

Development, description, and validation of the operations manual for EIRSAT-1, a 2U CubeSat with a gamma-ray burst detector

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ABSTRACT. CubeSats provide opportunities for science and technology demonstration missions with low-cost solutions and short project timescales, in particular, for studying gamma-ray bursts (GRBs) in the multi-messenger era. A robust operations strategy for scientific CubeSat projects is key to optimizing the results obtained from the experimental instruments. The Educational Irish Research Satellite-1 (EIRSAT-1) is a 2U CubeSat with three payloads, including a bespoke gamma-ray detector, gamma-ray module (GMOD), developed in-house for the detection of GRBs. The detection and reporting of GRB triggers to the scientific community complicates and drives the mission operational strategy. The operational procedures developed for commissioning and operating GMOD are detailed. The successful operation of EIRSAT-1 will facilitate the detection of ~15 GRBs/year in low Earth orbit. To increase the likelihood of mission success, the project is following a prototype model philosophy, building, and testing, both an engineering qualification model (EQM) and flight model. The EIRSAT-1 operations manual is the document that will instruct operators in commanding the spacecraft correctly and efficiently throughout the mission lifetime. The operations manual must be refined in parallel to payload development. This two-model philosophy has provided time for the early development of the EIRSAT-1 operations manual with the EQM. The EIRSAT-1 operations manual has undergone incremental updates based on feedback from operational development tests (ODTs), and a version with 35 procedures was frozen prior to the month-long EQM mission test (MT). Specifically, the objective of our work is to validate and refine the operations manual using the EQM MT process. Although the ODTs were effective preparation, the MT process highlighted issues, such as procedures operators found convoluted, and scenarios not yet considered during the initial development stages. Two new procedures were identified, 8 procedures required major updates, 15 required minor updates, and the remaining 12 required no improvements after the MT. The validation process facilitated operator training in mission representative conditions, such as GRB triggering data downlink with GMOD, and the major lessons learned during the development and validation process are presented.

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1 Introduction

CubeSats are small-scale satellites, usually conforming to a design standardization, defined by California Polytechnic State University specifications.¹ CubeSat designs are based on units where 1 unit, a 1U, is a 10 cm × 10 cm × 10 cm cube with a mass <1.33 kg. Their popularity is growing exponentially in recent years due to their science and technology demonstration capabilities.^{2–4} CubeSats were originally developed as an educational tool,^{5,6} and this led to the production of commercial-off-the-shelf (COTS) components. COTS components can be used for the fundamental subsystems of the satellite, e.g., power, communications, onboard computer (OBC), allowing for more resources to be applied to the science objectives of the mission.⁷ CubeSat missions must accept higher risk in return for low-cost and fast delivery.

Lower risk acceptance and lack of robust system-level testing have contributed to a high failure rate of CubeSat missions with half of the first 100 CubeSats launched by University teams being unsuccessful.^{8,9} The Educational Irish Research Satellite-1 (EIRSAT-1) mission is complex with three in-house developed payloads and an antenna deployment mechanism. The project aims to reduce risk and demonstrate a reliable spacecraft (S/C) by following, similar to the Aalto-1 mission,¹⁰ a prototype model philosophy. The EIRSAT-1 engineering qualification model (EQM) has been built,¹¹ and the flight model (FM) is currently being tested. Rigorous system level testing has been performed with the EQM being subject to a full functional test,¹¹ mission test (MT),¹² and environmental testing¹³ to qualification levels. The FM will undergo the same suite of testing to acceptance levels.

The primary payload of EIRSAT-1 is the gamma-ray module (GMOD), a <1 U scintillation-based detector.^{14,15} The objective of GMOD is to demonstrate novel technology for the detection of gamma-ray bursts (GRBs) and the operation of the instrument in-orbit, which requires on-board triggering, modification of the beacons when a GRB is detected, and prioritization of data for downlinking. GRBs are violent and short-lived explosions of gamma-ray radiation that are involved in the birth of a black hole.¹⁶ GMOD will be used to scale up to a configuration of CubeSat compatible gamma-ray detectors, with localization capabilities, as part of the 6U Gamma-ray Investigation of the Full Transient Sky project, which is also based on in-house instrument heritage.^{14,15,17–19}

In 2017, a breakthrough discovery was made when the electromagnetic (EM) counterpart to a gravitational wave (GW) event was detected (GW170817).²⁰ The coincident detection proved the hypothesis of a progenitor of short GRBs and marked the beginning of a new era of multi-messenger astronomy.²¹ This ground-breaking observation highlighted the importance of gamma-ray observatories in the multi-messenger era; however, a major challenge to future gamma-ray discoveries is the gap in planned future missions. The current fleet of GRB detecting missions has had remarkable success; however, many of the missions have far exceeded their nominal lifetimes. The Fermi Space Telescope,^{22,23} Neil Gehrels Swift Observatory,²⁴ and INTEGRAL²⁵ have been in orbit since 2008, 2004, and 2002, respectively. Currently, there is no sequential mission in advanced development from any major space agency, which will likely result in a gap in the technological capabilities of gamma-ray observatories in the time of major GW detector enhancements. CubeSats are relatively low cost and have short launch timescales²⁶ making them ideal candidates to bridge this gap. In addition to the current large-scale missions, a fleet of GRB detecting CubeSats (e.g., BurstCube,²⁷ MoonBEAM,²⁸ HERMES,²⁹ GRBAlpha,³⁰ CAMELOT,³¹ GRID,³² and GTM³³) could allow for adequate detection and localization of GRBs and increased sky coverage, during future GW instrumentation operating runs.

It is a challenge to operate a satellite in the harsh space environment.^{34,35} The main goal of the primary payload of EIRSAT-1 is to trigger on GRBs in real-time and rapidly report to the scientific community, further complicating the operations strategy of the mission. The EIRSAT-1 project identified that early development of an operations manual and operator training for a

student-led team with a lack of experience would increase the likelihood of mission success.³⁶ The EIRSAT-1 operations manual provides operators with the prerequisite knowledge and step-by-step instructions required to efficiently and successfully command the S/C and achieve the science and technology goals. Development began once a full system had been assembled, i.e., the EIRSAT EQM, to allow for rigorous testing of the operations manual.

This paper will focus on the development of the EIRSAT-1 operations manual and the validation during the EQM MT. Section 2 will summarize the EIRSAT-1 mission with a focus on the primary payload, GMOD. An overview of the EIRSAT-1 operations manual will be presented in Sec. 3. Section 4 will detail the operational procedures specific to GMOD, including commissioning, experiment configuration, and downlink of GRB data, which is a key driving factor in the communication operations strategy for the mission. Section 5 will detail the validation of the operations manual via operational development tests (ODTs) and during the EQM MT. Section 6 discusses the major lessons learned by the team during the development of the operations manual and details the operational planning objectives that will be achieved before launch.

