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Binar Space Program: Mission Two Payloads and Operations Plan

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ABSTRACT

The second mission of Western Australia's Binar Space Program consists of three 1U CubeSats targeting a 2023 launch. Aiming to improve the platform for future missions, the primary purpose of Binar 2, 3 and 4 is on-orbit testing of radiation shielding alloys developed by CSIRO. In this first-of-its-kind experiment, all three simultaneously deployed Binar spacecraft will contain radiation sensing payloads to assess the efficacy of various compositions of Australian made radiation shielding alloys. Alongside this, hardware changes to the Binar platform are discussed, including deployable solar arrays, additional communications solutions, and a removable payload bay. The Iridium network will be leveraged to test its suitability for CubeSat targeted re-entry. Several software-based payloads are implemented, including on-board hardware emulation, enabling an industry partner to control the spacecraft in a demonstration of remote operations capability. An undergraduate student lead project will continue on from Binar-1 to see a star tracker flown for testing alternative methods of attitude determination. From a community perspective, strengthening the engagement between amateur radio operators and the Binar Space Program will be explored by expanding on what amateurs can do with on-orbit satellites. Lastly, autonomous agile mission planning will be tested through an on-board multipurpose simulation running on the dual-core flight computer.

Introduction

The Binar Space Program was conceived as an engineering undergraduate honours project at Curtin University in 2018. The initial scope of the project was to purchase COTS subsystems from satellite manufacturers to assemble Western Australia's first spacecraft. It became evident however that this could hinder the Program in three areas: cost, size and subsystem limitations. Due to this, the scope of the Binar Space Program shifted towards in-house development of spacecraft subsystems. Three years later in 2021, Binar-1 was launched into Low Earth Orbit in what was the first flagship mission of the Space Science and Technology Centre at Curtin University. Leveraging the high reusability of the Binar platform, the Binar Space Program is already developing the next iteration of CubeSats: Binar-2, 3 and 4. Deployed simultaneously from the International Space Station, the three 1U satellites will be carrying various payloads for experimentation in Low Earth Orbit.

The design of the mission two satellites and the payloads flown are heavily biased towards platform development of the Binar CubeSat, supporting future missions from the Space Science and Technology Centre. This paper will provide an overview of the mission two satellites, detailing the areas that differ from the Binar-1 CubeSat design, namely the development of deployable solar panels; a custom communications solution comprising UHF, Iridium and S-band; and a removable payload bay. It will then discuss the hardware and software payloads being flown; the former comprising an undergraduate student built star tracker and an in-house designed radiation sensor, and the latter a robotic arm emulator and an autonomous agile mission planning software tool. Alongside its usage as a form of communication with the CubeSat, the Iridium module is also discussed as a tool for tracking the satellite as it re-enters the atmosphere at the end of life. Finally, a brief concept of operations is given for the three satellites, detailing the mission timeline.

CubeSat Overview

Binar-2, 3 and 4 are three 1U CubeSats planned for a 2023 launch through the JAXA launch broker SpaceBD. Deploying simultaneously from the International Space Station, the three spacecraft will be inserted into a 400 km altitude, 51 degree inclined mission orbit. The spring assisted deployment method will see the three spacecraft slowly separate over the mission lifetime. Continuing with a strong focus on platform development for future reuse, Binar-2, 3 and 4 will extend upon Binar-1 to feature deployable solar panels, a custom communications system, and a removable payload bay, seen in Figure 1.

At the centre of the satellite (3) is the Binar CubeSat Core, a highly integrated custom circuit board that comprises a primary and redundant flight computer, a Global Positioning System (GPS), Attitude Determination and Control System (ADCS) (Magnetorquer based, 1), on-board storage and Electric Power System (EPS) in a 0.25U stack. The 1U frame is surrounded by solar cells, both face mounted (4), and deployable (2). Finally, at the base of the satellite is the removable payload bay (6), housing the radiation sensing primary payload (5).

