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<td><strong>Authors(s)</strong></td>
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The CubeSat standard, relatively short launch timescale, and orders of magnitude difference in cost in comparison to large scale missions, has allowed universities and smaller institutions to develop space missions. The Educational Irish Research Satellite (EIRSAT-1) is a 2U CubeSat being developed in University College Dublin (UCD) as part of the second round of the European Space Agency (ESA) Education Office’s Fly Your Satellite! (FYS) Programme. EIRSAT-1 is a student-led project to build, test, launch and operate Ireland’s first satellite. CubeSats typically use commercial off-the-shelf (COTS) components to facilitate new teams in developing a satellite on a rapid timescale. While some of the EIRSAT-1 subsystems are COTS procured from AAC Clyde Space, EIRSAT-1 has three novel experiments on-board which have been developed in UCD. The spacecraft’s Antenna Deployment Module has also been designed and built in-house. The on-board computer (OBC), procured from AAC Clyde Space, has been adapted to interface with these novel hardware components, accompanied by in-house developed software and firmware.

All of these innovative subsystems complicate the CubeSat functionality making it essential to document and rigorously test the operations procedures for EIRSAT-1. In preparation for launch with these novel spacecraft subsystems, the EIRSAT-1 Operations Manual is being developed and incrementally verified. The Operations Manual contains the procedures to command and control the satellite, account for nominal and non-nominal scenarios and guide the operator in determining the cause of any anomalies observed during the mission and facilitate recovery. A series of operations development tests (ODTs) have been designed and conducted for a robust verification process. Each procedure is written up by a member of the EIRSAT-1 Operations Team in the EIRSAT-1 Operations Manual format. During an ODT, an in-flight scenario is considered in which the procedure under test is required. The procedure is then followed by a team member who has not been involved in the procedure development process. The feedback from these tests and from the operators is used to improve the procedures and continually update the Operations Manual. This paper will present the approach to operations development used by the EIRSAT-1 team and discuss the lessons learned for CubeSat operations development, testing and pre-flight verification.

Keywords: CubeSat, Spacecraft Operations, Fly Your Satellite!, EIRSAT-1

I. Introduction

The operations manual for a spacecraft (SC) contains all the step-by-step procedures required to control the satellite in-orbit, and must include contingency plans for all possible mission scenarios [1]. Preparing for the operation of a satellite in the harsh space environment with limited communications is challenging [2]. The operations manual must contain detailed instructions to ensure the satellite is in the correct configuration and can be controlled during routine scenarios, for example, experiment configurations and downlinking data. The manual must also guide the operator in
determining the causes of anomalies during the mission such as transitioning to Safe Mode. Each operations procedure consists of validated step-by-step instructions, with each step detailing the telecommand (TC) to be sent to the spacecraft and the expected telemetry (TM) response [1].

CubeSats have revolutionised the space industry. A CubeSat [3] is a subclass of nanosatellites that are comprised of CubeSat units where one unit is called 1U. Each 1U unit is 10 cm × 10 cm × 10 cm in volume and can have a maximum mass of 1.33 kg per unit. The motivation for the initial development of CubeSats was educational, to provide students with hands-on experience of the full development cycle of a space mission. This led to a design standardisation, defined by the Cal Poly specifications [4], and the evolution of commercial off-the-shelf (COTS) components. These factors and the relatively low cost of CubeSat missions has facilitated universities in developing, testing and operating space technology [5]. Additionally, CubeSats are now being used as technology demonstrators and for science missions relating to astronomy and space weather [5][7], as they are competitive solutions that are lower cost, have lower development timescales and less stringent testing and qualification required, in comparison to larger missions. EIRSAT-1 is an example of a CubeSat mission with educational, technology demonstration and scientific goals. The primary payload, GMOD, will be capable of detecting gamma-ray bursts, in addition to being a demonstration model for novel gamma-ray instrumentation [8]. One of the main objectives of this project is educational, with a focus on enabling Irish students to gain skills for working in the space sector with students taking leadership roles such as managing a subsystem or payload. Other aims include developing collaborations with industry partners and inspiring the next generation to follow careers in the space sector.

The Educational Irish Research Satellite [9], EIRSAT-1, is a project enabling a student led team to design, build, launch and operate a CubeSat as part of the second round of the ESA FYS Programme[10]. The ESA Education Office supports and mentors university teams in the FYS programme to develop a satellite. Through participation in the FYS programme, the EIRSAT-1 team are experiencing the full life-cycle of mission development from design, through to spacecraft operations. Data packs, written in accordance with the European Cooperation for Space Standardisation (ECSS) [11] and FYS standards, are submitted to ESA for review as part of the programme. The most recent submission in November 2020, for testing of the Engineering Qualification Model (EQM), included the EIRSAT-1 Operations Manual. As part of this programme, members of the EIRSAT-1 team have taken part in educational courses with the ESA Education Office, including the week long course on Spacecraft Operations [12]. These educational programmes provide the student teams with vital information on the different aspects of satellite development and operation.

The life expectancy of a CubeSat mission is limited due to the high failure rate of CubeSat missions. This is a result of higher tolerances in risk acceptance for CubeSat missions to reduce project timescales [10]. Of the 848 CubeSats launched between 2005 and 2018, 39% of the missions were not successful and 21% of mission failures were due to CubeSat malfunction [5]. It was found in the first 100 CubeSat missions, the university led mission failure rate was nearly 50% [11]. This high failure rate was largely attributed to the lack of system level testing in university projects due to time constraints. Two-thirds of CubeSat missions failures are due to failures in functional integration as student teams tend to concentrate on design, component level testing and assembly with less focus on rigorous system level and operations testing.