2 Educational Irish Research Satellite-1

EIRSAT-1, presented in Fig. 1, is a 2U CubeSat mission with science, technology demonstration, and education objectives being developed by a student-led team as part of the European Space Agency (ESA) Education Office's Fly Your Satellite! (FYS) Program.³⁷ As part of the FYS program, the team receives guidance and advice from ESA, and the team can make use of state-of-the-art ESA test facilities. All testing, results, and anomalies are tracked and reviewed by ESA experts. EIRSAT-1 has three novel payloads and an in-house developed antenna deployment module (ADM).³⁸ The objectives of each payload are scientific or to demonstrate novel technology. GMOD, discussed in more detail in Sec. 2.1, will perform real-time detection of the most luminous explosions in the EM universe, GRBs, and in doing so, demonstrate the use of bespoke gamma-ray instrumentation with miniaturized electronic readout.^{14,15} The ENBIO Module (EMOD) will monitor ENBIO Ltd.'s thermal surface treatments SolarWhite and SolarBlack.³⁹ These thermal coatings are on ESA's Solar Orbiter mission,⁴⁰ however, EIRSAT-1, will provide the unique opportunity to monitor their performance via resistance

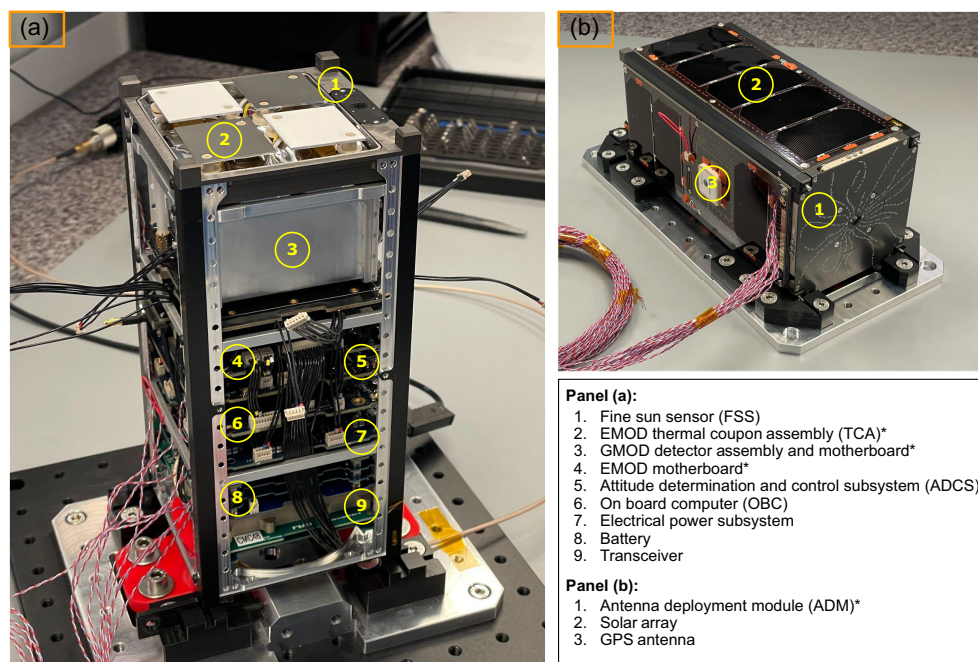


Fig. 1 (a) EIRSAT-1 FM internal components, both in-house developed payloads that are marked with an asterisk (*) and commercial off-the-shelf subsystems. (b) Completed EIRSAT-1 FM including solar arrays and ADM.

temperature detectors (RTDs). The wave based control (WBC) payload is a software demonstration testbed for a novel attitude control algorithm developed in University College Dublin (UCD).^{41,42} For communication, EIRSAT-1 makes use of the in-house developed ADM consisting of four coiled antenna elements. The elements are contained by doors held closed by two tensioned meltlines, which are cut by passing a current through one of two burn resistors.⁴³

The other foundational subsystems, the electrical power subsystem, attitude determination and control system (ADCS), transceiver, and OBC are all COTS components procured from AAC Clyde Space. The software on the OBC has been developed to interface with the in-house developed payload firmwares.⁴⁴ The prototype model approach was selected over building and launching one model (proflight) as EIRSAT-1 is a complicated mission incorporating three experiments with different objectives and a novel antenna deployment mechanism. The project is being developed, tested, and launched by a student team with no previous experience in operating a S/C. The EQM can also be used during the mission for hands on operator training and as a ground-based testbed for anomaly investigations. Some trade-offs of this approach include longer project timelines and financing the cost of building and testing two models of the satellite. The model philosophy allowed for early development of the operational strategies and the EIRSAT-1 operations manual, which will be vital in ensuring the goals of all payloads are achieved and the mission operates successfully throughout its lifetime.

2.1 GMOD and GRB Triggering

The GMOD experiment was designed to further the goal of detecting GRBs in the multimessenger era as introduced in Sec. 1. The EIRSAT-1 operational strategy (Fig. 2) needs to account for the transient nature of GRBs, which makes them unpredictable sources to study.

GMOD consists of two main components, the detector assembly and the GMOD motherboard (MB). In the detector assembly, a tiled array of 16 silicon photomultipliers (SiPMs) is

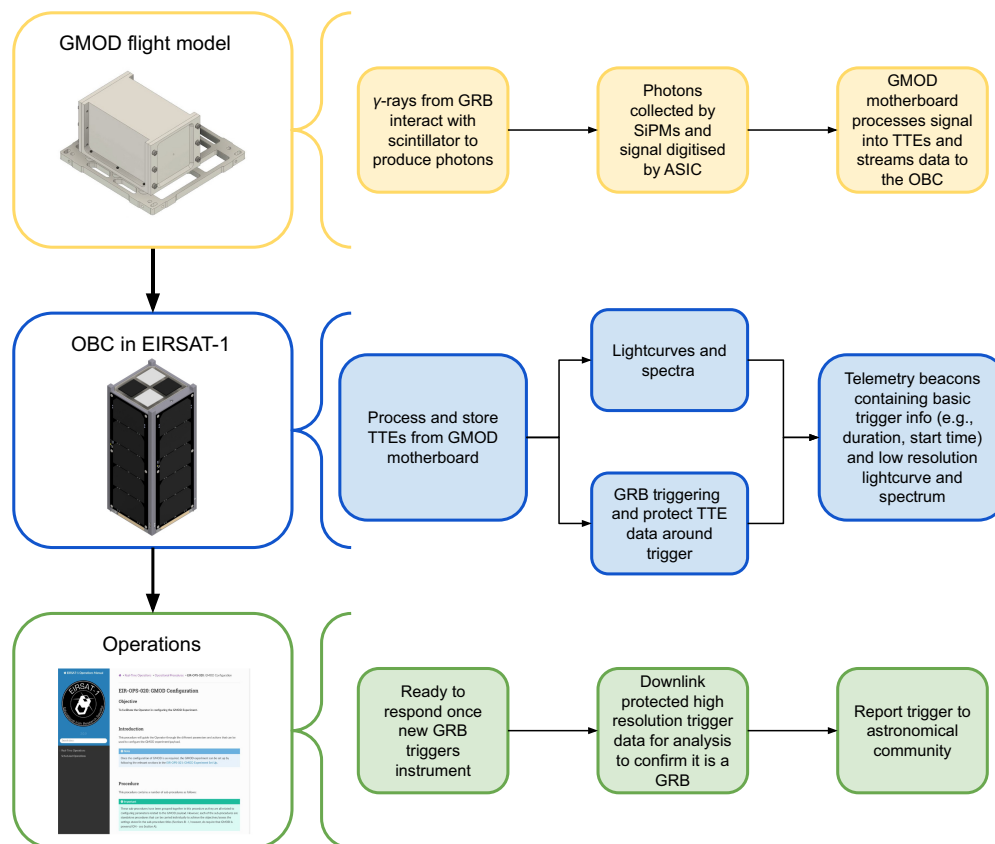


Fig. 2 GMOD operations: the GMOD instrument detects γ -ray events, streams them to the OBC, which makes data products and triggers on significant events. Operators downlink and report on the trigger data.

coupled to a scintillation crystal, which interacts with the gamma-ray photons to produce photons of characteristic energies that can be collected by the optical detectors. The outputs from the SiPMs are readout and digitized by an application-specific integrated circuit (ASIC), produced by Integrated Detector Electronics AS, called SiPM Readout ASIC (SIPHRA).⁴⁵ The GMOD MB supports the electronics required to power and operate the SiPMs and SIPHRA. The firmware on the GMOD MB has been developed in-house⁴⁶ to interface with the OBC of EIRSAT-1. The GMOD MB converts the channel data into time-tagged events (TTEs). There are TTEs generated for the 16 individual channels and for the sum channel (sum of 16 channels). Both sum and 16 channel TTEs are sent in pages to OBC, which stores them until a downlink of the data is requested from the ground station.