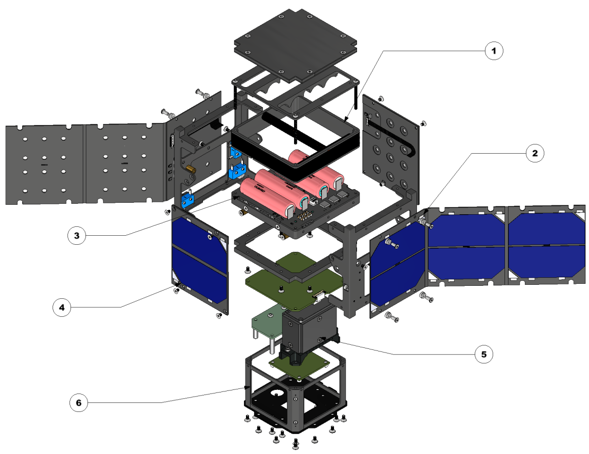

Figure 1: Exploded render of the mission two satellite design with key sections detailed.

Deployable Solar Panels

To satisfy the power budget for Binar 2, 3 and 4, additional solar cells need to be added to the existing 1U form factor. A deployable solar array system is implemented for the mission to meet current power requirements and to develop the in-house capability for supporting future missions with deployable arrays. The deployable solar array will have a chassis mounted panel that is attached to the mission two spacecraft in the same manner as the surface mounted cells on Binar-1, with the addition of two panels attached in series via rigid-flex PCBs on either side of the spacecraft, shown in Figure 2.

The deployable arrays will be held in a stowed configuration by burn wires, which when severed will allow for unfolding to occur. The primary actuation method for unfolding the solar panels will be nickel-titanium shape memory alloy. Compliant actuation was chosen due to its size, mass, and power efficiency, and also due to a reduced part count over classical actuation methods.

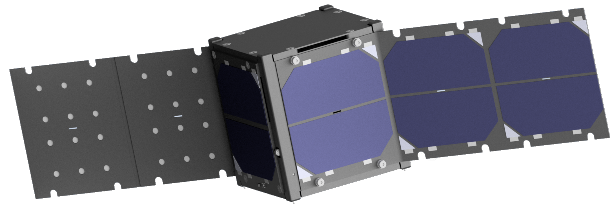

Figure 2: Render of the mission two spacecraft design with solar panels deployed.

Custom Communications Solution

Due to time restrictions and a lack of communications experience in the Binar Space Program, a COTS communications system was used on Binar-1. However, the solution purchased was very large, lacked redundancy, a repeatable deployment system, and had a black box software package and hardware design that was not easily modified to meet launch requirements. The integration issues that followed hindered some functionality of the spacecraft. Based on experiences from Binar-1, a custom communications solution has been developed for the mission two satellites that integrates three communication methods. The integrated system will contain a UHF, Iridium, and S-Band based communications system. The primary communications method will be the planar monopole deployable UHF. Based off of the OpenLST design, components used in the UHF solution have flight heritage. The UHF communications solution will operate in the amateur frequency band, satisfying our requirement for community engagement. The Iridium solution offers a much higher communications availability in comparison, not requiring the spacecraft to be over a ground station for communications. S-Band will be trialled for the mission as a test platform for future missions with higher data throughput requirements. A custom communications solution guarantees meeting requirements, and facilitates testing during the full mission life cycle. Moreover, a custom communications solution can be developed to efficiently use the space inside the spacecraft frame, increasing the space reserved for payloads.

Passionate about generating excitement for the space industry, the Binar Space Program plans to leverage the amateur radio platform on the mission two satellites to expand on what amateurs can do with spacecraft on-orbit. Conforming to the basic requirements of using the amateur radio band, the spacecraft will frequently generate data on a frequency accessible to radio amateurs, allowing them to design and build their own ground stations to listen to Binar-2, 3, and 4 as they pass overhead. For amateurs that have a license to transmit, the CubeSats will also allow amateurs to send packets of data for temporary storage to be recalled later. Due to the importance of the SatNOGS network in locating Binar-1, these amateurs are encouraged to link their ground stations into the SatNOGS network to listen to other satellites, and to recall their stored data packets from other ground stations around the world.

