WFS)	WildFireSat (WFS) has the objective to monitor all active wildfires in Canada from space on a daily basis. Overpasses will be in late afternoon, a time where there is currently a serious gap for this type of information. A WFS Pathfinder microsatellite is under development with a planned launch in 2026. The primary goal of WFS is to support wildfire management. In addition, it will provide information on smoke and air quality conditions, and accurately measure the carbon emitted by wildfires, an important requirement of international agreements on carbon reporting. The current Canadian WFS Pathfinder will be able to cover all Canadian territory every 3 days. While the mission does not include ground infrastructure outside Canada, it will have the ability to collect data over other parts of the world, and downlink this data directly in case these countries have ground infrastructure that can be used for this. Unique about the mission is the short delay in providing data products to the end-user. With antennas in view while passing over a country, collected data is expected to be delivered within 30 min. Canada is planning to assist countries that want to downlink the data, with the processing from raw data to end-products to ensure standardized, validated and calibrated end-products.	Phase B	Canadian Space Agency (CSA); the Canadian Forest Service (CFS), part of Natural Resources Canada (NRCan); and Environment and Climate Change Canada (ECCC). Keen to explore opportunities with Australian partners.
Ecometrica Space Programme	The Ecometrica Space Programme seeks to increase the accessibility, usefulness and continuity of satellite/sensor based information by connecting end user requirements to advanced applications of satellite data. Examples include (but are not limited to) applications for users in government, private companies and academia to monitor: protection and restoration of forests in 7 developing countries, impacts, risks and opportunities within commodity supply chains and physical assets against future climate risks. We have found that satellite/sensor derived data is often not mainstreamed into the workflows of the intended end users and sectors. There are myriad reasons for this: lack of technical expertise with processing satellite derived imagery, lack of digital		Ecometrica and funding partners: UK Space Agency, European Space Agency, UK PACT. Keen to explore opportunities with Australian partners.

	infrastructure to effectively share/disseminate satellite based information or a lack of commercial/business model to sustain and update insights for the long term. A space mission to support development of sensors/satellites to monitor meteorological/natural disaster risks and impacts would greatly benefit from a connection with the Ecometrica Space Programme to help tackle the 'last mile problem' of converting the outputs of upstream space hardware into useful applications for downstream end users.		
GNSS-Reflectometry for Soil Moisture Monitoring (GSMM)	Spire's Earth Intelligence GNSS-Reflectometry (GNSS-R) technique, with our GNSS-Radio Occultation payload, is a form of forward scattering bistatic radar using GNSS signals of opportunity to perform Earth surface scatterometry to obtain surface information relevant to meteorological and disaster resilience. These measurements include, but are not restricted to: • soil moisture • flood/wetlands mapping • ocean surface winds • sea ice height, classification and extent Using the example of bushfires, it is critical to obtain soil moisture data in order to prepare fire mitigation strategies, as well as to monitor post-event recovery. Water content in the soil affects the dielectric constant, which itself influences the reflection-coefficient to allow for beneficial measurements to be taken. With a growing constellation of over 120+ nanosatellites in LEO, Spire has the capabilities for data provision in order to accommodate recovery efforts through ongoing analysis of surface conditions. Additionally, Spire Space Services offers payload hosting to allow for additional capacity, with the ability to launch within a six month time window once the sensors have been prepared. Spire routinely collaborates with research, governmental and commercial organisations, and we would be looking to partner with Australian manufacturing and research institutions to further the impact of this potential project.	Spire platform is fully flight qualified with over 300 years of space flight heritage. The level of phase development of the project will depend on the project scope.	Spire Global Looking for partners in Australian Universities (research), CSIRO, BoM, other research institutions or agencies

GNSS Reflectometry (GNSS-R), such as existing NASA's CYGNSS mission and UK's planned HydroGNSS mission	Soil moisture and near surface winds estimates are important for studying and monitoring of climate extremes: droughts, tropical cyclones and floods; yet accurate and timely estimates of soil moisture and near surface winds are difficult to measure on a consistent and spatially comprehensive basis. CYGNSS mission will continue science operations through 2023. Its aim is to provide measurements of ocean surface winds, both globally and in tropical cyclones, which can be used to study meteorological processes and improve numerical weather forecasts. Over land, measurements of flood inundation and soil moisture are also continuously made, to be used in hydrological process studies and for disaster monitoring. HydroGNSS on the other hand has a 3 year launch schedule together with ESA. Australia should consider building and launching an Australian sovereign GNSS-R mission; and/or partner with other nations such as US, UK and Europe to deploy a global space mission for accurate soil moisture and near surface winds to enable accurate and timely measuring of droughts and tropical cyclones	Pre Phase A (for an Australian mission)	RMIT University

23 Appendix C: Bureau personnel survey: Ranking of missions

Eight Bureau personnel participated in a survey whose outcome was to rank in order of importance ten instruments/sensors with regard to their ability to impact on five criteria:

- Impact on weather predictions
- Create a secondary impact
- Address gaps in global observing system
- Strengthen key international partnerships
- Improve or deliver a sovereign industry capability

The participants were first asked to rank the importance of each of the five criteria with respect to each other. The results of this part of the survey are presented in Figure 4. This weighting is applied to the results of a rating exercise where the participants ranked a sensor's ability to fulfil each of the five goals. The ranking was a simple rating scale of 1 through 5. Five being the highest rating and 1 the lowest in terms of the ability of the sensor to meet a charter goal. For example, a sensor may have been ranked highly by all participants as making an important contribution to enhancing the Bureau's weather prediction capability but very low in terms of addressing gaps in the global observing system.

