Suitcase Satellites: The rise of CubeSats and their impact on environment and climate monitoring in Australia

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Key words: CubeSat, Earth Observation, Environmental monitoring, Climate, Remote-sensing

SUMMARY

CubeSats are transforming Earth Observation (EO) for environmental and climate monitoring by providing a more accessible and complementary approach to traditional, large satellites. Their reduced costs, quicker development timelines, and ability to launch as secondary payloads have broadened participation in space-based EO. The increasing availability of Commercial-Off-The-Shelf components further contribute to easier development and deployment.

CubeSats are becoming increasingly valuable for monitoring Australia's vast and diverse environment, which faces challenges including bushfires, drought, Great Barrier Reef degradation, land degradation, coastal issues, biodiversity loss, and extreme weather. EO from CubeSats provides useful data for addressing these issues through payloads including multispectral, hyperspectral, thermal infrared and atmospheric sensors. It's important to note that sensor miniaturisation involves trade-offs, often resulting in limitations in spatial, spectral, and radiometric resolution compared to larger satellite systems.

CubeSat Constellations such as Planet Labs (Dove), GHGsat, Wyvern (Dragonette), OroraTech offer improved revisit frequency and broader spatial coverage, enabling more frequent global imagery, enhanced weather data, and greenhouse gas monitoring. Combining data from multiple constellations and integrating it with traditional satellite and ground-based data enhances the overall information available. The South Australian Kanyini mission demonstrates how a state funded initiative utilise CubeSat technology for addressing regional environmental challenges and building domestic space capabilities.

Advanced developments for CubeSat EO are focusing on integrating onboard Artificial Intelligence (AI) and edge computing for faster data analysis and reduced data transmission needs, Inter-Satellite Links (ISL) to improve data flow within constellations, advanced propulsion for better orbital control and longer missions, and ongoing improvements in sensor miniaturisation and performance. There is also a trend towards more specialised CubeSat constellations designed for specific environmental monitoring tasks.

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1. INTRODUCTION

The urgency of addressing climate change and environmental degradation necessitates timely, accurate, and global Earth Observation (EO) data. Traditional, large satellite missions have been instrumental but often face limitations in cost, revisit frequency, and accessibility. The demand for more frequent and spatially distributed data is growing rapidly to tackle environmental challenges effectively.

CubeSats represent a paradigm shift in the space sector, democratising access to space-based EO. They offer a unique and complementary approach to traditional EO infrastructure by enabling more frequent data collection, targeted missions, and enhanced spatial coverage through constellations. CubeSats are not just about miniaturisation; they are about making EO more accessible to a wider range of users and applications.

This paper explores the transformative role of CubeSats in EO for environment and climate. We will delve into:

- What CubeSats are and their fundamental components.
- How CubeSats operate for EO.
- The diverse range of payloads employed for environmental and climate monitoring.
- The factors that have lowered the barrier to entry in CubeSat development.
- Examples of existing CubeSat constellations and their applications.
- A case study of the South Australian Kanyini space mission.
- Challenges and future directions for CubeSat EO.

2. WHAT ARE CUBESATS?

2.1. Definition & Standardisation

CubeSats are standardised small satellites built in modular units (U) of 10x10x10 cm. This standardisation is key to their accessibility and cost-effectiveness. Common configurations range from 1U to larger sizes like 3U, 6U, and 12U, allowing for mission scalability and complexity. This modularity extends to subsystems and payloads, fostering interchangeability and faster integration.

2.2. Key Components

Despite their small size, CubeSats contain all essential satellite subsystems:

- **Structure:** Provides the physical framework and mounting for all components, typically made of lightweight aluminum alloys.
- **Power System:** Solar panels convert sunlight into electricity, stored in batteries to power the satellite during orbit, including during eclipse periods.
- **Communication System:** Antennas and transceivers enable command uplink from ground stations and data downlink from the satellite. Common bands include UHF, VHF, S-band, and X-band.
- **Attitude Determination and Control System (ADCS):** Determines the satellite's orientation in space using sensors (sun sensors, star trackers, gyroscopes) and controls it using actuators (reaction wheels, magnetorquers, thrusters – for precise pointing or orbit adjustments).
- **Payload:** The sensor(s) dedicated to EO, tailored to mission objectives. This is the "eyes" of the CubeSat.