The OBC will use the GMOD TTE data to periodically generate lightcurves and spectra and store these in the GMOD lightcurve and GMOD spectrum storage channels for future downlink.⁴⁷ GMOD trigger generation is calculated based on a rolling average of counts in a specified energy range, the average count is compared to a predefined trigger significance level. If the significance level of the signal exceeds the trigger level, TTEs from a specified time period before and after the trigger time are copied and stored in a specific storage channel by the OBC.¹⁵ Due to communication constraints, it is not feasible to downlink all the data generated on board by GMOD. Priority will be given to the protected TTE data associated with triggers for GRB candidates. After a GRB triggers the on-board software (OSW), the satellite will emit beacons containing basic information about the trigger (e.g., duration, start time) and low-resolution spectra and lightcurves until the next communication pass with the EIRSAT-1 ground station.⁴⁸ The subsequent communication passes will be used to downlink the higher resolution protected TTEs around the time of the trigger for analysis, classification, and reporting to the community. The EIRSAT-1 operations manual needs to prepare operators to optimize communication with the satellite. In a communication pass of ~5 to 7 min, the operators will need to confirm the health of the S/C and downlink science data from any or all three experiments depending on the priority of the data to downlink, i.e., GMOD GRB data has a higher priority than EMOD RTD readings.

3 EIRSAT-1 Operations Manual

The EIRSAT-1 operations manual is generated using Sphinx⁴⁹ with the “read the docs” theme⁵⁰ to produce user-friendly HTML and PDF documents compiled from a set of reStructuredText (RST) markup files. The manual has two major components, the first section introduces the operators to the tools they will be using to interface with the S/C and the knowledge that will be required for successful operation. The second section contains the procedures required to operate EIRSAT-1 in nominal scenarios and procedures to guide operators in the case of an anomaly, try to determine the root cause, and how best to recover the mission.

3.1 Mission Control Software

The main interface with the S/C is currently via Bright Ascension’s Mission Control Software (MCS).⁵¹ At the start of 2022, the project was selected for the Bright Ascension Bright Start Academic Program and received a year’s sponsorship with their flight and ground software. The month-long EQM MT and previous testing were performed using an older version of the MCS with fewer features. Due to the timing of the sponsorship, the updates to the operations manual based on feedback and lessons learned from the test campaign, discussed in more detail in Sec. 5.2, and the updates for interacting with the new MCS could be implemented simultaneously. The MCS is similar to the previous interface with the S/C with an overview of the interface initially presented and then the main improvements outlined.

The operator loads a spacecraft database (SCDB) into the MCS, which is used to interact with the parameters and actions of the onboard software. Parameters can be set, obtained, queried, downlinked from, or uplinked to, and actions can be invoked. These terms are the building blocks of the interface to the S/C and are defined in Table 1.

The MCS has a number of components, with different roles, that can be displayed. Only the ones used by the EIRSAT-1 project to date will be discussed here. The default EIRSAT-1 layout of the S/C interface, before operator customization for a specific procedure, is presented in Fig. 3.

Table 1 Summary of main components used to operate and command EIRSAT-1 via the MCS.

MCS component	Definition
ACK	Acknowledgment packet from S/C to confirm TC received
NACK	TC not successfully executed, usually due to setting a parameter to an invalid value or requesting an invalid amount of data
Parameter	Configure some data associated with a spacecraft component, e.g., mission.ModeManager.Mode
Get	Read parameter value
Set	Change parameter value
Query	Obtain size of parameter value
Uplink	Transfer relatively large amount of data to a parameter/storage channel on the S/C
Downlink	Obtain relatively large amount of data from a parameter/storage channel on the S/C
Action	Function the S/C can be instructed to perform, e.g., payload.GMOD.TurnOnGMOD
Invoke	Command to instruct S/C to execute an action

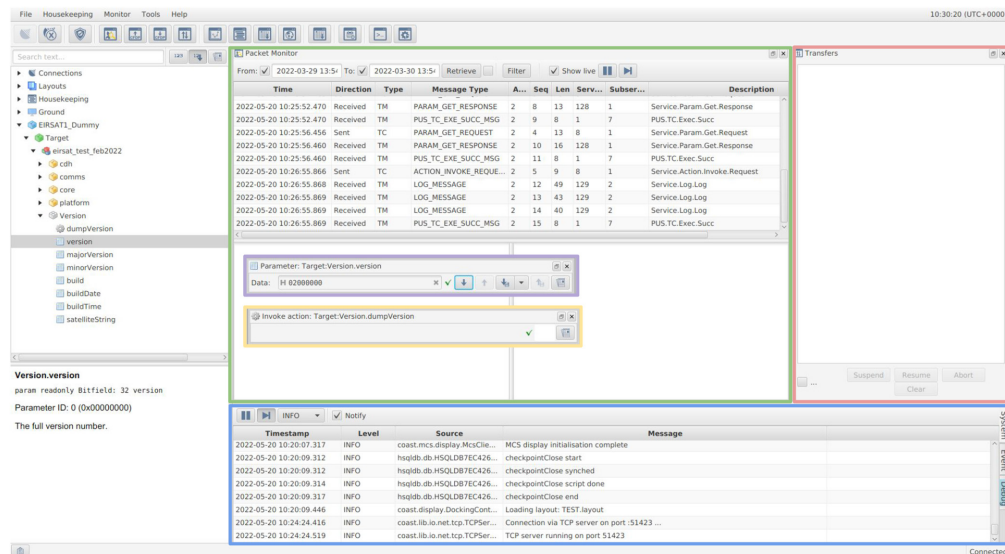


Fig. 3 Default MCS layout used by EIRSAT-1 team, including packet monitor (green box), transfer window (red), and system/event/debug console (blue). An example of an open parameter (purple) and action (yellow) is presented.

The panel on the left is the mission explorer containing a drop-down of the SCDB and connection settings to the S/C. The packet monitor window (surrounded by a green box) in the center displays the telemetry (TM) and telecommands (TCs) exchanged between the MCS and the S/C. The transfer window (red) is located on the right and displays the percentage complete of data being downlinked from/uplinked to the S/C. The transfer window can be used to abort, suspend, and resume any transfer of data between the MCS and the S/C. At the bottom of the layout is the System/Event/Debug console (blue). The System tab displays logs from the MCS itself, e.g., failing to connect to the S/C. The Event tab displays any events from the OBSW, e.g., transition to safe mode. The debug log shows debug information from the OBSW.

In addition to these components, parameters and actions can be opened and positioned on the console via the SCDB and used to interact with the S/C, with an example of each in Fig. 3. Layouts were created for different operational procedures during the MT as it prevented operators

from searching through the SCDB for a specific parameter during a communication pass. The first section of the EIRSAT-1 operations manual contains a comprehensive description of the aforementioned components of the MCS, how to load and change the SCDB, and how to set up communication via the MCS.

The EIRSAT-1 operations manual required a revision after transitioning to the MCS, the major updates to the introductory sections were to describe the new features available on the MCS summarized below:

1. The MCS has a graphical tool, in which multiple periodically polled parameters can be monitored in real-time during communication passes. This will be used to monitor the overall health of the S/C including its sensors (e.g., magnetometers, gyros, sun sensors, and temperature sensors) and actuators (i.e., magnetorquers). The interface during the MT had no graph generation capabilities, and all data were exported and monitored using a web-based tool, Grafana.⁵²
2. The MCS has internal scripting functionality, which allows operators to write programs to instruct the MCS to do a variety of operations, including getting/setting parameters, invoking actions, and commencing data transfers. The scripts are written in the Groovy language⁵³ and the team was provided with an MCS user manual⁵¹ and example scripts to help with the development of the EIRSAT-1 operational scripts.
3. The scripting functionality is the basis of the scheduling feature of the MCS. The MCS allows for scheduling of operations and provides tools to automate passes, including handling the uplink/downlink of data. These features will allow for the optimization of communication passes with EIRSAT-1. Scripts can be executed via absolute and relatively timed schedules, and the MCS has a color-coded indicator for each scheduled job. The indicator will be green when the script executes successfully, amber if the script never executed, and red if the execution of the script failed. Scheduled operations are part of the future work for the operations team (Sec. 6).
4. The MCS provides a more user-friendly interface with the S/C. As an example, when the S/C receives a TC, it will always respond with an acknowledgment packet (ACK). In the previous software, the operators were required to track the ACKs in the packet monitor. This made errors more likely in failing to observe or assigning an ACK to the wrong command. In the MCS, a green tick appears if an ACK is received from the S/C, instantly confirming to the operators that their command successfully reached the S/C. This improvement in the new MCS made available by the Bright Ascension sponsorship has reduced the risk of error in reading the packet monitor and improved operator efficiency.