Removable Payload Bay

The payload bay is designed to provide a separation between the core spacecraft systems and the experiments being flown, adding abstraction and removing hardware-enforced links between the core bus and payloads. This removes the need for the Binar CubeSat Core to be modified for each launch. This will ensure the Binar bus can be tested, verified and locked into a working design that can be reused for future launches. The addition of the payload bay enables payloads to be assembled and tested separately to the main CubeSat to ensure functionality before being integrated into the core system. This design choice was influenced by the BinarX program, which will see Western Australian school students developing payloads to be flown on Binar spacecraft.

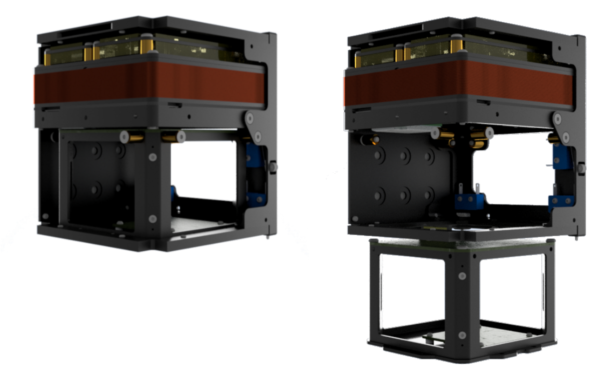

Figure 3: Render of the payload bay in the stowed and removed configuration.

The payload bay is designed to be a rigid unit that is inserted into the CubeSat from below. It interfaces with the spacecraft motherboard through a custom designed payload adaptor PCB that mates with the motherboard when inserted into the CubeSat frame. Each individual payload will connect to the payload adaptor board using a locking cable connector. The following section provides details about the payloads that will be flown in the payload bay on the Binar-2, 3 and 4 missions.

Payload Design

Radiation Detection

The primary objective of the Binar-2, 3 and 4 satellites is on-orbit testing of radiation shielding alloys developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). It is well understood that spacecraft in orbit around Earth are subject to radiation originating from the Sun. The Earth's magnetic field traps electrons, protons and heavy ions in common spacecraft orbits, and radiative particles are also known to traverse through these orbits.[1] As spacecraft move further away from the protection Earth provides from ionisation radiation, the dosage increases.

The electronics that enable spacecraft are susceptible to the detrimental effects of the radiation present in space. Total radiant exposure and time-dependent radiant flux are two major areas spacecraft electronics are susceptible to.[1] In high risk components such as commercially available off the shelf integrated circuits (ICs), these areas manifest in single event effects (SEE) and total ionising dose (TID) radiation events. TID refers to the damage components face from long-term exposure to a radioactive environment. This impacts areas such as device voltage threshold levels and component leakage currents, leading to irreparable faults. Conversely, SEEs refer to the short term damage ICs can suffer from transient events. In these situations, energy deposition from a radiative particle can cause bit-flip errors that effect software runtime.[2] These faults often present through degraded integrity of non-volatile flash memory, impacting data storage recall, and also through program memory corruption, potentially resulting in a processor executing erroneous instructions that can lead to system failure.[3]

To combat the detrimental effects radiation has on sensitive electronic components, shielding is often employed externally to a spacecraft, or sometimes internally directly around specific components.[1] Traditionally, aluminium is used in spacecraft shielding due to its density properties. However, recent advancements into the usage of composite materials in radiation shielding have shown an increase of shielding efficacy and a reduction in mass, whilst still providing high mechanical strength[4].[5] Due to this, composite materials are being viewed as a viable alternative for spacecraft radiation shielding. Device sensitivity to radiation events vary largely depending on the component used. In the same orbit, the SEE rate can increase by several orders of magnitude in technologies more susceptible to radiation.[6] With compositions of alloys and epoxy showing promise in the future of spacecraft radiation shielding, the primary science experiment on mission two will determine the efficacy of newly developed compositions both for radiation protection close to home, and as the Binar Space Program explores deeper into the solar system.

The purpose of the radiation detection payload is to test the efficacy of the shielding material developed by CSIRO. All three of the CubeSats will contain a radiation sensor developed in-house, but will have varying compositions of the structure surrounding the payload. The payload is expected to provide input into the decisions regarding the structural design of Binar CubeSats as the program targets missions beyond Low Earth Orbit. The payload consists of three independent radiation detection methods, and the varying shielding compositions. Figure 4 highlights the detection methods of the payload, as well as the supporting circuitry.