The small size of CubeSats offers significant advantages:

- **Cost-Effectiveness:** Lower manufacturing costs due to simplified design, COTS components, and smaller scale.
- **Rapid Development Cycle:** The wide ecosystem of users and developers holds promise for more modular standards to emerge for CubeSat equipment, which would shorten development and integration times of reliable missions. This potential for rapid development is further enhanced in Australia, which benefits from readily available testing and qualification facilities specifically suited for CubeSat-sized spacecraft, a capability less easily accessible for larger satellites.
- **Piggyback Launch Opportunities:** CubeSats can be launched as secondary payloads on larger missions, significantly reducing launch costs and increasing launch frequency. Dedicated small satellite launchers are also emerging.

3. EARTH OBSERVATION: A CRITICAL TOOL FOR MONITORING AUSTRALIA'S ENVIRONMENT AND CLIMATE

EO technologies, including CubeSats, are becoming indispensable tools for understanding and managing the complex environmental and climate challenges facing Australia. As a vast continent with diverse ecosystems ranging from arid deserts to lush rainforests and extensive coastlines, Australia presents unique monitoring needs. EO provides the synoptic, consistent, and cost-effective data required to track environmental changes across this expansive and often remote landscape.

Australia is on the front lines of climate change impacts and faces a range of pressing environmental issues. These challenges are amplified by the continent's inherent variability and the increasing frequency of extreme events. Key areas where EO is proving invaluable include:

- **Bushfire Monitoring and Management:** Australia is highly susceptible to devastating bushfires. EO, particularly thermal infrared and multispectral imagery, plays a crucial role in all phases of fire management. Satellites can detect fire hotspots, map fire extent and severity in near real-time, monitor smoke plumes and air quality impacts, and assess post-fire vegetation recovery. This information is vital for early warning systems, fire suppression efforts, and long-term ecological restoration planning. CubeSats, with their potential for frequent revisits, can be particularly useful in rapidly evolving fire situations.
- **Drought and Water Resource Management:** Water scarcity is a persistent challenge in many parts of Australia, exacerbated by climate change and prolonged droughts. EO provides essential data for monitoring water availability. Multispectral and hyperspectral imagery can assess vegetation health and stress, which are indicators of drought conditions. GNSS Reflectometry and soil moisture sensors can directly measure soil moisture levels across large areas. Satellite data also helps monitor surface water extent in rivers and reservoirs, track water quality in inland and coastal waters, and manage irrigation efficiency in agriculture.
- **Great Barrier Reef Monitoring:** The Great Barrier Reef, a globally significant marine ecosystem, is under immense pressure from climate change, coral bleaching events, and water quality degradation. EO is critical for monitoring the reef's health at scale. Multispectral and hyperspectral imagery can detect coral bleaching, map coral reef habitats, monitor water turbidity and sediment plumes, and track algal blooms. This data supports reef management efforts, informs conservation strategies, and helps assess the effectiveness of interventions.
- **Land Degradation and Desertification:** Vast areas of Australia are susceptible to land degradation, including soil erosion, vegetation loss, and desertification. EO is essential for monitoring land cover change, detecting vegetation degradation, assessing soil health, and tracking the expansion of arid and semi-arid areas. Multispectral and hyperspectral data can identify areas at risk, monitor rangeland condition, and assess the effectiveness of land management practices aimed at combating degradation and promoting sustainable land use.
- **Coastal Zone Management and Sea-Level Rise:** Australia's extensive coastline is vulnerable to erosion, inundation, and the impacts of sea-level rise. EO provides vital information for coastal monitoring. Multispectral imagery can track coastal erosion, map intertidal zones and mangrove ecosystems, and monitor water quality in coastal areas. This data is crucial for coastal planning, infrastructure development, and adaptation strategies to sea-level rise.
- **Biodiversity Monitoring:** Australia is a biodiversity hotspot, but faces significant biodiversity loss due to habitat destruction, invasive species, and climate change. EO can assist in monitoring biodiversity at landscape scales. Hyperspectral and multispectral imagery can map vegetation types and habitats, track deforestation and

habitat fragmentation, and monitor changes in vegetation phenology. This information supports conservation planning, helps track the effectiveness of protected areas, and informs strategies for biodiversity preservation.