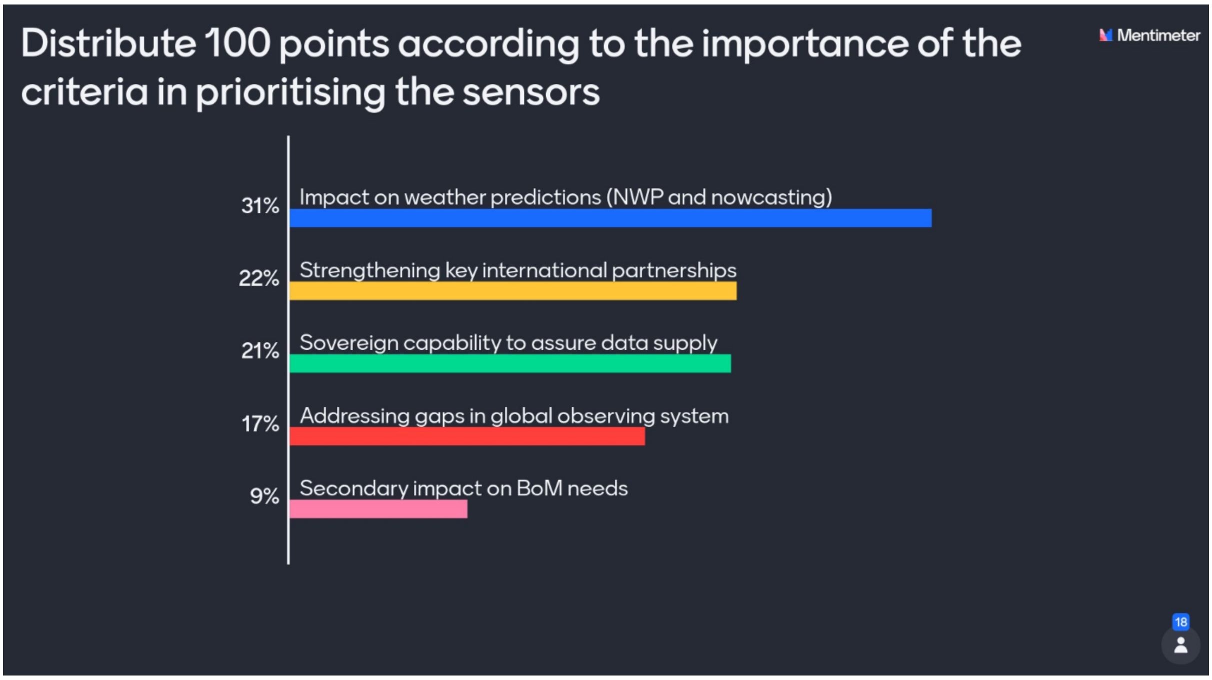

Figure 4 Rank ordered importance of the Bureau's goals

The result of this rating and the rank order of the ten instruments is presented in Table 26. The results indicated that the top three sensors are:

- lightning detection instrument,
- microwave sounder and
- SAR instrument for ice monitoring.

It was noted during the CDF study that the capability to deliver near real time data dissemination from Geostationary and LEO orbit was critical for operational meteorological applications, but beyond the scope of this study. This capability was not counted in the ranking which led to the selection of the three sensors discussed in Section 12.

Table 26 Mission/Instrument ranking and consideration for conceptual design

Criteria	Weight	Mission 1	Mission 2	Mission 3	Mission 4	Mission 5	Mission 6	Mission 7	Mission 8	Mission 9	Mission 10
		Real Time Vertical IR Soundings	Real Time Vertical MW Soundings and Radiances	Real time weather imaging	Extended observations of the Antarctic	Lightning observations	3D wind field (horizontal component)	Precipitation and clouds	Wave height, direction and period	Day Night VIS/SWIr Imaging	Real time data dissemination for large data volumes from GEO orbit
		Rating (Note)	Rating (Note)	Rating (Note)	Rating (Note)	Rating (Note)	Rating (Note)	Rating (Note)	Rating (Note)	Rating (Note)	Rating (Note)
Impact on weather predictions	***0.31***	5.00 Equal with Mission 2	5.00 Equal with Mission1	4.14	3.83	3.50	4.14	4.00	3.50	2.17	4.00
Secondary impact	***0.09***	2.00 Atmospheric pollution, volcanic ash (dep. On frequency)	3.25 Climate studies	3.57	3.17 SAR also valuable for tropical cyclones, soil moisture	3.00 Bushfires	1.86	2.86	2.00	2.83	3.00
Addressing gaps in global observing system	***0.17***	2.00 Assuming baseline resolution	2.63	1.14	4.83	3.33	4.14	3.71	3.67	2.17	2.14

Strengthening key international partnerships	***0.22***	1.00 Unrealistic to be provided from Australia to int'l partner	2.50	1.86	3.50	4.67	2.43	2.57	2.17	2.00	4.43
Sovereign industry capability	***0.21***	1.00	1.75	1.17	1.17	1.67	1.29	1.00	1.67	1.00	2.71
Total score **Criteria weighting* rating**		**2.5**	**3.2**	**2.4**	**3.3**	**3.3**	**3.0**	**2.9**	**2.7**	**1.9**	**3.4**
Rank		**8**	**4**	**9**	**2**	**3**	**5**	**6**	**7**	**10**	**1**

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