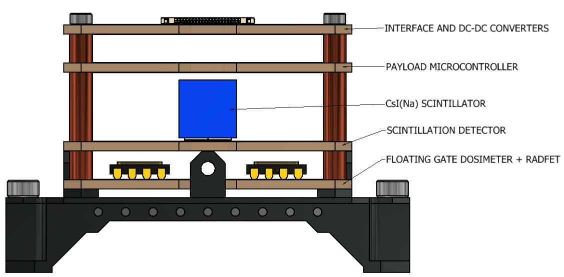

Figure 4: Cross sectional view detailing the radiation detector payload.

Shielding

Whilst the radiation sensors will be identical between the launch two spacecraft, the shielding surrounding the payload will vary. Binar-2 will operate as a control, with Binar-3 and Binar-4 offering varying compositions to assess the efficacy of the radiation shielding methods in LEO.

The control shielding will comprise of 3mm aluminium plates, being the same grade aluminium used for the spacecraft frame. As the payload is to influence the decisions made for the composition of future spacecraft frames, this is to represent a spacecraft structure with no radiation shielding. The impinging radiation data collected from this will be compared against a shielding composition of doped aluminium, and against dual layer aluminium and epoxy plates. Whilst the doped aluminium may provide better total radiation shielding protection, the dual layer shielding is being investigated to ascertain shielding to mass ratio performance.

Figure 5: A render of the shielding surrounding the radiation detection payload.

Scintillation Detector

The scintillation detector is the primary method of measuring impinging radiation on the payload. It comprises a sodium-doped caesium iodide crystal fixed to the top of four silicon photomultipliers (SiPM). When ionising radiation passes through the crystal, it re-emits the absorbed energy in the form of light to be detected by the SiPMs. When struck with the emitted photons, the SiPMs will generate a voltage to be measured by the payload microcontroller. This voltage is directly proportional to the energy of the ionising radiation. Due to this, the voltage recorded by the payload microcontroller can be matched to the energy range of the expected radiating particles, and hence discern what particle produced the scintillation. This can provide insight into if the radiation received is due to pass-throughs of the radiation shielding, or if the shielding itself is producing secondary ions.

Floating Gate Dosimeter

The floating gate dosimeter is a digital radiation sensor located on the secondary sensor board of the payload seen in Figure 4. Unlike the scintillation detector, this sensor cannot determine the particular impinging particle. The detection method sees the implementation of a floating gate capacitor. The floating gate normally exists in a charged state, of which it can hold indefinitely until a dose of ionising radiation is received. The impinging radiation causes the floating gate to discharge at a proportional rate to the dose received. After reaching a discharge threshold, the floating gate is recharged to its nominal state. Using the discharge rate coupled with the charge cycle count, the instantaneous dosage intensity can be inferred.

RadFET

The radiation-sensitive metal-oxide-silicon field-effect transistor (radFET) payload is used to determine the total amount of radiation received over the lifetime of the mission. A reverse bias current is forced into the radFET and the voltage is read at the source. The amount of gate leakage current is permanently changed as radiation impinges the sensor,[7] allowing the computer sampling the voltage to infer the total amount of radiation that has been received.

Targeted Re-entry

Alongside offering redundancy in communications, flying an Iridium module on the mission two spacecraft enables the exploration of small satellite re-entry systems. Leveraged through a dedicated operational mode, Binar-2, 3 and 4 will de-activate unnecessary systems and focus power towards transmitting Iridium beacons at high frequencies. These re-entry beacons comprise power, temperature and location information which the ground station will use to monitor the satellite entering the atmosphere. Testing of the Iridium based tracking system on the mission two spacecraft will be a precursor to creating a future targetable re-entry system, with the eventual goal of re-entering a Binar spacecraft above the Western Australian Desert Fireball Network.[8] Early re-entries over the network will see optical tracking of the satellite as it ablates in the atmosphere. Future stretch goals involve the implementation of heat shielding and a landing system to attempt to land a CubeSat in the Australian desert.