- **Extreme Weather Event Monitoring:** Australia experiences a wide range of extreme weather events, including cyclones, floods, and heatwaves. EO plays a crucial role in monitoring these events and their impacts. Satellite imagery can map flood extent, track cyclone paths and intensity, monitor heatwave impacts on vegetation and urban areas (using thermal infrared), and assess damage after extreme events. This data supports disaster response, early warning systems, and climate change adaptation planning.

3.1 Unique Local Challenges and EO Solutions

Australia's vastness and remoteness present particular challenges for environmental monitoring. Traditional ground-based monitoring can be expensive and logistically difficult across such large and sparsely populated areas. EO, especially from CubeSat constellations offering increased revisit frequency and broader spatial coverage, becomes a highly efficient and cost-effective solution. Furthermore, Australia's diverse ecosystems and unique flora and fauna require tailored monitoring approaches. The spectral richness of hyperspectral EO data, for instance, can be particularly valuable for discriminating between subtle vegetation types and monitoring the health of specific ecosystems unique to Australia.

Various Australian initiatives and research programs are actively utilising EO data for environmental and climate monitoring, including national programs for bushfire monitoring, water resource management, and Great Barrier Reef health assessment. The Kanyini mission, as discussed earlier, exemplifies Australia's commitment to leveraging CubeSat technology for addressing local environmental challenges.

4. HOW CUBESATS WORK FOR EARTH OBSERVATION

4.1 Orbit and Operation

CubeSats are typically deployed into Low Earth Orbit (LEO), ranging from a few hundred to around 700 km altitude. LEO provides good spatial resolution for EO sensors and allows for relatively frequent revisits as the satellite orbits the Earth every 90-100 minutes. Operational lifetime varies but is generally increasing, from months to several years, depending on mission design and orbit.

4.2 Data Acquisition Process

CubeSats collect EO data using their onboard payloads. For imaging payloads (multispectral, hyperspectral, thermal), this involves:

- **Targeting:** Maneuvering the satellite (using ADCS) to point the sensor towards the desired area on Earth.

- **Sensor Activation:** Activating the sensor and initiating data acquisition as the satellite passes over the target area. This can be line-by-line scanning (pushbroom) or frame-based imaging.
- **Data Storage:** Temporarily storing the acquired raw data onboard the CubeSat. For other payload types (GNSS-R, atmospheric sensors), the data acquisition process is tailored to the sensor's measurement principle (e.g., receiving reflected GNSS signals, or measuring atmospheric spectral absorption).

4.2 Data Downlinking

CubeSat's typically can't support enough data download to be full-time monitoring imaging systems like large satellite. Rather they are most commonly tasked intermittently throughout their orbits for specific targets of interest. Once data is acquired and stored, it needs to be transmitted to ground stations:

- **Ground Station Network:** Missions utilise ground station networks strategically located around the world to maximise downlink opportunities.
- **Downlink Scheduling:** Downlink passes are scheduled when the CubeSat is within the communication range of a ground station.
- **Data Transmission:** Data is transmitted using the communication system to the ground station antenna.

4.3 Data Processing

Raw data received at ground stations is not directly usable. Essential data processing steps include:

- **Calibration:** Correcting for sensor imperfections and biases.
- **Geometric Correction:** Removing distortions and accurately georeferencing the data.
- **Atmospheric Correction:** Reducing atmospheric effects to retrieve surface reflectance or other geophysical parameters.
- **Data Product Generation:** Creating user-friendly data products (e.g., orthorectified images, spectral indices) that can be used for environmental analysis and applications. Software and algorithms are crucial for efficient and automated data processing pipelines.
- **Validation:** Assessing the quality and accuracy of the processed data products. This involves comparing the data against independent and reliable sources of information, such as ground-based measurements, airborne data, or data from well-validated larger satellite missions. Validation is critical to ensure the data is fit for purpose and to quantify its uncertainties for users.

