

Lessons Learned in Operating Heterogeneous SmallSat Missions

Yuri M. D. Pereira^{a*}, Todor Toshkov^b

^a *EnduroSat, Bulgaria, yuri@endurosat.com*

^b *EnduroSat, Bulgaria, toshkov@endurosat.com*

* Corresponding Author

Abstract

EnduroSat has the goal of making space universally accessible and achieves this by providing customers with the capability of easily getting their payload to orbit, enabling them to collect data from space. For this purpose, different missions at varied SmallSat sizes have been launched and operated successfully through our user-centric mission control software, SpaceOps, which has empowered both EnduroSat's Spacecraft Operations Team and our global clientele to seamlessly transition their payloads into orbit, thereby opening new avenues for space-based data acquisition. The similarities and differences in the missions have introduced extensive requirements for spacecraft operators, which have then been used as feedback for the development of future missions. These have also created opportunities and challenges, that were seen on a technical level combined with the human factor of decision-making in crucial situations. In this work, lessons learned for over a dozen smallsat operations will be presented, being described in situations of launch and early orbit phase (LEOP), nominal operations, orbital determination, human reaction in contingencies and their further mitigation. The expected situations before launch, the observed situations after operations started and the interventions that determined mission success will be described, with their potential lessons learned described and summarized. One standout lesson involves the adaptive strategies employed during the LEOP phase, which significantly mitigated mission risks and underscored the value of flexible, on-the-fly decision-making protocols. By synthesizing these real-world experiences and operational insights, this work endeavors to not only share EnduroSat's journey in enhancing SmallSat accessibility but also to spark a broader conversation on the evolution of space operations. After analysis of the observations, the lessons taken can serve as a useful case study for defining methodologies of new space operations training and the human factors and traits that enable making space universally accessible.

Keywords: CubeSats, SmallSats, LEOP, Knowledge Transfer, SatOps.

Acronyms/Abbreviations

Launch and Early Orbits Phase (LEOP)

1U (one Unit of a CubeSat)

1. Introduction

EnduroSat's goal is to make space universally accessible. To achieve this, space missions and space data must be cost-effective, easy to develop, operate, and most importantly, be easy to transfer knowledge for how that whole process should be performed. This goal leads the company to be in a state of constant knowledge transfer: customers are not just buying ready-made hardware and software, but also doing their own developments and having their own design philosophies and contrasting goals, which then need to be incorporated in the organization's knowledge.

This leads to the scenario where the Mission Operations Team has to operate spacecraft that is jointly built with customers, using the tools and capabilities provided by the EnduroSat Platforms. And so it is necessary to operate very different platform, who share a common bus but have different goals, desires and faults.

Furthermore, due to sheer accessibility, the different missions are spread in various space domains, requiring flexibility and willingness to learn from each operator. For example, while operating multiple earth observation missions has transferrable skills to astronomy telescope operations as they both involve optics, some of the knowledge in one area is not relevant to operations in another.

In this paper, these situations are presented as challenges to be overcome, a few of the solutions in response to those challenges are shown, and the most relevant lessons learned from that process are enumerated.

2. Challenges

2.1 Heterogeneous Mission Architectures

The first major challenge emerges from the diversity of mission architectures encountered during satellite operations. EnduroSat's customer-centric approach involves incorporating multiple design philosophies, technical

requirements, and operational goals into a common bus that supports many different payloads. As a result, the Mission Operations Team frequently has to adapt to unusual subsystem combinations, unique payload integrations, and varying onboard software configurations. This has impact on LEOP and nominal operations, as the customer demand for commissioning a new architecture, or with specific restrictions, is significant, and has to be taken into account during planning.

2.2 Dynamic Knowledge Transfer

Each customer brings distinct expertise, development processes, and mission objectives. Incorporating this external knowledge in a structured, reproducible way becomes a challenge—particularly given the need to maintain technical clarity, version control of operational procedures, and consistency across organizational documentation. Equally, EnduroSat must transfer its in-house expertise to customers rapidly. This push-pull of knowledge often necessitates frequent revision of training materials, operational protocols, and data interpretation methodologies.

2.3 Multi-Domain Expertise

With different missions spanning earth observation, in orbit demonstrations, astronomy, science observatories, Internet-of-Things, telecommunications, and other scientific explorations, the Mission Operations Team is required to possess multi-domain competencies. While some operational principles—such as data management or planning image captures—may overlap, niche knowledge and mission-specific demands varies significantly. It is common to have satellites with opposing operational requirements, such as one set of mission always wanting to be in a specific attitude mode, while this would be damaging and fully undesirable for another set of missions, and it is necessary to understand why this is so. Managing the breadth of expertise needed for each customer’s mission without overwhelming the operational staff is a key challenge.