A major motivation for the development and testing of the EIRSAT-1 Operations Manual is to address the high failure rate for CubeSat missions. To reduce the risk of system level functional failure, the prototype model philosophy is being implemented for EIRSAT-1, two models will be assembled and tested, the EQM and the Flight Model (FM) [11]. The EQM will undergo more rigorous qualification testing, while the FM will be tested to lower acceptance levels and launched. Initially, each model is tested in a FlatSat configuration. The purpose of the EIRSAT-1 FlatSat is to have a flight-like model while still being able to access the individual subsystems for anomaly investigations. This configuration flexibility is important for risk reduction in the initial stages of hardware, software and operations development [13]. For both spacecraft models, a system level Full Functional Test (FFT) campaign and a Mission Test campaign [14] will be performed prior to the Environmental Test campaigns. Ref. [12] contains a detailed description of the verification and validation plan for the EIRSAT-1 mission.

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[1] https://www.esa.int/Education/CubeSats_-_Fly_Your_Satellite/Fly_Your_Satellite!_programme
[3] https://www.esa.int/Education/ESA_Academy
EIRSAT-1 consists of traditional CubeSat subsystems; an on-board computer (OBC) [15], communications module, attitude determination and control subsystem (ADCS) and an electrical power subsystem (EPS). These traditional components are all AAC Clyde Space COTS subsystems. Additionally, EIRSAT-1 has three payloads and a novel Antenna Deployment Module (ADM) [16]. The scientific goal of the Gamma-ray Module, GMOD [8,17], the primary payload of the mission, is to successfully detect cosmic gamma-ray explosions called gamma-ray bursts (GRBs), that are associated with the birth of a black hole. In achieving this goal, EIRSAT-1 will provide in-orbit validation of novel gamma-ray technologies. GMOD is built on a heritage of research on novel gamma-ray instrumentation and development [18,22]. In collaboration with the Irish Company ENBIO Ltd, the performance of the thermal surface treatments SolarBlack and SolarWhite will be monitored with the ENBIO Module (EMOD) [9]. The final payload, is the Wave Based Control (WBC) software payload [23,24]. WBC is a novel attitude control algorithm that has been developed in UCD for flexible systems. EIRSAT-1 will provide the first in flight performance test of this algorithm, though it has been tested rigorously via simulations.

The incorporation of three experiments and a bespoke antenna deployment mechanism into a CubeSat complicates the operations of the satellite throughout the mission. The EIRSAT-1 Operations Manual must contain procedures to conduct these complex experiments and to maintain the functionality of the spacecraft via the COTS components of the satellite. Currently, there is one ground station being developed for EIRSAT-1 [25], which is expected to have ~29 minutes of communication with the satellite every day, depending on the orbit. There will be 3-4 communication windows everyday with a duration of ~7.5 minutes. Outside of these communication passes the spacecraft must operate and survive on its own. Part of the operators role is to ensure these autonomous operations have been working successfully and assessing the current state of the spacecraft during each communication pass. The restricted time of these communication windows has driven the development of the Operations Manual, to ensure the operators are fully prepared to perform all the required procedures in the most time efficient manner.

The prototype model philosophy has allowed the EIRSAT-1 team to develop operations procedures and compose an EIRSAT-1 Operations Manual with the aim of validating the document during both the EQM and FM Mission Test.
Campaigns. This regular testing and updating of the operations procedures will increase the likelihood of mission success. Section II describes the Operations Manual and the considerations taken in the format, layout and contents of the manual. The philosophy of selecting procure to develop in the operations development tests (ODTs) is discussed in Section III. These ODTs are performed to incrementally develop the operations procedures and allow the student team to gain experience in operating the satellite in nominal and non-nominal scenarios in a flight-like configuration. This paper will present the approach and lessons learned by the EIRSAT-1 team in developing a robust Operations Manual, for a CubeSat with three experimental payloads.

II. EIRSAT-1 Operations Manual

The EIRSAT-1 Operations Manual contains the procedures required to control the 2U CubeSat in space and operate the three experiments on board. The Operations Manual is generated using Sphinx, a tool originally created for Python documentation, and now used in many other projects, with the “Read the Docs” theme, a popular service used to host many open source project documentation. Sphinx is used to produce user-friendly HTML and PDF documents, where the content is composed from a set of reStructuredText (RST) markup files. The main components of the Operations Manual are detailed in this section and summarised in Figure 2. The procedures to initiate communication with the spacecraft, downlink data and perform fault analysis have all been developed by the team. The manual also includes prerequisite knowledge required by operators before interacting with the spacecraft and provides an explanation of the set up of the operator’s interface to the spacecraft. Each procedure is written using a common template with an objective stating the aim of the procedure and a step-by-step guide of the telecommands/operations that need to be performed. The manual also makes use of RST features to draw the operator’s attention to important facts or prohibited actions.

A. Operations Manual Introduction

The EIRSAT-1 Operations Manual contains an introduction section which contains all of the knowledge required to operate EIRSAT-1. The following is detailed in the introduction: Spacecraft Interface, Spacecraft Database, Prerequisite Knowledge, Operator Tips and an Operations Procedure example.