5. PAYLOADS FOR ENVIRONMENTAL AND CLIMATE EO

5.1 Multispectral & Hyperspectral Imaging

Multispectral and hyperspectral imagers represent essential payloads for environmental monitoring applications. Functionally, multispectral imagers acquire data within a limited number of discrete spectral bands, typically spanning the visible, ear-infrared, and shortwave infrared regions of the electromagnetic spectrum. In contrast, hyperspectral imagers capture data across a broader spectral range, utilising hundreds of contiguous, narrow bands. These instruments facilitate a diverse array of applications, including vegetation health monitoring through indices such as NDVI, land cover classification for mapping forests, agriculture, urban areas, and water bodies, and water quality assessment by quantifying parameters like chlorophyll-a, turbidity, and sediment concentration. Furthermore, they are employed in precision agriculture for monitoring crop stress and nutrient levels, forestry management for tracking deforestation and assessing forest health, and disaster response for applications such as flood mapping and damage assessment. Examples of sensors commonly used in CubeSat platforms include pushbroom scanners, filter-based imagers, and miniature hyperspectral imagers, such as those based on acousto-optic tunable filters (AOTF).

5.2 Thermal Infrared Sensors

Thermal infrared sensors are employed to detect thermal radiation emitted from the Earth's surface. Their primary functionality is to measure temperature within the infrared spectrum. Applications of these sensors are multifaceted and include surface temperature monitoring, encompassing land surface temperature and urban heat island analysis, as well as wildfire detection and monitoring through hotspot identification and fire spread tracking. They are also utilised in volcanic activity monitoring for detecting thermal anomalies, evapotranspiration studies for water balance assessments, and ocean surface temperature mapping to determine sea surface temperature distributions. Uncooled microbolometers are frequently used in CubeSats due to their suitability for size and power constraints, while cooled detectors, offering higher performance, are more complex to implement in these platforms.

5.3 Atmospheric Monitoring Sensors

Atmospheric monitoring sensors are designed to measure the composition of the atmosphere. These instruments, which include spectrometers and gas analysers, operate by measuring the absorption or emission of light by atmospheric gases. Applications encompass greenhouse gas monitoring, targeting gases such as $CO2$, methane, and $NO2$, a capability that is becoming increasingly feasible for CubeSats despite inherent challenges. They are also used for air quality monitoring, detecting ozone, aerosols, and various pollutants, and for atmospheric profiling, determining temperature and humidity profiles through techniques like radio occultation. Examples of sensors utilised for atmospheric monitoring include Non-Dispersive Infrared (NDIR) sensors, UV/VIS spectrometers, and GNSS radio occultation receivers.

6. SENSOR MINIATURISATION

CubeSat Earth Observation packs powerful sensing into small packages, but miniaturisation balances sensor performance against size, weight, and power. Understanding these trade-offs reveals both the potential and limitations of CubeSat EO data.

6.1 Spatial Resolution Limits

CubeSat sensors use smaller optics, resulting in lower spatial resolution compared to larger satellites. Early CubeSats had resolutions in tens of meters, versus sub-meter for large satellites. However, smarter integration of optic systems is rapidly improving resolutions to a few meters, sometimes even approaching one meter. This is sufficient for many environmental applications, especially with enhanced temporal resolution from constellations.

6.2 Spectral Resolution Challenges

Hyperspectral sensors, complex instruments analysing light across many bands, face miniaturisation challenges in CubeSats. Trade-offs include fewer spectral bands, wider bandwidths, or limited spectral range. Despite this, CubeSat hyperspectral technology is advancing, offering valuable and accessible spectral data for frequent environmental monitoring, even if not always matching larger systems in spectral richness.

6.3 SNR Considerations

Smaller sensors collect less light, leading to a lower Signal-to-Noise Ratio (SNR) and potentially noisier images affecting analysis accuracy. CubeSat missions mitigate noise through optimised integration, low-noise detectors, and data processing. Constellations also improve SNR by averaging data from multiple observations, reducing random noise.

6.4 Accuracy and Calibration

Achieving high accuracy in CubeSats is challenging due to less stable platforms and limited onboard calibration resources. Constellations and advanced data processing are key. While individual CubeSats might have slightly lower absolute accuracy, constellations offer superior temporal accuracy for tracking rapid changes, crucial for environmental monitoring. Data fusion and geometric correction further enhance data usability.