3.2 Prerequisite Knowledge for Operators

In addition to describing the interface with the spacecraft, the operations manual contains details of all the knowledge that operators are required to have before commanding EIRSAT-1. This Prerequisite Knowledge section of the operations manual is an outcome of the ODTs, discussed in Sec. 5.1. Any background knowledge that applies to most, if not all, of the operational procedures is described. An in-depth description of the contents of this section can be found in Ref. 36, but the following points summarize the main topics:

1. Spacecraft TM: details the different types of TM that can be received from the S/C, and the appropriate response from operators in the case of a negative-ACK (NACK) or timeout (no response received from S/C).
2. Live event handling: during communication passes, live events from the S/C and house-keeping data can populate the MCS packet monitor, operators should monitor these and contact the software and/or systems engineer in the case of anomalous behavior.
3. Large data transfers (LDTs): transfers of large quantities of data are separated into LDT parts, which are downlinked in succession. Operators are instructed on how to monitor these LDTs via the transfer window and how to suspend/resume an LDT.
4. On-board storage: description of the different types of memory data stored onboard the S/C and clear instructions on when certain memory types are accessible. For example,

while the primary image is operating, data are primarily being logged to Flash, and so, data will primarily be downlinked from Flash.

5. Data downlink considerations: data are stored in rows in linear and circular storage channels on the OBC. The operations manual includes details of the downlink logic required to request the newest or oldest rows from both types of storage channels. It also provides guidance on data downlink priorities. For example, during nominal operations, if there are GRBs in storage, the operator should first downlink some housekeeping data to determine the health of the S/C and then use the remainder of the downlink window to obtain GMOD GRB data.
6. Example operational procedure: all of the EIRSAT-1 operational procedures follow a similar format with a statement of the objective of the procedure and a step-by-step guide of all the TCs/operations. An example procedure is presented in Fig. 4. Each step has a TM/TC table containing the details of the TC to send and if there is TM to be returned and its expected contents. The operations manual makes use of RST features, such as the Important and Note boxes in Fig. 4 to draw the operators' attention to vital information considering the parameter/action being used, remind them of procedures that need to be followed prior to the current one, or to link to the form for reporting any issue encountered during the communication pass.

3.3 Operational Procedures

The operations manual currently has 37 manual operations procedures for nominal and anomalous mission scenarios. The operational procedures can be split into four groups: early mission, nominal, payload, and fault analysis. Examples of each procedure category are presented, and the full list used in the EQM MT can be found in Ref. 36:

1. Early Mission: Initial Acquisition of Signal (AOS), Commissioning
2. Nominal: Start a Communication Pass, Downlink Data, Operational Mode Change, Boot into OBC Image
3. Payload: Upload Payload Image, EMOD Configuration, GMOD Experiment Set Up
4. Fault Analysis: Safe Mode Entered, Low Battery Fault Analysis, Failsafe Entered.

A more detailed description of the objectives of these example procedures is presented in Sec. 5.2. In summary, early mission procedures will only be required in the initial phases of the

EIR-OPS-020: GMOD Configuration

Objective
To facilitate the Operator in configuring the GMOD Experiment.

Introduction
This procedure will guide the Operator through the different parameters and actions that can be used to configure the GMOD experiment/payload.

Note
Once the configuration of GMOD is as required, the GMOD experiment can be set up by following the relevant sections in the EIR-OPS-021: GMOD Experiment Set Up.

Procedure
This procedure contains a number of sub-procedures as follows:

Important
These sub-procedures have been grouped together in this procedure as they are all related to configuring parameters related to the GMOD payload. However, each of the sub-procedures are standalone procedures that can be carried individually to achieve the objectives/assess the settings stated in the sub-procedure titles (Sections B - I, however, do require that GMOD is powered ON - see Section A).

A. Basic Settings - Turn On, Mode, Error Counter
 B. Bias Offset Settings (Configure and Enable Bias Offset and Disable Bias Offset)
 C. Boost Converter Settings (Enable Boost Converter and Disable Boost Converter)
 D. Constant Current Settings (Configure and Enable Constant Current and Disable Constant Current)
 E. External Trigger Settings
 F. SIPHRA Configuration
 G. Lightcurve and Spectrum Configuration
 H. OBC Triggering Configuration
 I. Turn Off GMOD

A. Basic Settings

Important
You are about to send the first TC of this procedure - Have you completed the EIR-OPS-003: Start a Communication Pass procedure? A Communication Pass must be started prior to carrying out the operations planned for the pass. Don't forget to open and set up the parameters/actions that will be used during the pass in TMTCLab before the pass begins!

1.A Turn on GMOD using the action `plataform.OPS.TurnOnGMOD`

TC Details	
TMTCLab: Operation	[invoke]
Action/Param Name	<code>plataform.OPS.TurnOnGMOD</code>
Action/Param ID	1222
Data Expected with TC	Yes
Data Size	N/A
Data Info	N/A
Allowed Value(s)	N/A
Expected Value(s)	N/A
TM Details	
Data Expected from TC	ACK
Data Size	11 bytes
Data Info	N/A
Allowed Value(s)	N/A
Expected Value(s)	N/A

Note
Were any issues encountered in this step? If so, use the following link to log the issue and do NOT continue with the remainder of the procedure until the Software and/or Systems Engineer have reviewed the issue. Refer back to this note after each step of the procedure occurs.

Fig. 4 Extract from GMOD configuration procedure in the EIRSAT-1 operations manual. The format (objective, introduction, and step-by-step procedure, TM/TC tables) is displayed.

mission, such as making first contact with the S/C after launch and checking the functionality of the subsystems and payloads in the commissioning phase. Nominal procedures will be used on a daily basis by operators, some will be used during every pass. For example, Start A Communication Pass will be performed every time contact is made with the S/C to determine its current state and if any new GRBs have been detected. Nominal operations will also include the downlinking of housekeeping data to assess the health of the S/C and science data from the three experimental payloads. There are procedures specific to the configuration and experiment running of the two hardware payloads, EMOD and GMOD. The development of the WBC procedures will be part of the future work updates in preparation for the flight-ready operations manual.

The most challenging operational procedures to develop were the fault analysis procedures. Seminars were held to discuss the possible points of failure in the mission. These seminars resulted in a list of off-nominal operational procedures, which can be split into two categories—procedures to determine the cause of entering an unexpected mode or OBC image (e.g., Safe Mode Entered, Failsafe Entered) and procedures to determine the root cause(s) of the anomalous behavior and how to recover the mission (e.g., Low Battery Fault Analysis, S/C Reboot Fault Analysis). Ref. 36 contains a detailed example of a procedure from each of the four categories. This paper provides more detail on the GMOD operational procedures (Sec. 4) and describes the operational manual validation methods employed by the team (Sec. 5).