1. Spacecraft Interface

A full explanation of the interface to the spacecraft is initially described. The graphical user interface (GUI) allows operators to efficiently interact with the on-board software of the spacecraft. The Mission Explorer displays the spacecraft database, described below, in a tree structure that can be expanded to view the different software components. A log of packets sent between the ground and the on-board software is presented in the Packet Monitor window. The System/Debug/Event Console contains three tabbed windows containing an overview of the actions, events and debug outputs from the satellite. The Transfer Window displays a progress bar (percentage complete) when data is being downlinked/uplinked to the satellite. The Operations Manual also instructs operators on the optimal layout for this interface so that all these windows can be monitored while communicating with the satellite. This description was written by one of the Operations Engineers as they were learning to communicate with the satellite to ensure that the description would contain all the information required for an operator to establish communication with the satellite and understand all the components in the spacecraft interface.

The Operations Manual contains a detailed description of the spacecraft database and how it is used to transmit commands to EIRSAT-1. The manual contains step-by-step instructions on loading the SCDB into the GUI and how to navigate through the different components. The SCDB contains all the spacecraft commands, grouped into different components, in the form of actions and parameters. An action is a function that a component of the satellite can be instructed to perform via an Invoke command e.g. mode transition, turning on an experiment. A parameter can be read-only, or read-write to determine, or configure, some data associated with a component of the satellite e.g. operational mode, measurement of a sensor. There are a number of operations that can be performed with a parameter: Get: Read parameter value, Set: Change parameter value, Query: Determine current size of parameter, and for large data transfers, parameters can be downlinked or uplinked via commands Downlink and Uplink, respectively. The SCDB groups the actions and parameters into different components e.g. the ModeManager component contains all the actions and parameters related to the operational modes of the satellite where the possible modes are: Separation

https://readthedocs.org/
Sequence (SS), Commissioning, Nominal, WBC and Safe Mode. The Operations Manual contains examples for the different command operations and how to navigate the SCDB to find the desired parameter or action when given the path to a particular component e.g. mission.ModeManager.transitionToNominalMode.

### 2. Prerequisite Knowledge

The Prerequisite Knowledge section of the manual is a result of the ODTs, discussed in Section III. It contains any background knowledge that applies to the majority, if not all, of the operations procedures, that an operator of EIRSAT-1 should be aware of prior to communicating with the CubeSat. A major focus of this section is on the downlinking of data from the spacecraft. The Operations Manual must provide a guide for operators to determine the priority of data downlink between the different experiments, housekeeping and the status of the COTS subsystems. It is vital for the operators to be acquainted with the different aspects of data downlink so they can make informed decisions on what data has the highest priority in any given mission scenario.

Initially, the operators are introduced to the different types of telemetry (TM) that are expected from the spacecraft. Alongside the TM that contains the data requested via a telecommand (TC), the spacecraft will send an acknowledgement packet called an ACK. If the TC was not successfully executed, which could be due to setting an invalid value to a parameter or requesting an invalid amount of data, the spacecraft will send a negative-acknowledgement packet, or a NACK. Usually, a NACK can be resolved by ensuring the valid data and data size are being sent to the spacecraft. ACKs and NACKs appear in the Packet Monitor window. If no response is received from the spacecraft, this is termed a timeout, and the procedure should be paused and the the Software and/or Systems Engineer should be contacted to determine the plan of action. Additionally, Live Event (status messages raised by the spacecraft for transmission and/or logging when different events occur) and Housekeeping (HK) TM will automatically and periodically be transmitted by the CubeSat and populate the Packet Monitor during communication windows. Including the different types of expected TM from the spacecraft and how an operator should react is important to prepare the operators for the appropriate actions if a NACK/timeout is unexpectedly received.
A full description of the approach to large data transfers (LDTs) is included in the Prerequisite Knowledge section. LDTs are when large quantities of data are requested for downlink. The data will be separated over multiple downlinks which can occur over multiple communication passes. A key advantage of LDTs is that they can be paused and resumed. When a communication pass ends, the LDT will automatically be paused, and a command is required from the ground station to resume the LDT during the following communication pass. The progress of an LDT must be monitored by an operator in the Transfer Window of the ground station GUI. An important rule being implemented is that only one transfer may be requested at a time. It was found during the ODTs that while more than one transfer can progress in parallel, the downlink efficiency is reduced. The team plan to have LDTs on-going during communication passes while also sending other TCS required for the operations procedures that need to be completed.

The configuration for storage of on-board data and the downlink logic required to determine what quantity of data from memory to downlink during a communication pass are also detailed. Data is stored in two locations on-board, flash and magnetoresistive random-access memory (MRAM) [20]. EIRSAT-1’s on-board memory is budgeted to hold two primary software images (in non-volatile MRAM) and one failsafe (in non-volatile flash) image. The primary images contain the full software functionality required for the mission. In contrast, the failsafe image has minimal functionality and is used as a redundancy image for critical operations. While MRAM is accessible in the primary 1, primary 2 and failsafe images, the flash memory is only used by and accessible in the primary images. Therefore, the non-critical data such as science data and backlog of other data types (e.g. HK, ADCS) are stored in flash memory. It is important that operators are aware that if the spacecraft is pushed into the Failsafe image, critical data will need to be downlinked from MRAM as the flash memory will not be accessible. The data is stored in two types of storage channels in the on-board software (OBSW), circular channels and linear channels, where each has a Channel ID. Table 1 contains a brief explanation of the storage channels that are discussed in this paper. The first twelve Channel IDs are assigned to MRAM, while the remaining Channel IDs are assigned to flash memory. In the case of circular channels, the rows of the channel are filled with data until the channel is full. Once full, each new row of data will be logged to the end of the channel and the oldest row of data at the start of the channel will be lost. For linear channels, the rows of the channel fill with data until the channel is full and once full, no new data will be logged to the channel until the channel is cleared of data via a TC.