7. DEMOCRATISATION OF SPACE: LOWERING BARRIERS TO ENTRY

The democratisation of space, particularly within the CubeSat domain, is significantly enabled by several key factors. Firstly, standardisation, embodied by the CubeSat specification itself, is paramount. This extends beyond the basic form factor to the increasing availability of Commercial-Off-The-Shelf (COTS) components for all essential satellite subsystems, including power, communication, attitude determination and control (ADCS), and onboard computers. The utilisation of COTS components has demonstrably reduced development costs, as these parts are significantly more economical than custom-designed, space-grade hardware. Furthermore, the simplified integration facilitated by COTS components shortens development cycles, compressing typical timelines to only a year or two. This streamlined approach and more modest missions also lowers the level of complexity required for fundamental CubeSat missions, broadening the range of institutions and organisations capable of engaging in space activities.

Secondly, commercialisation and commoditisation of CubeSat launch opportunities has fundamentally altered access to space. No longer reliant solely on national space agencies, CubeSat developers can leverage commercial launch providers offering diverse options. Rideshare or piggyback launches, where CubeSats are deployed as secondary payloads on larger missions, substantially reduce launch expenses. Dedicated CubeSat deployment dispensers further facilitate this approach. Concurrently, the emergence of companies developing launchers specifically tailored for small satellites provides more flexible launch scheduling and orbit selection. The overall effect is an increased launch frequency, making space access more readily available and less constrained.

Thirdly, the burgeoning open-source ecosystem represents a significant factor in the evolution of CubeSat development. This is evidenced by the increasing accessibility of open-source software solutions, encompassing operating systems, flight software, ground station control systems, and data processing tools, all distributed under open licenses. While this trend demonstrably reduces initial software development expenditures and fosters collaborative development efforts, it is pertinent to acknowledge potential trade-offs, particularly regarding flight software reliability and performance. As is commonly understood, resource allocation often correlates with outcome quality; consequently, the adoption of open-source flight software may necessitate a degree of compromise in these critical operational parameters. However, a defining characteristic of the contemporary CubeSat sector is the considerably reduced overall mission cost. This diminished financial barrier facilitates a paradigm shift towards a higher risk tolerance at the individual satellite level. Rather than prioritising highly sophisticated, long-duration, and costly satellite systems, the prevailing strategy is evolving towards iterative development cycles and increased mission frequency. This approach prioritises accelerated innovation and knowledge acquisition, acknowledging the potential for shorter operational lifespans of individual satellites, while the overarching program benefits from continuous improvement and an accelerated pace of technological advancement.

Finally, university and research programs play a crucial role in democratising space. CubeSat projects serve as exceptional platforms for education and training, providing students with hands-on experience in space engineering, remote sensing, and data science, thereby cultivating the next generation of space professionals. Universities are also at the forefront of research and innovation in CubeSat technology, pushing the boundaries of miniaturisation, novel payload development, and innovative mission concepts. Critically, CubeSats make space research accessible to university departments with limited financial resources, fostering scientific discovery and technological progress across a wider academic landscape.

8. EXISTING CUBESAT CONSTELLATIONS FOR ENVIRONMENT AND CLIMATE

8.1 Planet Labs (Dove Constellation)

A massive constellation of hundreds of Dove CubeSats providing daily global imagery.

- Capabilities: Multispectral imagery, high revisit frequency (daily), global coverage.
- Applications: Agriculture monitoring, deforestation mapping, urban change analysis, disaster response, environmental monitoring at scale. Enables time-series analysis of environmental changes.

8.2 GHGSat (GHGSat constellation)

Constellation dedicated to greenhouse gas monitoring.

- Capabilities: High-resolution methane monitoring from space.
- Applications: Tracking methane emissions from industrial facilities, oil and gas infrastructure, landfills, agriculture. Crucial for climate action and emissions reduction efforts.

8.3 Wyvern (Dragonette constellation)

Constellation dedicated to unlocking hyperspectral information.

- Capabilities: Hyperspectral imagery with high spatial resolution (5.3m), rapid revisit rates with constellation deployment, focus on spectral richness for detailed analysis.
- Applications: Agriculture and forestry management, mining and resource exploration, environmental monitoring and conservation, urban and infrastructure analysis. Designed to provide accessible and actionable hyperspectral data for a range of commercial and scientific users.