Robotic Arm Emulation

Aiding in the bridging of industry and research, the Binar Space Program has an ongoing collaboration with the Fugro Space Automation AI and Robotics Control Complex (SpAARC). The SpAARC is developing unique remote operation capabilities to support space robotics projects both within Australia and internationally. On the mission two satellites, the collaboration with the Binar Space Program will see Fugro SpAARC remotely operating an emulation of a robotic arm from their ground station in Perth, Western Australia. As a case study, a solar panel is to have failed to deploy correctly, requiring the use of an on-board robotic manipulator to aid the deployer in completing its full actuation.

Requesting the solar panel deployment angle from Fugro SpAARC, the spacecraft will generate, log, and return a random angle to the ground station. A task can then be scheduled to actuate the virtual payload, involving interpolation of the three degrees of freedom simulation. The updated virtual manipulator state and the solar panel angle will be logged on the spacecraft before being returned to Fugro SpAARC when queried and displayed in real-time on their remote operations front-end software.

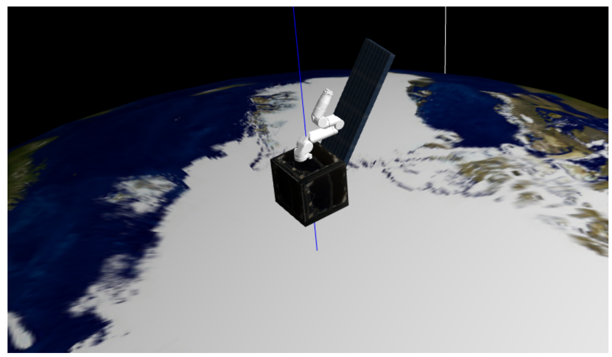

Figure 6: Screenshot from the Fugro SpAARC remote operations tool, showing a manipulator and a deployable panel on-orbit.

The simple experiment aims to demonstrate the capabilities being developed in Western Australia, supporting the growth of local space industries.

Star Tracker

Passionate about lowering the barrier to entry of working on space missions in Australia, the Binar Space Program will be flying a star tracker payload built by undergraduate students at Curtin University. The aim of the payload is to test the hardware the could be used on future Binar missions that extend beyond LEO. The hardware will consist of a lens, image sensor, microcontroller, supporting electronics and a mechanical structure. The microcontroller will be running star tracking algorithms written by the students to perform attitude determination. The payload is expected to produce lessons learned, and some information about the suitability of COTS lenses, CMOS sensors and microcontrollers for star tracking applications.

Digital Twin

The digital twin payload aims to create a virtual replica of the Binar spacecraft that can be used for on-board simulations. The goal is to develop a multipurpose simulation in which subsystems possess knowledge about their own state, the environment they operate in, and how they integrate with other submodules in the system. On the mission two satellites, the payload will recommend changes to the mission plan based on on-board power consumption. Figure 7 shows a high level flowchart of the digital twin implementation.