<table>
<thead>
<tr>
<th>Storage Channel</th>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Housekeeping</td>
<td>HK</td>
<td>Housekeeping data contains the condition of the satellite and its subsystems e.g. mode, battery levels.</td>
</tr>
<tr>
<td>Telemetry for Enhanced Diagnostics</td>
<td>TED</td>
<td>TED contains additional data regarding the state of the spacecraft. It contains additional error counters, error codes, status parameters, etc. that are not seen as essential enough for the main HK packet but could be useful in an anomaly investigation.</td>
</tr>
<tr>
<td>Event</td>
<td>-</td>
<td>The software has the ability to “raise events” which are status messages that can be raised at different points of the software for transmission and/or logging. These events help determine what parts of the software were run on board/what events occurred and when.</td>
</tr>
<tr>
<td>Power Aggregator for Satellite Currents and Voltage Levels</td>
<td>PASCAL</td>
<td>Logs additional data on the power systems that were not seen as essential for the main HK packet but could be very useful when commissioning the power systems and/or assessing anomalies related to the power systems.</td>
</tr>
<tr>
<td>Attitude and Determination Subsystem</td>
<td>ADCS</td>
<td>Logs additional data on the ADCS that were not seen as essential for the main HK packet but could be very useful when commissioning the ADCS and/or assessing related anomalies.</td>
</tr>
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Table 1 Description of the storage channels discussed in the development of the EIRSAT-1 Operations Manual

The Operations Manual contains detailed downlink logic steps to determine what rows of data are left to be downlinked for both types of storage channels. It also contains a link to a document the EIRSAT-1 team are using to record the rows of data downlinked during each pass, and from which storage channels. The satellite operators for the next communication pass can refer to this when calculating the rows to downlink in preparation for their upcoming communication pass. A table on the storage channels is also included in this section which details the Channel ID, logger type (e.g. HK, Event, ADCS), row size, max number of rows for that channel, whether it is circular or linear and if it is in MRAM or flash storage. The EIRSAT-1 operators will use this table while preparing for every communication pass to estimate the number of rows to downlink and the time required to downlink the data assuming certain downlink capabilities, and to confirm the correct channel ID is being requested. For a nominal case, operators are to assume
downlink capabilities are at a baud rate of 9600 bps (UHF) with 30% overhead. Operators must also be aware if convolutional encoding is enabled [25], as when Transmit (Tx) Encoding is enabled, the data rate of the science data is reduced by half. A number of example downlink scenarios have been included in this section to guide operators on the downlink priorities of the different storage channels. For all nominal scenarios, data should be downlinked to assess and monitor the health of the spacecraft e.g. HK, Event. Three nominal scenarios are included where a subset, all or none of the experiments require data to be downlinked. In these scenarios, once the satellite health check data is downlinked, EMOD data takes next preference as EMOD will only generate a small amount of data between communication passes. In the case of a GRB detection by GMOD, the remaining downlink time in each pass is allocated to GMOD data. The GMOD data will be separated each day between GB data (which may take a couple of days to downlink in full, depending on the characteristics of the burst) and background data around the time of the detection. GRB data has a higher priority than WBC data. In the case there is WBC data to downlink and no GRB detection, the remainder of each downlink window, after obtaining health check and EMOD data, will then be used to downlink WBC data. A guide for Non-Nominal Operations is also included, however, more detail on dealing with non-nominal scenarios are detailed in the Fault Analysis Operations discussed in Section III.D. In mission critical scenarios, experiment data (GMOD, EMOD and WBC) will not be considered for downlink. HK and Event data will be prioritised and then depending on the anomalies identified, the operators will need to identify the subsequent data to downlink e.g. PASCAL data if an issue is identified with the battery.

By ensuring the operators are familiar with these different aspects of operating EIRSAT-1, the communication pass times can be optimised as the Operations Manual guides the operator in the preparatory tasks that need to be completed prior to the communication window. During the development of the Operations Manual, and the ODTs, many non-critical but useful lessons were learned to optimise the operation of EIRSAT-1. These were compiled into an Operator Tips section that can be easily accessed in the introduction drop down menu of the Operations Manual. Some examples of these tips include how to change the format of the data output between decimal, hexadecimal and binary and how to remove data that is no longer needed from a previous session in the Packet Monitor and System/Event/Debug console.

3. Operations Procedure Example

The final section in the EIRSAT-1 Operations Manual Introduction is an example of an operations procedure, as presented in Figure 3.

![Example procedure format for EIRSAT-1 Operations Manual. The left side presents the objective of the Operational Mode Change procedure and the introduction. On the right, the first step in the Operational Mode Change procedure is displayed with the blue box surround the TM/TC Table example and the red box surrounding the additional information required by operators on what operational mode corresponds to the TC response from EIRSAT-1.](image-url)
This is included to help operators understand how to approach the operations procedures in the manual and understand what is required in the step-by-step instructions. All of the operational procedures follow the same format and contain the same sections:

1) **Objective** - States the aim of the procedure
2) **Introduction** - Brief description of what the procedure will achieve
3) **Procedure** - Step-by-step guide of how to perform the telecommands/operations
4) **Statement** saying "END OF PROCEDURE"

Most steps in a procedure require the use of an action or parameter, as described in Section II.A.1 The table in the blue box in Figure 3 is filled out for any action or parameter that is used in a procedure step, and each entry is explained, as shown in Figure 4.