4 GMOD Operational Procedures

As the detection and generation of gamma-ray trigger alerts are key to the science output of EIRSAT-1, the operation of GMOD is discussed in more detail in this section. The operations are split into sections of commissioning, experiment configuration, and data downlink, with a focus on GRB data acquisition. These procedures were developed by the collaboration of the EIRSAT-1 operators and GMOD team members. All the procedures were subject to at least one ODT (Sec. 5.1) in their development and were tested during the EQM MT (Sec. 5.2). Feedback contributing to the improvement of these procedures is discussed. The GMOD procedures are also included in the MT validation approach discussed in Sec. 5.2.

4.1 Commissioning

Initially, GMOD was to be assigned one operational procedure during the commissioning phase of the mission. However, the ODTs exhibited that breaking the GMOD commissioning into two sections would be more beneficial. Once the core subsystem health checks (battery and ADCS) are completed, a GMOD health check will be performed to assess the basic functionality after launch. The second subset of commissioning procedures involves setting up the S/C for more routine operations. These include a GMOD operations procedure, which will set the experiment running in-orbit for a short duration of time to verify functionality. Both GMOD commissioning phase procedures are described in detail in Fig. 5. The MT verified this approach to commissioning GMOD, and the updates that are required for the flight operations of GMOD are based on advancements made in the firmware.

4.2 Experiment Configuration and Running

The GMOD configuration and GMOD experiment running operational procedures were developed and adapted from the commissioning procedures. The GMOD configuration procedure guides the operator through the different parameters and actions that can be used to configure the GMOD payload. There are eight sub-procedures that can be carried out individually to assess and update the GMOD experiment parameters. The sub-procedures contain the basic configuration instructions, e.g., to turn the experiment on/off, get and change the operational mode, and set voltage and current values. It also contains sections to customize the lightcurve and spectrum parameters (e.g., bin width, integration time) and set up and enable GRB triggering.

The GMOD experiment running procedure consists of items detailed in points A, B, C, and F in the outline of the GMOD commissioning operations procedure in Fig. 5. GMOD will primarily run with just sum channel data being generated and streamed to the OBC and the OBC triggers on sum channel data. There is a separate operational mode for the generation and stream

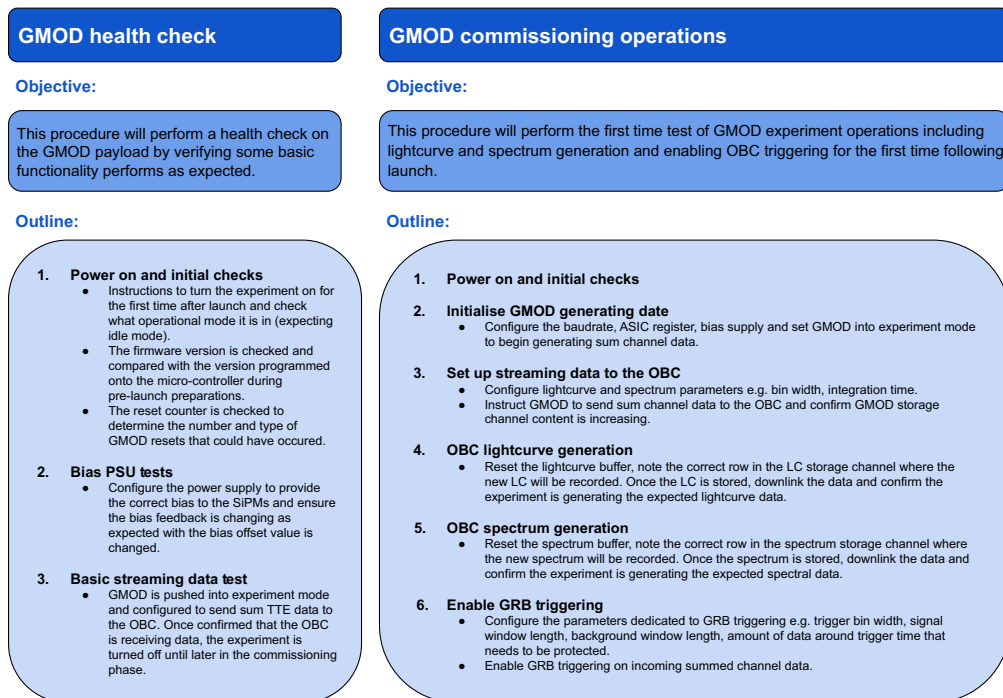


Fig. 5 Summary and statement of the main aims of the GMOD health check and GMOD operations commissioning procedures in the EIRSAT-1 operations manual.

of 16 channel data from GMOD to the OBC, this will be performed as a technical demonstration but will not be part of the daily operations of the GMOD experiment.

4.3 GRB Data Downlink

The scientific objective of the GMOD experiment is to detect GRBs and report triggers to the high-energy astrophysics community. This requires a complex operational strategy as these short-lived (approximately seconds long), and isotropic events need to be reacted to in real time. This operational requirement is unlike many other science-based observatories running on scheduled observations of known sources.

The OBSW includes a GRB trigger counter in the satellite beacon whose format will be made publicly accessible. This is to facilitate large communities of ground stations, e.g., SatNOGS⁵⁴ in decoding the beacons and informing the team of new GRB data. The S/C will beacon basic trigger information, compressed lightcurves, and spectra until it communicates with the ground station. Once a trigger has been identified, the following communication passes will prioritize downlinking the protected higher resolution TTE data around the time of the event for ground-based analysis. This analysis will include confirming if the event was a GRB and reporting the observation to the community. As shown in Fig. 6, knowing about a new trigger before a communication pass will increase the efficiency with which the team can respond to GRBs. If the amateur radio community can inform the operators that a new trigger has been detected (grey panel on left of Fig. 6), the next pass plan can include downlinking GRB data. However, if the operators discover the GRB trigger counter has increased during a pass, the downlink of the data will be included in the subsequent pass plan but this delays initiating data acquisition by approximately hours, i.e., the right-hand side of Fig. 6 will need to be followed before proceeding to the downlink of GRB data (left-hand side) during the next communication pass.

It will take multiple passes to downlink the data from a GRB, so commencing the downlink rapidly is vital. The downlinking of GRBs will make use of the suspend/resume feature of data transfers in the MCS. At loss of signal, due to the S/C passing beyond the TM/TC horizon, the MCS will automatically suspend the transfer of GRB data, this can then be resumed by the operator during the next pass(es) until all the data have been successfully downlinked. At the start of each communication pass, the most recent housekeeping data will be downlinked before resuming any GRB data transfer to monitor the current health of the S/C.

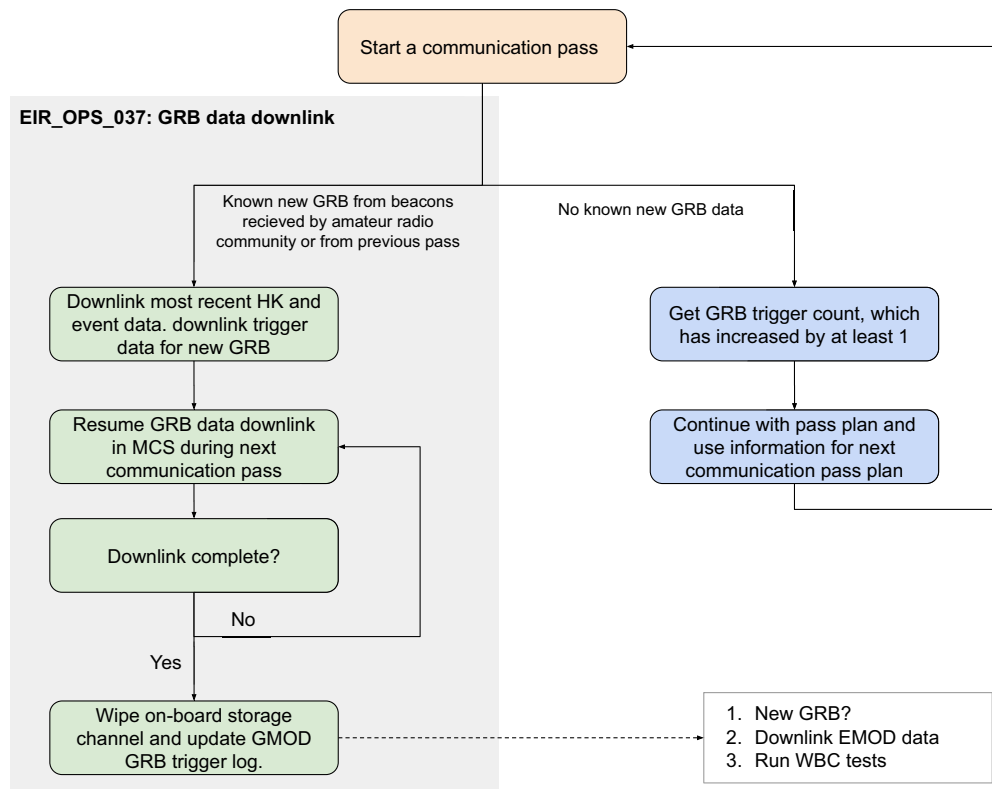


Fig. 6 Approach to determining when there is new GRB data and downlinking this data with time-constrained communication passes.