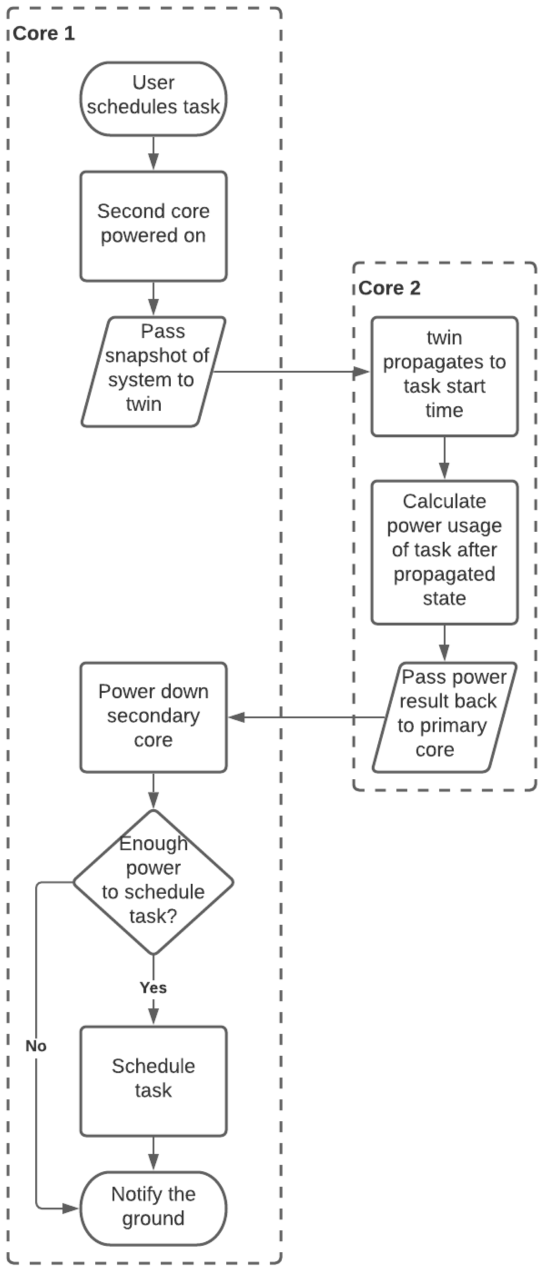

Figure 7: Digital twin virtual payload proposed functionality diagram.

One core of the flight computer will be dedicated to running the simulation to ensure that possible intense loads from interpolations will not impact the flight logic of the spacecraft. When the ground station schedules a task for the spacecraft to complete, the flight logic will power the second core of the flight computer on, passing a snapshot of the satellite into the simulation. This snapshot will contain current readings of all spacecraft systems, inclusive of onboard power usage and thermal information. Whilst the main core continues executing the flight logic, the second core will propagate forward on-orbit until the start time of the scheduled task. The spacecraft will then estimate the total power usage, including the battery heaters, and the expected continued usage of on-board peripherals. The flight logic is then notified of the outcome of the simulation, and is able to determine if it is safe to progress with task execution, or recommend another time slot in an agile manner.

The models used by the digital twin payload during simulation were derived from testing in lab-based environments. A future goal of the digital twin payload is to facilitate on-orbit inference of pre-trained machine learning models using data obtained from the Binar satellites on-orbit.

Concept of Operations

A high level overview of the operation modes and corresponding state transitions for the mission two spacecraft can be seen in Figure 8. The red arrows represent automated transitions, whilst the green show manual transitions.

Post-deployment from the ISS, the three spacecraft will enter a separation sequence where the EPS will power the spacecraft and begin a 30 minute timer. This is to satisfy the ISS deployment requirement of refraining from deployment actuation until a safe distance has been achieved. After this timer has lapsed, the planar monopole UHF antenna will deploy followed by the solar arrays. Following a successful deployment, the spacecraft will transition into the bootloader to run a system health check. Verifying nominal system operations, the spacecraft will transition into a low power mode with high frequency, long duration communications to aid in locating the spacecraft from the ground station. A telecommand received from the ground station will permit the spacecraft to transition into the nadir pointed application mode where the spacecraft systems will be brought online. Two weeks post deployment from the international space station, the spacecraft will begin to achieve it's on-orbit objectives, as shown in Figure 9.