![Image of EIRSAT-1 Operations Manual](image)

**Fig. 4** Explanation of the TM/TC Table included in each step of the manual that requires interaction with any EIRSAT-1 action or parameter.

The content of these tables went through numerous iterations to make them applicable to all communication with EIRSAT-1, and to ensure they provided all the relevant information to the operators. The table has two main sections: TC Details containing the telecommand details and TM Details stating if a TM is expected and what the content should be. Also included in the step-by-step procedures is any additional knowledge required for completing the operations in the procedure. The table surrounded by a red box, in Figure 4 is an example and explains what the allowed data values mean for this operation.

### B. EIRSAT-1 Operational Procedures

In the first iteration of the Operations Manual, a list of essential procedures for the mission was made by the Systems Team and the Operations Engineers. This initial list has since been incrementally updated as development of the manual and performance of ODTs revealed other required procedures. The current, but non-exhaustive list of procedures is displayed in Figure 2 and is sorted into four categories: Start of Mission, Nominal, Payload and Fault Analysis. The procedures marked with an * are an example of benefits of ODTs as they were not initially considered for the Operations Manual, but instead the need for these procedures resulted from carrying out the ODTs. In addition to these new procedures, the ODTs highlighted missing scenarios and steps in the original procedures.

The list contains nominal spacecraft operational procedures that will only be required at the start of the mission e.g. Initial AOS. Other nominal procedures will be required routinely e.g. *Upload OBC Image, Boot Into OBC Image, Downlink Data From Storage* and two will be required for every communication pass after initial acquisition of signal (AOS) i.e. *Pre-Communication Pass Checklist* and *Start a Communication Pass*. There is also a subset of procedures that will be followed in non-nominal scenarios to determine the cause of any anomalies observed during the mission i.e. *Failsafe at Initial AOS*, *Safe Mode Entered, Primary2/Failsafe Entered, Low Battery Fault Analysis, SC Reboot Fault*...
Analysis and NACK/Timeout/Unexpected TM*. While these nominal and fault analysis procedures would be required for any CubeSat mission, there are operations procedures required that are mission specific to the experiments on board EIRSAT-1 e.g. GMOD Configuration and EMOD Configuration. The following section describes the ODTs used to develop these procedures and takes a subset of these nominal, fault analysis and experiment specific operational procedures and outlines the main considerations, taken by the EIRSAT-1 Operations Team, in their development.

### III. Operations Manual Development

#### A. Operations Development Tests (ODTs)

A strategy was developed, as presented in Figure 3, to generate the first and successive versions of each of the procedures required for the Operations Manual. The ODTs have been performed with both the EIRSAT-1 FlatSat and the EQM. The Operations Developers selected a procedure and met with a subset of the Systems team to outline the steps that would need to be followed to complete the objective(s) of the procedure. These steps were composed by one of the Operations Team into the format of the Operations Manual, as presented in Figure 3. An ODT was scheduled to perform a run-through of the procedure, and the day before the Operations Developers reviewed the procedure to ensure it was ready to undergo an ODT.

During the ODT, team members, that had not contributed to the writing up of the operational procedure, followed the procedure in the Operations Manual. Each ODT has two SC operators present, as in-orbit operations are expected to be performed with two operators from the team. At least one member of the EIRSAT-1 Operations Team attended the ODT to record all the feedback on the procedure. There was feedback specific to each procedure including comments on the clarity of the steps, if certain steps were missing or if the procedure needed to consider a different scenario or outcome. The feedback from these tests and from the operators were used to improve the procedures and continually update the Operations Manual. If considerable changes needed to be made based on the feedback, the procedure was rewritten and then retested. If only minor changes are required these can be made quickly and a new procedure selected for development.

More general feedback was accumulated for a more extensive revision of the Operations Manual, where the format of each procedure was updated. For example, after the first step in every procedure, a link to an anomaly form is provided so if the satellite displays any unusual behaviour during that procedure, the operators know how and where to submit their report. A full test of all the operations procedures in flight-like scenarios will be performed during the Mission Test Campaign for both the EQM and FM.

For the first set of ODTs, there were no time constraints when following the procedures, and the ground station was in continuous communication with EIRSAT-1. This configuration is not representative of operating the satellite in space. However, this was considered the best approach by the Operations Team considering the procedures were being developed for the first time by a student team with no previous experience in writing an Operations Manual for a CubeSat. Another important goal of the first set of ODTs was to provide all the EIRSAT-1 team members with the opportunity to control the satellite via the spacecraft interface using the Operations Manual.

Every procedure has had to be subjected to more than one ODT in the incremental development of the EIRSAT-1 Operations Manual. However, once the first version of the main procedures were developed, they could be grouped together and a subset reviewed and updated during an ODT. Furthermore, the subsequent set of ODTs were performed using realistic communication pass time durations. While the first set of ODTs was important for introducing the team to the Operations Manual and preparing the first version of the manual, the ODTs performed within pass time durations were vital for the optimisation of the Operations Manual for in-flight operations.