The satellite industry is witnessing a surge in companies, including OroraTech, that are moving beyond individual satellite mission. These organisations, whether in the design phase or already operational, are increasingly pursuing constellation architectures for their technologies.

8.1 Data Integration

The utility of CubeSat constellations is significantly augmented through strategic data integration. Firstly, combining data streams from multiple CubeSat constellations, such as Planet Labs yields a more holistic and comprehensive understanding of Earth system processes. This synergistic approach allows for the aggregation of diverse datasets, capturing a broader range of spatial, spectral, and temporal information. Secondly, data fusion with traditional satellite platforms is crucial. CubeSat data can effectively complement data acquired from larger, high-resolution satellites like Landsat and Sentinel. This integration addresses limitations in temporal and spatial coverage inherent in individual systems, providing a multi-scale perspective and filling observational gaps. Finally, integration with in-situ data sources is essential for validation and enhanced analysis. Combining satellite-derived information with ground-based sensor networks, drone-acquired data, and other terrestrial measurements results in a richer, more robust, and critically, a validated dataset, significantly strengthening the basis for environmental analysis and informed decision-making.

9. CASE STUDY: KANYINI – SOUTH AUSTRALIAN SPACE MISSION

9.1 Australia's NewSpace Frontier and Regional Capability Growth

Within the rapidly evolving global space sector, fuelled by the NewSpace economy's innovation and accessibility, Australia is strategically developing its national space capability. A key focus is establishing sovereign EO assets to address critical national challenges such as environmental monitoring and disaster management. Historically reliant on international EO data sources, Australia is now taking initial steps towards domestic investment to enhance data security and develop tailored regional solutions. South Australia's Kanyini mission, the state's first government funded satellite, serves as a trailblazing example of this emerging approach. Kanyini demonstrates the potential for regional space capability development and, if successful, could pave the way for emulation by other states and potentially inspire a larger-scale, nationally coordinated effort in the future. This pioneering mission contributes to industry growth and fosters valuable international collaborations.

9.2. Mission Overview

Spearheaded and program-managed by SmartSat CRC, and funded by the South Australian Government, Kanyini is a 6U CubeSat launched in August 2024 on a SpaceX Falcon 9. Designed and operated in South Australia, this mission is crucial to building Australia's sovereign EO capability, acting as a foundational step in this national undertaking. SmartSat CRC architected the Kanyini mission in collaboration with the SA Government, Myriota and Inovor Technologies, and is responsible for integrating, managing, and operating the EO payload. This includes a Cosine HyperScout 2 hyperspectral imager with onboard AI for image processing, and a Myriota IoT payload. Inovor Technologies built and are responsible for the operations of the Apogee 6U CubeSat bus. Currently undergoing commissioning and projected to operate for 3 years, Kanyini will provide valuable EO data and serve as a vital platform for technology development. Crucially, SmartSat CRC is also funding and leadingll research associated with Kanyini, encompassing both downstream applications and onboard processing. This includes research projects architected and brought to the SA Government by SmartSat. Furthermore, SmartSat's Scarlet Lab is developing the essential software and hardware environments to rigorously test the onboard AI networks, ensuring mission success.

9.3. Technological Innovation: Hyperspectral Imaging and Onboard AI for Edge Processing

Kanyini integrates advanced EO technologies, featuring the HyperScout 2 instrument with VNIR and TIR hyperspectral channels for detailed land and water analysis and thermal monitoring. It also incorporates Onboard AI-Driven Edge Computing with a Myriad-2 AI board, enabling data processing in orbit to reduce downlink needs and latency, and allowing for payload autonomy. A Myriota IoT Payload expands data acquisition beyond EO sensors, enhancing integrated environmental monitoring and building on the constellation of Myriota IOT satellites

9.4. South Australian Expertise and Collaborative Ecosystem

The Kanyini mission showcases South Australia's growing space sector and collaborative partnerships. It leverages local strengths, with Inovor Technologies building the Apogee satellite bus, demonstrating sovereign manufacturing capability. SmartSat CRC led payload integration, combining international technology (HyperScout 2) with local expertise. South Australian universities are involved in data processing and AI algorithm development. The SA Government's funding and end-user role highlight space's contribution to economic and societal benefits, with pilot projects using Kanyini data for regional challenges like heatwave monitoring.