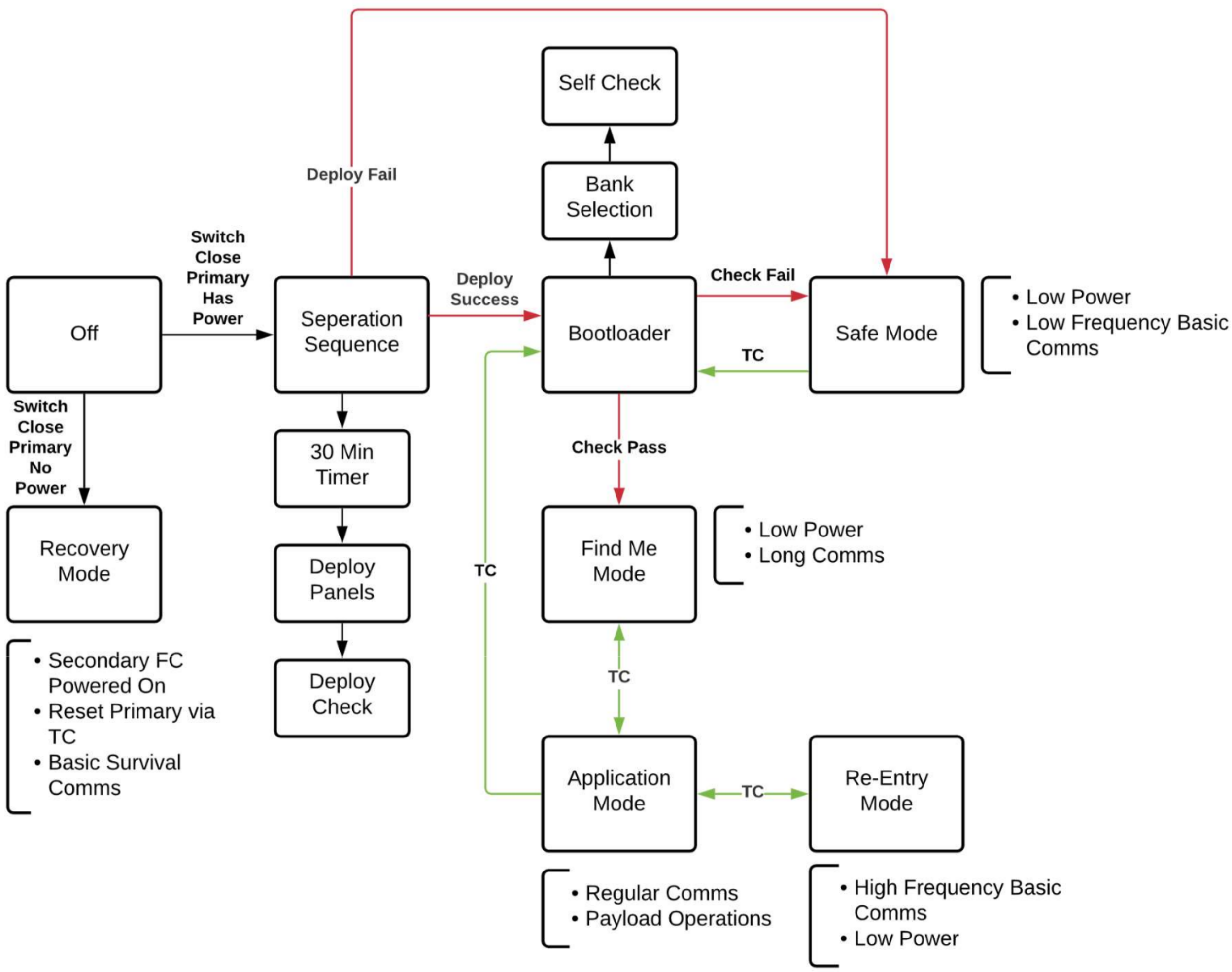

Figure 8: Binar-2,3 and 4 Operation Modes.

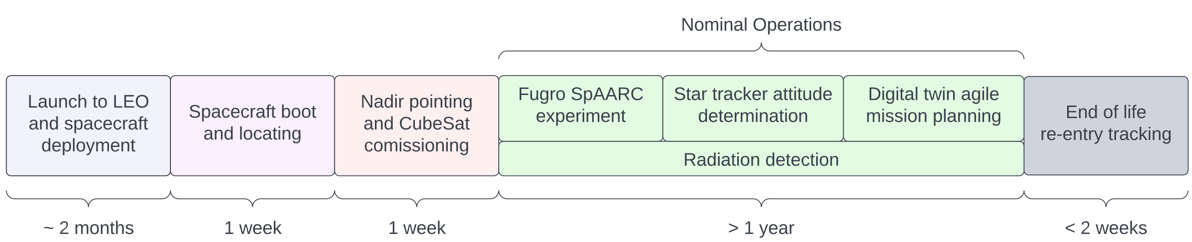

Figure 9: Proposed timeline of the Binar-2, 3 and 4 CubeSats.