A Python GUI was developed to simulate realistic communication pass windows, in duration and frequency, based on the communication windows the EIRSAT-1 ground station would have with the International Space Station (ISS). The communication windows observed during the ODTs were between ~3 and ~7 minutes long. The Python GUI had the option of fast-forwarding to the next communication pass which was made use of during the ODTs, as sometimes there are gaps of ~ 18 - 20 hours between successive communication windows. Once these simulated communication passes were integrated into the ODTs, it was evident that operators would need to prepare for communication passes to optimise what can be achieved in these short communication windows. These flight-like ODTs lead to the addition of the
Prerequisite Knowledge (Section II.A.2) and Pre-Communication Pass Checklist procedure (Section III.B) to the manual to guide the operators through the tasks required to be fully prepared for a communication window. The Operations Team also decided it was important that all members of the team that intend to be an Operator would need to take part in these flight-like ODTs to acclimatise to the stress and pressure associated with these restricted communication windows.

The subsequent sections present the considerations and decisions made by the EIRSAT-1 Operations Team for specific procedures including nominal, fault analysis and payload focused operational procedures.

B. Start a Communication Pass and Pre-Communication Pass Checklist

The Pre-Communication Pass Checklist procedure will be used by operators to prepare for each communication window with EIRSAT-1. The Start a Communication Pass procedure will then be used at the very start of each pass, to confirm 2-way communications have been established and to rapidly assess the state of the spacecraft. The Pre-Communication Pass Checklist was added as a result of ODTs, to have a list of tasks the operator must complete in preparation for a communication pass. A summary of the four items on the checklist are as follows:

1) Check the last known image and mode the satellite was operating in, this could be from the previous communication
pass or from the community. EIRSAT-1 will emit a beacon, in regular intervals, with information on the state of the spacecraft. The public will have access to the format of the beacon so the amateur radio community can receive and decode it.

2) Determine if a LDT was paused from a previous communication pass and needs to be restarted, or if a new LDT needs to be set up. If a new LDT must be set up, the operator must clearly have defined the channel(s) from which to downlink the data, the approximate number of rows to be downlinked from each channel type, and any additional information (e.g. whether the oldest or newest data takes highest priority).

3) Review the procedures that are to be followed in the upcoming communication window.

4) Prepare ALL parameters and actions (i.e. open them in spacecraft interface GUI) that will be used during the pass.

The last item on this checklist, in preparing the parameters that will be used during the communication window, greatly improved the efficiency of operators communicating with the satellite during ODTS. Once this checklist is completed, the operators are ready for the next communication window, and every communication pass must begin by following the Start a Communication Pass procedure. As part of this procedure the operator determines the current boot image of the satellite, the operational mode (if applicable) and an LDT will be commenced. Since this is done for every communication pass, this procedure must account for all possible configurations for the satellite (boot images and operational modes). The satellite could be booted into the primary, secondary or failsafe image and in one of the following operational modes: Separation Sequence (SS), Commissioning, Nominal, WBC and Safe Mode.

To assist the operators in understanding the variety of outcomes of the Start a Communication Pass procedure, a flow chart, as displayed in Figure 6, is included in the Introduction section of the procedure. Once the ground station is expected to be able to communicate with EIRSAT-1 using two line element sets (TLEs), a telecommand will be sent to request the Current Boot Image of the satellite. If the satellite is unexpectedly in the failsafe image, the operator will be guided to the Primary/2Failsafe Entered procedure to determine what triggered the satellite to transition into the failsafe image. If the satellite is in the primary image and is not in SS or Safe Mode, then the planned procedures for the communication pass can be commenced. If the satellite is unexpectedly in SS mode, the operator will be instructed to follow the SS Re-Entered procedure, and similarly, if in Safe Mode will be guided to the Safe Mode Entered procedure, to determine what caused the satellite to be in these unexpected operational modes.

![Flowchart](attachment:flowchart.png)

**Fig. 6** Example of the flow diagrams included in the operations manual when a variety of outcomes are possible depending on the configuration of the CubeSat. During Start a Communication Pass, the procedure followed by the operator depends on the current spacecraft mode and image.

In the nominal case, where the current boot image and operational mode of EIRSAT-1 are as expected, the operator will be instructed to start an LDT and continue with any other planned procedures for the communication window. The operator is also instructed to update the document that tracks the data downlinked from the satellite, which will be required to prepare for the next communication window. This procedure can also be used to provide an example of how the EIRSAT-1 Operations Manual makes used of the RST Note, Warning and Important box features to draw the attention of the reader.
operators attention to vital information. Since this procedure is required for every communication window, all the remaining operations procedures in the manual are prepended with the reminder in Figure 7.

![Important]

**Fig. 7  Example of the RST Important box feature used in the Operations Manual to highlight vital information for the operators.**

C. Downlink Data from Storage

The *Downlink Data from Storage* operational procedure is another nominal procedure that will be used in most, if not all of the communication windows. This procedure is written in a general manner, with no data storage channel specified i.e. all the steps include the path cdh.logging.XXXLogger.AbsRowsLogged, where XXXX is the Logger associated with the storage channel (e.g. XXXX = HK, TED, ADCS, etc.).

In some procedures, including this one, the first section is a reminder of the information required by the operator to complete the procedure. However, this should have been prepared by the operator when completing the *Pre-Communication Pass Checklist*. In Section A of this procedure, the operator is reminded to ensure they know the last row of data downlinked from the desired storage channel and the absolute number of rows logged for the storage channel in the last data downlink. This section is included to ensure the operator is fully prepared to determine the number of rows to be downlinked during the upcoming communication pass.