Once that GRB has been successfully downlinked, the storage channel needs to be wiped manually by an operator to free the storage channel for future GRB trigger data. The OBC has 40 storage channels allocated to GRB data. There will be a trigger log on the ground that operators will be responsible for populating when data have been downlinked, from which storage channel and if the channel was wiped successfully. Once data for a GRB have been successfully transferred from the satellite, operators will need to determine the next highest priority task, which could include downlinking the next GRB, some RTD data from the EMOD experiment, or running the WBC experiment.

5 Operations Manual Validation

The EIRSAT-1 operations manual has undergone numerous iterations, and has been subject to rigorous testing. Examples of the procedures for the GMOD instrument were given in the previous section, and a similar process was followed for the commissioning and operation of the other subsystems and payloads on the S/C. Figure 7 outlines the approach taken in developing and verifying the operational procedures for all possible contingencies.

Initially, possible nominal and off-nominal mission failure scenarios were conceived and discussed. The accumulated list of operational procedures to be developed and tested were assigned to a member of the operations team, and a first draft was developed. The first procedures outlined the step-by-step instructions for an operator to command the S/C using MCS (Sec. 3.1) to achieve the operational objective, e.g., GMOD experiment configuration. The prerequisite knowledge topics (Sec. 3.2) were also discussed and assigned for an initial draft. Prior to any testing, operators were required review and be familiar with its contents, as the remainder of the procedures assume this fundamental knowledge of MCS and the S/C.

These first drafts were reviewed by the operations team and then subject to an operations development test, as described in Sec. 5.1. Feedback from the ODTs was used to improve the procedures, and for more complicated procedures, multiple ODTs were performed. In August 2021, the month-long MT was conducted, and a version of the EIRSAT-1 operations manual was

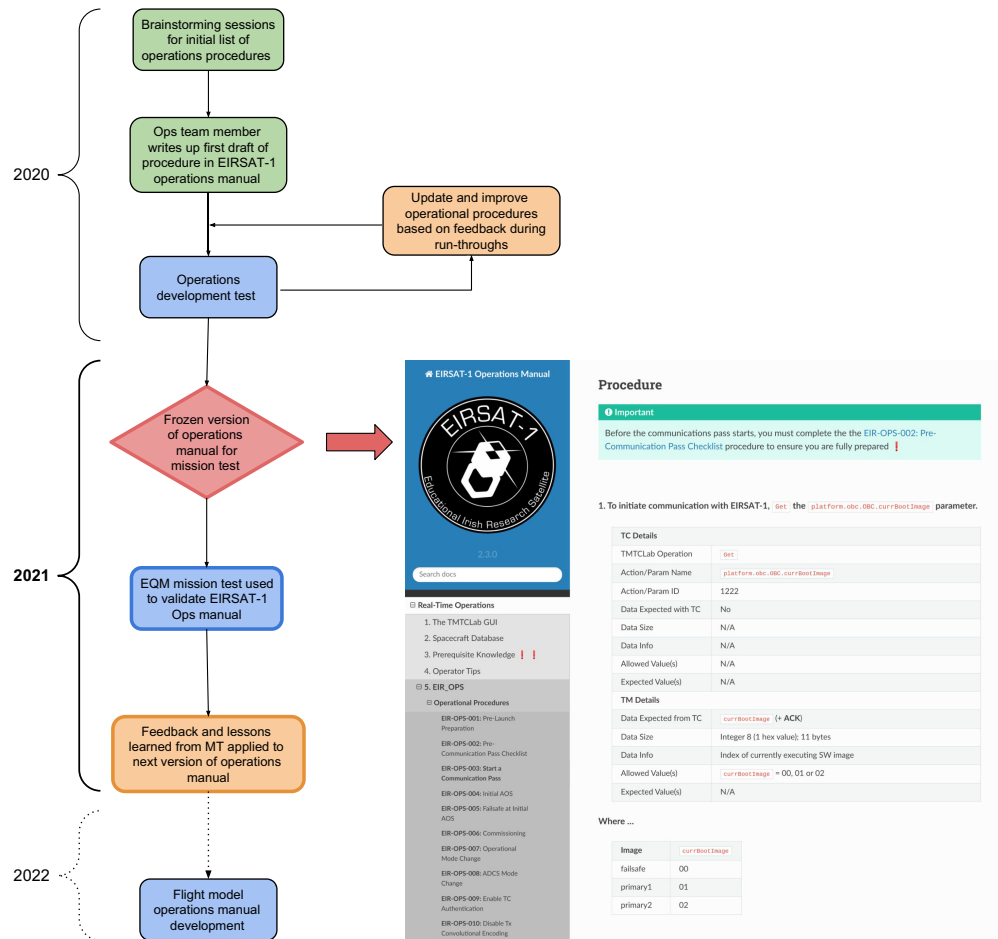


Fig. 7 Flow diagram displaying the past and future development stages of the EIRSAT-1 operations manual.

frozen for this test campaign. The MT provided the opportunity to extensively test the procedures that had been written to date and also revealed procedures that needed to be created. An overview of the MT, the feedback on the operations manual, and the main lessons learned by the team will be presented in subsequent sections. The team is currently preparing the FM version of the operations manual, implementing feedback from the MT and updates based on the new MCS interface.

5.1 Operations Development Tests

ODTs were used to initially test the procedures individually or in small subgroups (e.g., Upload Payload Image and Rewrite Payload Firmware). Once an initial draft of a procedure was prepared and reviewed, an ODT was organized. Members of the team not involved in the development of that procedure would follow it with the EQM and provide feedback. Any procedures that required large updates were subject to more than one ODT.

The ODTs revealed the importance of initiating operations development once a full system configuration is accessible. Missing scenarios, procedures, and steps were all revealed in the iterative process of testing the individual operational procedures. ODTs were essential in introducing the team to the operations manual and familiarizing them with the prerequisite knowledge and format of the procedures. ODTs also facilitated all team members interacting with the S/C via an interface similar to the MCS. This S/C interface was used during the ODTs, as at that point, the project did not have access to Bright Ascension's MCS. This predecessor to the MCS had the same major components but not as many user-friendly features, as discussed in Sec. 3.1. The ODTs were the initial stage of operator training of the EIRSAT-1 team.

The ODT approach also had its limitations, the tests were not conducted in a flight-like configuration to complete the first assessment of the procedures efficiently and with the available resources, i.e., the full operational chain had not been developed, and the analysis tools for processing the downlinked data had not been completed. In flight, there will be constricted communication pass times with approximately minutes to complete procedures. Communication pass times were not implemented during ODTs as the main objective was to improve the step-by-step instructions. Without time pressure, the operators could progress through the procedure, pause for feedback and discussions, and there was time to note the required updates for the operations team to implement. For efficiency, the ODTs were performed using serial communication with the S/C. In flight, all communication will be over radio frequency (RF), increasing the time taken to receive responses and data from the satellite. The EQM MT was a more rigorous assessment of the EIRSAT-1 operations manual, and Sec. 6 outlines the major differences between validating the EIRSAT-1 operations manual using the ODTs and MT.