To maximise the chance of satisfying the industry collaboration requirements, the Fugro SpAARC remote operations experiment will be the first on-orbit objective. During an overhead pass, the Binar Space Program will hand over control of the satellites to the SpAARC ground station facility in Perth, Western Australia. This experiment will be completed multiple times with the three satellites to demonstrate the robustness of their remote operations capability. Following completion of the demonstration, the three Binar spacecraft will be tasked with using the star tracker payloads to capture images of the visible stars. These images will be used on-board the spacecraft in attitude determination to be referenced against location information from the GPS. As the three CubeSats are expected to slowly drift over the course of the mission, the images captured will provide a comprehensive view of stars visible from LEO and hence will be also downlinked for use in future testing. After having sampled a sufficient catalogue of stars, the satellites will begin the agile planning stage of the mission using the on-board digital twin. The digital twin payload is to suggest changes to scheduled task times if the on-board simulations predict insufficient available power to safely complete a task. To force this situation to occur, high power tasks will be scheduled for periods of the orbit where the CubeSats are in Earth's shade, not charging, and using battery heating. To verify the reasonableness of the simulations recommendations, an override will be granted to allow a task to run regardless of the agile recommendations. Observing the spacecraft booting into safe mode will demonstrate the recommendation was sound, showing the plausibility of using on-orbit agile mission planning in more complex cases.

The nominal operations stage of the mission timeline is expected to last for at least one year. Whilst sequentially operating the previously mentioned payloads, the primary radiation sensing payload will be constantly operational, downlinking measured radiation data that leaks through the shielding flown. This information will be periodically transmitted along with general housekeeping data. When green time exists within the nominal operations schedule, the Binar Space Program will work with the amateur radio community to listen and transmit to Binar-2, 3 and 4.

Two weeks prior to the end of life, the CubeSats will be transitioned into the re-entry mode via a telecommand from the ground station. This mode will orient the spacecraft such that the deployable cells create sufficient drag to aid in orbit degradation. This mode will see the spacecraft enter a low power mode, conserving energy to support high frequency communications over the Iridium network to track re-entry in the atmosphere.

Conclusion

Binar-2, 3 and 4 comprise the second launch of the Binar Space Program, with a strong focus on platform development for the future. The three 1U CubeSats will be primarily testing radiation shielding compositions created by the CSIRO. The varying compositions used will be assessed based on the three radiation detection methods flown, showing types of radiation received, dosage intensity, and total ionising dose received. The data collected from this experiment will aid in determining the efficacy of shielding on CubeSats, enabling future Binar missions that extend beyond LEO.

Platform development will also be explored on mission two through the testing of deployable cells, redundant communications, and the unique removable payload bay. The deployable cells on the spacecraft will provide an extra power margin over the surface-mounted only cells on Binar-1, supporting growing payload needs as the platform is reused in the future. Flying multiple communications solutions allow for a backup communication method through the Iridium network, with S-band also supporting testing of higher bandwidths as data throughput requirements increase in the future. The Iridium communications solution will also be flown, with a focus on transmitting telemessages from the spacecraft during spacecraft re-entry to aid in tracking. Second to this are software and hardware payloads that will help the Binar Space Program develop necessary systems for future missions planned from the Space Science and Technology Centre at Curtin University.

As the main goal of the platform is to mature towards a static design where only the payload changes between launches, the removable payload bay will be tested on the mission two satellites carrying an inhouse developed radiation sensor, and a star tracker camera. The radiation sensor will provide information on the radiation that passes through the payload-surrounded shielding, whilst the undergraduate star tracker payload will provide preliminary data for the development of future deep-space attitude determination as Binar spacecraft strive further from Earth.

Software payloads are used on the mission two satellites for facilitating industry engagement, and for agile mission planning. The ongoing collaboration with Fugro SpAARC will see the inclusion of a robotic arm emulator to be controlled by Fugro ground station operators, demonstrating the use of their remote operation facility. When commanded to schedule a task for completion, the spacecraft will use the digital twin software to propagate on-orbit and assess the power state of the spacecraft for safe task execution.

Finally, the mission two spacecraft will expand on what amateur radio operators can do with a spacecraft on-orbit. Whilst supporting unencrypted access to beacons transmitted from the spacecraft, the satellites will also allow radio amateurs with a transmission license to store small data packets on the spacecraft that can be downlinked using the SatNOGS network.

The Binar Space Program intends to launch satellites frequently to support the program goal of space systems education at Curtin University. Binar-2, 3 and 4 provide a test platform in the constant development of the Binar CubeSat bus. The data collected from the operations of the satellites and the payloads they are flying will influence the decisions made for the next Binar CubeSats, and aid in the eventual development of satellites that venture beyond LEO.

Acknowledgements

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