The *Downlink Data from Storage* procedure was challenging to develop. Initially, all the downlinking data considerations were included in this procedure, but due to the short communication windows with the satellite, on the order of 10 minutes, it was found during the ODTs that the operators were spending too much time determining what data to downlink. The optimisation of downlinking data by fully equipping the operator for the upcoming communication window, was a major motivation for the development of the Prerequisite Knowledge section and pre-communications pass checklist. The aim of the manual is to provide detailed instructions to the operators, however, with the downlinking of data, calculations are going to have to be made during the communication window and inevitably, the decision on how much data and from what storage channels is ultimately left to the operator. For this procedure, the EIRSAT-1 Operations Manual has provided the operator with all the required knowledge - data priority for different scenarios, the rows of data already downlinked from the channel, how to calculate what rows need to be downlinked and an estimate of how long it will take to download the data.

As part of the future work on the Operations Manual and based on the outcome of the ODTs, the EIRSAT-1 Operations Team plan to create a GUI that operators can use for data downlink calculations for increased efficiency during communication windows. The operator will provide the absolute rows logged for the desired channel, the time allocated to the storage channel for downlink and the downlink capabilities i.e. baudrate, overhead, telemetry encoding enabled/disabled. The first row and last row for downlinking data from the storage channel will be provided to the operator.

D. Fault Analysis Procedure Example

The Fault Analysis procedures are a major section of the Operations Manual. These procedures guide operators in determining why the satellite has encountered the anomaly and when it is appropriate to return to a nominal configuration. In discussing two of the major non-nominal procedures, *Safe Mode Entered* and *Primary2/Failsafe Entered*, it was concluded that both events could be caused by similar anomalies e.g. reboot, power cycling or low battery voltage. The Fault Analysis procedures were then divided into two groups - the procedures to determine why an unexpected mode/image was entered (*Safe Mode Entered, Primary2/Failsafe Entered, SS Re-Entered*) and the
procedures investigating these causes and how to recover (Low Battery Fault Analysis, SC Reboot Fault Analysis). This section will initially discuss the considerations taken by the EIRSAT-1 team for the Safe Mode Entered procedure. To begin the development of the procedure the possible causes for the SC entering Safe Mode were determined: Command from Operator, OBC Reboot/Full SC Powercycle or Low Battery Voltage (< 7.5V). The procedure then provides the operators with the data and parameters to use to investigate the cause of the mode transition. This procedure focuses on the cause of the entry to Safe Mode so during the following communication passes, the correct data will be assigned highest priority and can be downlinked to investigate and resolve the anomaly.

To rule out a command from the operator, the operators are instructed to ensure no TC was sent to instruct the SC to enter Safe Mode using the spacecraft’s telemetry logs. Then the operators search the Event log data to determine when the Safe Mode Trigger event was raised. This timestamp can be used to search other data sets. The operator is instructed to inspect any events that occurred around this time and is provided with an event that means Safe Mode was triggered by an OBC Reboot/Full SC Powercycle and an event that signals a Low Battery Voltage (< 7.5V). The operator is then guided to the procedures to be followed if one or both of these events are observed i.e. Low Battery Fault Analysis or SC Reboot Fault Analysis.

Taking the Low Battery Fault Analysis procedure as an example, the highest downlink priority would be assigned to the PASCAL and HK data, where all the battery voltage and current level values are logged by the SC. Initially, the operators are instructed to use the HK data to determine when the battery started to drain at a higher than normal rate, if ‘normal’ battery voltage levels are now observed, and if the ‘normal’ battery charging-discharging cycle has resumed. If the charging rates are abnormal, the manual instructs the operators to determine the cause e.g. malfunctioning solar array, satellite in eclipse, pointing scheme error. If the charging rates have returned to normal, the operators must examine the current draw from the four EPS buses during the window where the battery was draining at a higher rate before triggering a low battery anomaly. Depending on which bus was experiencing a high current draw, the sub-systems (e.g. OBC, ADCS) powered by that bus should then be examined to determine why it was drawing excess current.

To realistically test these Fault Analysis procedures, ODTs were performed where the operators were unaware the SC was in Safe Mode and what caused the mode transition. Prior to the ODT, the SW Engineer introduced a scenario which pushed the SC into Safe Mode e.g. allowing the battery to deplete below 7.5V. This approach made the testing of the ODTs more flight-like and ensured the procedures equipped the operators with the correct tasks and parameters to successfully determine the cause of the anomaly and how to recover the mission. The Fault Analysis procedures for the Operations Manual are still in their development phase as many considerations need to be addressed to prepare for all possible non-nominal scenarios.

E. GMOD Commissioning

The procedures discussed in the previous sections are all general operational procedures that would be required for any mission. However, in addition to the development of these nominal and non-nominal scenario procedures, the EIRSAT-1 team have been developing procedures specifically for the three on-board experiments, GMOD, EMOD and WBC.

To develop the payload operational procedures, ODTs were performed with both the Operations Team and Payload Team to ensure that the operation of the payload is regarded independently and as part of the full satellite system. In this section, the GMOD Commissioning procedure will be used as an example to convey the considerations made by the EIRSAT-1 team when developing the payload specific operational procedures. The EIRSAT-1 Commissioning procedures will be followed for a number of weeks following launch and Initial AOS. During this time, extensive functional checks of the system and its payloads will be performed.