5.2 Engineering Qualification Model Mission Test

The EQM MT was conducted during August 2021, and a full description of the approach taken to MT can be found in Ref. 12. The MT is a long-duration test campaign simulating flight-like scenarios, including early mission, nominal, and anomalous scenarios. The MT was designed to run through as many scenarios as feasible in 4 weeks and was therefore the logical advanced test of the EIRSAT-1 operations manual. The first week of the MT simulated initial AOS and commissioning of the subsystems and payloads. The remaining 3 weeks tested nominal operational procedures for EIRSAT-1, experiment running procedures for GMOD and EMOD (WBC was not advanced enough to be included in the EQM MT), and off-nominal scenarios, such as low battery events and unexpected S/C reboots.

Throughout the MT, the spacecraft operators could only interact with the S/C during simulated communication passes of ~3 to 5 min. There were 4 to 5 passes per day, 7 days a week. Test support operators monitored the test ground support equipment (GSE) and manipulated the S/C to inject non-nominal scenarios, e.g., turning off S/C charging and allowing the battery to fall below a certain threshold to trigger entry into safe mode. The MT was utilized for operator training, and the team was exclusively self-taught. Prior to the start of the test campaign, seminars were run for the team by the lead operations engineers to provide an overview of the EIRSAT-1 operations manual and the operator tools, e.g., MCS and Grafana. The manual was provided to the team in advance of the MT to allow time for them to become familiar with the prerequisite knowledge sections and the procedures. Two operators are always required to command EIRSAT-1, the lead operator commands the S/C via MCS while the supporting operator reads the instructions in the manual. During the EQM MT, there was always one experienced operator present for each communication pass but as the MT progressed, the operators in training took on the lead operator role. For the FM MT, the same approach was taken, where less experienced operators began with the supporting role, then as their confidence and competence in commanding the S/C increased, they were given the responsibility of being lead operator.

The majority of the operational procedures were tested during the MT, and the test campaign revealed two new procedures that needed to be developed around downlinking data in atypical scenarios. Of the 35 procedures tested during the MT, 12 required no updates due to sufficient development in the ODTs, 15 required minor updates, and 8 required major updates. Minor updates included typos or small clarifications in a step of the procedure, whereas major updates incorporated a reformatting of the procedure or adding multiple steps/sections. The procedure updates made from the EQM MT were validated during the FM MT. A frozen version of all of the procedures validated during the FM MT will comprise the EIRSAT-1 operations manual used during flight. Any new procedures or improvements required after the FM MT can be validated with the EQM in “mini-MTs,” which are 1-day MTs focusing on a specific scenario or procedure. Table 2 provides examples from each of the operational procedure categories, the number of ODTs that were conducted, and whether updates were required based on feedback from the MT.

Table 2 Examples of each of the EIR_OPS procedure categories (early operations, nominal, payload, and fault analysis) are presented. For each example procedure, the number of ODTs that were included is given in the third column. The final column states the updates required based on EQM MT feedback, with minor updates including typos, adding single steps in, or clarifying a confusing step. Major updates required multiple step changes, addition of new sections, or re-visiting the entire structure of the procedure. The minor* procedures require updates based on advanced FM firmware, rather than issues revealed by the MT.

Title	Description	ODTs	MT updates
EIR-OPS-004: Initial AOS	Prepares the operator to make first contact with the S/C following launch. The main objectives are to assess the state of the S/C (OBC image, mode) and to verify that the antennas are fully deployed.	2	Minor
EIR-OPS-006: Commissioning	The EIRSAT-1 commissioning phase will continue for a number of weeks following launch. During this time, extensive functional checks of the system will be performed. There are 11 commissioning sub-procedures for each of the subsystems on board. A payload commissioning example (GMOD) is presented.	4	Major
EIR-OPS-006.6: GMOD Health Check	Verify the basic functionality of the GMOD experiment. GMOD is powered on, the mode and error counters are checked and a basic streaming of some data to the OBC is initiated.	2	Minor*
Nominal operational procedures			
EIR-OPS-003: Start a Communication Pass	Initiate a communication pass with EIRSAT-1 and determine the current state of the satellite. The operator will determine the current boot image of the satellite, the uptime (i.e., elapsed time since the last reboot), the operational mode (if applicable), the number of GRB detected in GMOD data (if applicable), and will start an LDT (if applicable).	All	Minor
EIR-OPS-007: Operational Mode Change	The operator determines the current operational mode of the S/C, and the procedure details the steps to change the mode.	—	None
EIR-OPS-012: First-time Nominal Mode	Guide the operators through using some of the post-commissioning, non-sequential procedures in this manual to enter nominal mode for the first time and set up some “nominal” mission operations, such as GMOD/EMOD experiment running and science data collection.	—	Major
Payload operational procedures			
EIR-OPS-016: Upload Payload Image	Upload a new firmware to a storage channel on the OBC for later reprogramming of the GMOD/EMOD microcontroller.	2	Minor
EIR-OPS-019: Reset/Power-cycle a Payload	Operator will be instructed on how to (1) reset (i.e., a software reset of the microcontroller) and (2) power-cycle the GMOD/EMOD payload.	2	None
EIR-OPS-021: GMOD Experiment Set Up	Guide the operator through steps to set up GMOD to run an experiment, generate data, and pass it to the OBC. It also contains optional procedures to enable GRB triggering.	1	Minor*
Fault analysis operational procedures			
EIR-OPS-025: Safe Mode Entered	Instructs the operator to downlink data from the S/C to determine the most likely cause of the unexpected entry to safe mode and how to recover the mission based on the root cause.	3	Minor
EIR-OPS-026: Low Battery Fault Analysis	Assess the status of the S/C’s power systems after a low voltage event. Using this procedure, the operator attempts to determine the cause of the low battery voltage, the timeline of the issue, if it is still ongoing and what could be a potential fix.	2	None

5.2.1 *Early mission*

All of the early mission scenarios were subject to at least one ODT. Initial AOS required minor updates because during ODTs, the S/C was always ready for communication. During the MT, the operators had a time window where AOS was expected; only during the MT, it was realized that the operations manual only told operators to send the first command once. In reality, the first command should be sent frequently at the expected AOS time. The commissioning procedures, while undergoing ODTs, had never been completed in sequence for all subsystems and payloads. During the MT, it was found that the sequence of testing was not optimal and has been reorganized for the FM operations manual. The GMOD commissioning procedures only required minor updates related to improvements made to the firmware for the flight model.

5.2.2 *Nominal*

The Start a Communication Pass procedure had the same issue as Initial AOS and required only a minor update to send the first command frequently around the expected AOS time until the S/C responds. The Operational Mode Change procedure never underwent an ODT, but the software team followed it regularly during testing and no issues were found during the MT.

The First Time Nominal Mode procedure was one of two procedures that were never subject to an ODT due to time and resource constraints. Each step is linked to a different procedure that could be followed to transition to nominal mode, set up EMOD, set up GMOD, or perform an ADCS health check. During the MT, operators found this procedure very confusing and hard to navigate leading to a re-evaluation of the procedure format. This procedure highlighted the importance of the ODTs in determining the optimal format and content for operational procedures that are both functional and user-friendly.

5.2.3 *Payload*

None of the payload procedures required major updates, which is likely due to extensive testing independent of the MT. All underwent at least one ODT and during payload functional testing, the operational procedures were regularly used to configure and run the experiments providing further validation of the steps. The MT did reveal that the payload procedures could make use of more informative steps for operators not familiar with the experiment. The GMOD configuration and experiment set up procedures are currently being updated based on feedback from the MTs and revision of the firmware on the GMOD MB in preparation for the FM test campaigns.