9.5. Impact and Significance: Local, National, and Global Dimensions

The Kanyini mission is anticipated to have impacts across local, national, and global dimensions.

9.5.1. <u>Local Impact for South Australia</u>

Within South Australia, Kanyini is anticipated to support natural resource and environmental management. Hyperspectral data is intended to improve resource monitoring, exemplified by the SAEcoMap project mapping vegetation and species, with data informing land management and biodiversity efforts. Environmental monitoring is also a focus, with the Heatwaves project using thermal imagery for urban heat island analysis to potentially aid public health planning. Kanyini is also expected to contribute to technology development and job creation in the South Australian space sector, providing opportunities for scientists and engineers and supporting AI and hyperspectral data analytics research.

9.5.2. <u>Broader Significance and Global Reach</u>

Beyond its local impact, Kanyini holds broader significance by demonstrating the capability of smaller entities to undertake space missions, potentially serving as a model for regional space development and increasing space accessibility. The mission fosters international collaboration through partnerships like ESA Phi-Lab, and its EO data is expected to contribute to the global scientific community. Ongoing research includes cross-calibration with other missions to maximise data value. Kanyini's development process and collaborative approach may offer a blueprint for regional space initiatives worldwide.

9.6. Early Applications and Pilot Projects: Exploring Practical Applications

Kanyini is facilitating research and development activities. Pilot projects, some funded by the South Australian Government, are designed to explore the potential applications of Kanyini data. These projects include:

- Heatwaves Project (SmartSat CRC, Flinders University and SA Department of Environment and Water): Developing a satellite-based monitoring system for land surface temperatures (LST) using Kanyini's thermal imagery. This project aims to provide regular and timely data on urban heat islands, potentially offering a supplement to existing airborne surveys. It explores the utility of tasking a dedicated space asset like Kanyini for targeted data acquisition during heatwave events.
- SAEcoMap Project (SmartSat CRC, University of Adelaide and Department of Primary Industries and Regions, South Australia): Using Kanyini's hyperspectral VNIR data to map native vegetation communities and key species across South Australia. This project involves comparing Kanyini's performance against drone and ground-based assessments, as well as data from other satellites, including Sentinel, Landsat, EMIT, PRISMA, and PACE, for cross-calibration and data fusion. The primary aim is to develop processing pipelines for vegetation mapping, aligning with government objectives for biodiversity monitoring and carbon sequestration. This project also focus on bushfire post-recovery in Kangaroo Island and forestry applications related to water stress.
- Coral and Seagrass Mapping Project (SmartSat CRC, University of Queensland, University of Adelaide, Commonwealth Scientific and Industrial Research Organisation, South Australian Water Corporation, Department for Environment and Water): Investigating the capabilities of hyperspectral sensors, including Kanyini, for mapping live coral cover and seagrass species composition in marine environments. This research project is focused on developing AI and machine learning models to differentiate these habitats using hyperspectral data, with the goal of contributing to improved marine ecosystem monitoring and conservation efforts.
- Energy-efficient on-board AI processing of hyperspectral imagery for early fire-smoke detection (University of South Australia, Swinburne University, Geoscience Australia): The project aims to develop AI algorithms for Kanyini's HyperScout-2 instrument that can efficiently detect fire smoke directly on the satellite, addressing limitations in onboard computing power and data downlink.

9.7. Broader Value Beyond Research Outputs

While the research outputs from Kanyini are anticipated to be valuable, the mission also has broader value beyond scientific publications. Kanyini has contributed to the development of South Australia's space technology capabilities across areas such as satellite design, manufacturing, payload integration, data processing, and mission operations. The mission has supported workforce growth and development, providing jobs and training opportunities. Furthermore, Kanyini provides a demonstration of South Australian space industry capabilities, potentially attracting investment and supporting sector growth. Crucially, Kanyini has also placed the South Australian Government in a better position, equipping it with valuable experience as an informed end-user of space data and enhancing its understanding of the complexities inherent in space mission design. The mission may also contribute to commercial opportunities in EO data services, onboard AI solutions, satellite manufacturing, and related space technologies. Finally, Kanyini has facilitated international collaboration, strengthened partnerships and potentially supporting technology transfer and collaborative research ventures.