The GMOD Commissioning procedure was initially one procedure and the first iteration consisted of fundamental configuration checks e.g. payload power on, operational mode transitions, setting the value of the bias power supply. During the first GMOD Commissioning ODT, it was decided that the payload commissioning procedures would be split into a Health Check procedure and an Operations procedure. The same split was also applied to EMOD. Using feedback from this ODT, the GMOD Health Check procedure was improved such that all the critical functional checks for the subsystem are completed ensuring that the payload can be turned on and all the configuration parameters are performing...
as expected. Later in the EIRSAT-1 Commissioning phase, the running of the GMOD experiment will be evaluated in the GMOD Operations Commissioning procedure which focuses on the advanced functionality of the payload. During this procedure, the streaming of data from GMOD to the OBC will be assessed and the processing of this data into light curves and spectra will be evaluated.

The firmware for the GMOD microcontroller [27], and the GMOD software component on the OBC [15], are both currently being developed in UCD, and undergoing regular updates. Once these firmware and software components are frozen for the EIRSAT-1 EQM campaign, an ODT for the GMOD Commissioning Health Check and Operations procedures will need to be performed. This ODT will establish any parameters and actions that are not fully assessed in the current Health Check procedure, and any experiment running features that have been implemented that need to be tested during the GMOD Operations procedures.

IV. Discussion and Future Work

The EIRSAT-1 Operations Manual is still under development and only accessible internally. The team have learned it is essential to begin developing the spacecraft operations procedures once a full system configuration is available i.e. EQM FlatSat. By commencing operations development early in the project, the Operations Manual can be thoroughly tested to improve the likelihood of mission success and provide the student team with experience in operating the satellite in flight-like scenarios.

The EIRSAT-1 Operations Manual has been continuously updated using ODTs to develop procedures for routine and non-nominal mission scenarios. The ODTs performed to date have been essential in revealing procedures not considered initially e.g. NACK/Timeout/Unexpected TM, or scenarios not originally contemplated e.g. SS Re-Entered. A major motivation for the continued development of the EIRSAT-1 Operations Manual is to optimise the relatively short communication passes the team will have with the satellite. Through performing ODTs, it was found that there were many time-consuming considerations for data downlink. A preparatory checklist procedure was developed to ensure operators had the information and skills for optimal use of the communication window to assess the health of the spacecraft and downlink experiment data. In addition to the Pre-Communication Pass Checklist procedure, a detailed Prerequisite Knowledge section was produced by the team which contains all the essential information the operator must have before communicating and controlling EIRSAT-1.

The development of the experimental operational procedures require a different approach, as the both the Payload Team and Operations Team must be involved in the development. In the first ODT for GMOD Commissioning, it was revealed that the commissioning of GMOD required two procedures to assess the health of the payload and then to investigate the performance of the experimental instrument. Since the in-house developed firmware for the payload is still under development, the operations procedures will need to be re-assessed in an ODT once the experimental firmware is frozen to ensure the functionality of all aspects of the payload is addressed.

The ODTs are still being performed for new procedures revealed from the incremental testing and to refine the mission critical procedures such as those for fault analysis and recovery. To obtain more perspectives and input, the team aim to involve all members in their development to try to include all potential scenarios and, where applicable, all possible causes/solutions. The EIRSAT-1 Operations Manual development will be frozen prior to the EQM Mission Test Campaign in May 2021. During this ~3 week Mission Test [14], the team will carry out a series of flight-like nominal and non-nominal scenarios where all aspects of the Operations Manual will be rigorously tested. The feedback from this test campaign will be used to update the Operations Manual for the FM Mission Test Campaign, which will be the final large-scale assessment of the Operations Manual prior to launch.

It is vital for teams to gain experience in controlling the satellite within the time constraints expected for the communication windows. In addition to the ODTs highlighting missing steps and missing procedures, they have emphasised the importance of operations training for student teams as an important aspect of the approach to operations development. The ODTs and Mission Test Campaigns will be conducted to provide all members of the team with the opportunity to control EIRSAT-1 within communication window time constraints.
There is on-going development of tools that the EIRSAT-1 team will use during the ODTs e.g. Python based tool to simulate realistic communication windows. As mentioned in Section III.D the EIRSAT-1 team are currently creating a GUI interface to optimise the data downlink calculations during communication passes. This GUI will be tested extensively during ODTs and Mission Test campaigns to ensure it is optimised for in-flight operations. The team will continue to disseminate the progression and analysis of its approach to the development of its operations procedures and manual.

V. Conclusion
To reduce the risk of mission failure, the EIRSAT-1 team present their approach to rigorously test and develop a robust Operations Manual. The operation of EIRSAT-1 is complicated by the three novel on-board payloads and a custom-built antenna deployment mechanism. The Operations Manual introductory sections contain an explanation of the operator’s interface to the 2U CubeSat and all the prerequisite knowledge required by the operator to be fully prepared to communicate and command the spacecraft. The manual contains the procedures required during the mission for commissioning, routine operations, experiment running and fault analysis and recovery. A series of ODTs have been performed by the team to individually develop and assess each of these operations procedure. These tests have highlighted critical issues within procedures and missing procedures. A subset of procedures have been presented as an example of the considerations and improvements made based on feedback from the ODTs. The EIRSAT-1 Operations Manual will continue to be updated after assessment in future ODTs and the EIRSAT-1 EQM and FM Mission Test campaigns.

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