5.2.4 *Fault analysis*

The fault analysis and recovery procedures all were subject to at least two ODTs to allow the majority of the team to operate during an anomalous scenario and provide feedback on all the scenarios considered for determining the root cause(s). This rigorous testing and involvement of the majority of the team proved beneficial as the procedures performed well during the MT and required only minor updates.

The EQM MT facilitated a long-duration test of the majority of the operational procedures required in flight-like scenarios for the EIRSAT-1 mission. In CubeSat projects, operations are often only developed late into the project due to time and resource constraints. The approach taken in developing the operations manual with the EQM highlights the importance of early development of the mission operational strategy as testing can be incorporated into other necessary test campaigns, such as the MT.

6 Discussion

Developing and validating all the operational procedures for a mission with multiple payloads is a challenge. GMOD complicates and drives the operational strategy of the EIRSAT-1 mission with its requirements to detect GRBs, which are short-lived, unpredictable events. The operational procedures developed for GMOD are presented to provide insight into the considerations required for operating a GRB detecting instrument on a CubeSat mission with multiple scientific

and technology demonstration goals. The EIRSAT-1 project made use of two forms of testing the operations manual, ODTs, and the EQM MT, to ensure the procedures could reliably instruct operators in nominal operations of the mission, such as GRB data downlink, and recovering from fault scenarios. The MT provided a comprehensive test of the EIRSAT-1 operations manual that could not have been performed via ODTs. Both the ODTs and EQM MT were important milestones in the testing and validation of the EIRSAT-1 operations manual.

The ODTs allowed for incremental development of the operational procedures from an initial version and each ODT focused on only one or two procedures. The EQM MT tested a well-developed frozen version of the operations manual and provided the opportunity to test the full suite of operational procedures over an extended period of time. Operators were aware of the procedures they would be following during initial ODTs, making it unrealistic from an operations perspective. However, during the MT, spacecraft operators only interacted with the satellite during communication passes and would only find out the state of the S/C (e.g., new GRB trigger or the S/C transitioned into safe mode) once contact had been made. This is much more realistic and an important aspect of operator training. The MT assessed how operators handled navigating between procedures in the operations manual. In the ODT, only one procedure would need to be opened, whereas the MT revealed that links to related or useful procedures could be useful but in moderation, e.g., first time nominal procedure was just composed of links to other procedures to set up GMOD and EMOD, and operators found this challenging to navigate. Other operational tools for data visualization, e.g., Grafana, were not developed during the ODTs. The MT facilitated observing how operators interacted with the different tools, such as the MCS (Sec. 3.1), EIRSAT-1 operations manual, and Grafana, simultaneously during and after communication passes to assess the health of the S/C and its experiments. The operational manual updates required after the MT were mostly minor due to the incremental development performed during the ODTs and regular feedback from the entire CubeSat team. The ODTs revealed the preference to split the GMOD commissioning procedures into a health check and experiment running procedure. The MT facilitated the development of the GRB data downlink procedure and training operators in reacting to new triggers and planning passes based on a new potential GRB triggering the GMOD instrument. The major lessons learned in developing and testing a robust operations manual are as follows:

1. Preparation is key: preparation is essential in the development of a comprehensive operations manual. The early development of the EIRSAT-1 manual allowed for multiple iterations and updates to account for all nominal and off-nominal mission scenarios. In addition, the preparation done by operators prior to communicating with the S/C is vital. Operators need to be familiar with all the prerequisite knowledge (Sec. 3.2) and operational procedures to successfully communicate with the S/C as there is no time during communication passes to consult finer details.
2. Involve the full team in operations development: during the initial development of the EIRSAT-1 operations manual, the operations team consisted of three members. This was due to limited resources; however, it was beneficial as it allowed the rest of the team to provide a fresh perspective on the operational procedures. An anonymous google form was also sent around the team for feedback and facilitated the team in providing honest feedback and constructive criticism on procedures, manual layout, and introductory sections.
3. Begin operator training early: the early development of the EIRSAT-1 operations manual allowed the team to gain experience in operating the satellite in mission scenarios, including responding to GRB triggers with GMOD. Both the ODTs and MT exposed the team to using operations manual in time-constrained communication passes along with the spacecraft interface (Sec. 3.1) and data visualization tools.
4. Prepare to incrementally update manual for firmware/software payload developments: numerous updates to the GMOD firmware have been made since the EQM MT, changing the operational steps for configuring and running the experiment. These will need to be included in the updates to the GMOD operational procedures.
5. Missing steps/operational considerations found during validation process: during ODTs, the S/C was in a known configuration, and often parameters were in their default states. It was found during the MT that since the S/C was on for a long time, steps were missing to

reconfigure the S/C. Certain parameters make use of timeouts where, after a specified amount of time, the parameter will return to a default value, e.g., ADCS Mode. However, during the MT, the ADCS mode needed to be set with a timeout multiple times, and steps were missing to reset the timeout parameter so it could be re-used. These types of missing reconfiguration steps were only found during the MT.

6. Include pre-pass and post-pass checklists: a pre-pass checklist was developed as a result of the ODTs and is discussed in more detail in Ref. 36. However, during the MT, it was found that a post-pass checklist would also be beneficial to remind operators to note the deviations from the pass plan and record the state of the S/C (OBC image, operational mode, GRB trigger count). These can then be used to prepare and compare in the next communication pass.
7. Make use of spacecraft interface layouts: both the interface used during MT and the MCS (Sec. 3.1) have a layout functionality. This functionality was only implemented the week before the MT and therefore was not included in the frozen version of the EIRSAT-1 operations manual used during the EQM MT. However, layouts were used extensively during the MT as parameters and actions associated with specific procedures could be prepared in advance. The EIRSAT-1 operations team will have a subset of standard layouts for the operational procedures that will be followed regularly, e.g., Start a Communication Pass and update the operations manual to explain how to set up and use the MCS layout feature.

Currently, the FM of EIRSAT-1 is undergoing its suite of tests in ambient and space representative conditions. Once these are completed successfully, the FM will be accepted as flight-ready. The two major updates to make to the operational manual before it is flight ready is to include information on scheduled operations via the MCS and to develop the WBC operational procedures. The EIRSAT-1 FM will be launched and operated by students in UCD, detecting and reporting cosmic gamma-ray events to the astronomical community using GMOD. Science data from the thermal surface treatment experiment, EMOD, and the attitude control testbed, WBC, will also be collected. The EIRSAT-1 mission will share the operational lessons learned during the early phases of the mission and reflect on how early development and rigorous testing of the operational procedures contributed to the success of the project in achieving its scientific and technology demonstration objectives.

7 Conclusion

The EIRSAT-1 project is employing a number of strategies to increase the likelihood of mission success. CubeSat projects are associated with low cost and short timelines, with a trade-off in that there is a higher level of risk acceptance and a significant rate of failure. The prototype model philosophy executed by EIRSAT-1 provided time for early development of the operational strategy and manual. The operational procedures of EIRSAT-1 must balance monitoring the health of the S/C and running three experimental payloads. The primary payload GMOD makes the operational strategy more complex with its main objective of detecting violent EM explosions, GRBs, and efficiently reporting them to the scientific community. In this paper, the rigorous validation processes of the operations manual at both a procedure level (ODTs) and during a long-duration flight representative test campaign (MT) are presented. Both ODTs and the MT highlighted the importance of early development of the operations manual. The training of operators on an educational team was easily incorporated into the testing of the operations manual. All members of the EIRSAT-1 team are now proficient in navigating the operations manual while communicating with the S/C and using it during nominal and anomalous mission scenarios. Ultimately, the final test of the EIRSAT-1 operations manual will be after launch; however, the testing approach taken has provided a high level of confidence in the EIRSAT-1 operations manual.

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