10. CHALLENGES AND FUTURE DIRECTIONS

While CubeSat Earth Observation has demonstrated remarkable progress, several challenges remain alongside promising future directions. Current technological limitations include constraints on sensor resolution (spatial, spectral, and radiometric) imposed by size, power, and cost considerations. Historically, mission lifetimes have also been shorter compared to larger satellites, although advancements in component reliability and orbit control are extending operational durations. Furthermore, limited onboard processing power restricts complex data analysis in space, creating a reliance on ground-based processing, though edge computing capabilities are emerging to address this.

Beyond technological constraints, data volume and management present significant challenges. CubeSat constellations generate vast datasets, leading to a data downlink bottleneck due to bandwidth limitations. Efficient data processing and storage infrastructure are thus critical, requiring scalable pipelines to handle the influx of information. Ensuring data accessibility and distribution to a wide range of users remains crucial to maximise the societal benefit of CubeSat EO.

However, the future trajectory of CubeSat EO is marked by exciting advancements poised to overcome these limitations and unlock enhanced capabilities. Artificial Intelligence and edge computing are central to this evolution. Embedding sophisticated processing power onboard CubeSats will enable real-time data analysis, feature extraction, and anomaly detection directly in orbit. This onboard intelligence promises to dramatically reduce downlink data volume, accelerate insight generation, and facilitate more autonomous and responsive satellite operations.

Inter-Satellite Links (ISL) represent another transformative technology. By enabling direct communication between CubeSats, ISL creates mesh networks in space, reducing reliance on ground stations and facilitating faster data relay, especially from remote regions. This interconnectedness will enhance constellation coordination, optimise tasking strategies, and improve data availability for time-critical applications.

Advancements in advanced propulsion systems are also crucial. Innovations in electric and chemical propulsion are providing CubeSats with enhanced orbital control. This newfound agility will extend mission lifespans through orbit maintenance, improve pointing accuracy for better data quality, and enable tailored orbits for specific monitoring objectives. Looking further, advanced propulsion may even facilitate CubeSat missions beyond Earth orbit.

Continued progress in sensor miniaturisation and performance is fundamental. Breakthroughs in detectors, optics, and microelectronics are leading to smaller, lighter, and more power-efficient sensors with enhanced resolution, sensitivity, and spectral capabilities. This relentless advancement is narrowing the performance gap between CubeSat instruments and traditional satellite sensors, expanding the range of addressable applications.

Finally, a trend towards specialised CubeSat missions is emerging. Future constellations are likely to be increasingly tailored for specific environmental monitoring tasks, such as high-resolution air quality monitoring, biodiversity assessment, or targeted greenhouse gas emission detection. This specialisation will allow for optimised sensor design, data processing, and mission operations, maximising the effectiveness of CubeSat EO in addressing specific environmental and climate concerns.

11. CONCLUSION

CubeSats are transforming Earth Observation for environment and climate. They offer unprecedented accessibility, affordability, and rapid deployment capabilities. Their constellation approach provides increased spatial and temporal coverage, generating valuable data for environmental monitoring, climate change studies, and resource management.

CubeSat technology is democratising access to space-based EO, empowering a wider range of users, from researchers and governments to NGOs and businesses, to utilise EO data for informed decision-making and sustainable development. They are crucial for achieving Sustainable Development Goals related to environment and climate.

The CubeSat sector is characterised by continuous innovation and rapid advancements. The future is bright for CubeSat-based Earth Observation, with ongoing developments promising even more powerful and versatile capabilities for understanding and protecting our planet. We are entering a new era where space-based environmental monitoring is more accessible, frequent, and impactful than ever before.

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Fabrice MARRE is a seasoned senior Earth Observation Specialist at SmartSat CRC (Australia), bringing over two decades of geospatial industry expertise. His diverse background includes leadership roles in R&D, 3D technologies, and AI product management within Australian geospatial companies, alongside experience as a Remote Sensing Engineer at IRD (France). Fabrice's core expertise lies in spatial data analysis, computer vision, remote sensing, photogrammetry, and GIS. Fabrice holds degrees in Remote-Sensing and Image processing (Master's – Toulouse, France), Electric Engineering, Computer Science and Telecommunications (Bachelor's).

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