2.4 Operational Continuity and Scaling

Providing seamless operational support to multiple satellites while reliably implementing new processes and tools demands a well-designed and flexible operations framework. The challenge intensifies when the number of customers grows; small inefficiencies in scheduling, telemetry analysis, or anomaly resolution can proliferate and cause large-scale delays or failures. Achieving a scalable operation that can maintain efficiency and high-quality customer service is critical yet complex. On the SmallSats domain, this is further exacerbated by the varying sizes of spacecraft, in which operations for a 1U reduced version of a 16U mission are run differently,

2.5 Fault Tolerance Across Varied Mission Goals

Different customers may have distinct priorities regarding risk, resource optimization, and time-to-market. For example, a research institute might tolerate a slower delivery schedule but demand precision pointing for its scientific payload, whereas a commercial entity may prioritize cost-effectiveness and quick data turnaround. Designing operational procedures that ensure fault tolerance for each unique requirement remains a challenge, especially when resource-sharing and scheduling conflicts arise between concurrently operated missions.

3. Solutions

3.1 Modular Operational Framework

A central solution involves adopting a modular approach to spacecraft operations, wherein commonalities—such as telemetry acquisition, command and control interfaces, and core housekeeping tasks—remain the same, while mission-specific procedures are encapsulated as add-on modules. By segregating domain-specific tasks (e.g., optical payload calibration) within dedicated workflows, the organization can effectively manage variability in mission profiles without losing the efficiencies of a standardized operations bus.

3.2 Iterative Knowledge Management System

To handle the demands of continuous knowledge transfer both internally and externally, EnduroSat has implemented an iterative knowledge management system. This includes:

- A centralized documentation repository with rigorous version control, ensuring that all members of the Mission Operations Team and customer contractors have immediate access to the latest operational procedures.
- Shared data analytics workflows and dashboards that allow multiple collaborators—both within EnduroSat and in customer teams—to visualize data in real time.
- Standardized training modules and workshops that can be easily customized for each new mission, effectively bridging knowledge gaps.

3.3 Cross-Training and Domain-Specific Mentoring

Because many different space domains are represented in ongoing missions, cross-training programs and mentoring initiatives have been established. Senior operators who have expertise in a particular area (e.g., communications or earth observation) guide junior operators. This ensures that new or less experienced team members gain domain insights quickly, while simultaneously reinforcing a collaborative culture where knowledge is openly exchanged.

3.4 Scalable Scheduling and Resource Management

Recognizing that operational continuity across multiple spacecraft requires robust scheduling, EnduroSat has developed an automated resource management system. By leveraging time-slot optimization algorithms and real-time telemetry monitoring, the Mission Operations Team can more easily prioritize tasks, detect conflicts, and allocate critical ground-station resources. This automation significantly reduces mission overlaps, ensuring that varied operational tasks can be handled efficiently without unnecessary delays or errors.

3.5 Customizable Fault-Detection and Isolation Procedures

To address the range of faults that may occur in varied mission contexts, the organization has embedded customizable fault-detection and isolation modules into its ground control software stack. These modules:

- Implement rule-based anomaly detection, triggered by predefined thresholds or pattern recognition.
- Support rapid reconfiguration of fault-response procedures, so operators can easily tweak anomalies' tolerances and remediation steps to align with customer-driven risk profiles.
- Log contextual data from each detected anomaly, feeding back into the iterative knowledge management system for future improvement.

4. Lessons Learned

4.1 Embracing mission diversity

While the variety of customer missions represents a frequent operational hurdle, it also spawns creative problem-solving approaches and drives ongoing improvements in the organization's processes. By systematically harnessing the lessons from each mission or anomaly, EnduroSat has found that diversity in missions ultimately leads to greater operational robustness and fosters technical innovation.

4.2 Importance of Two-Way Knowledge Transfer

It is insufficient simply to provide training and documentation for customers; a reciprocal exchange of ideas, lessons, and requirements is key. Facilitating open communication channels, whether via regular technical reviews or shared development platforms, fosters trust and expedites solution timeframes. Mishaps in early mission phases were traced back to one-sided knowledge transfer, reinforcing the need for a continuous "feedback loop."

4.3 Standardization Does Not Imply Uniformity

A modular architecture is most beneficial when it enables both reuse of common components and easy adaptation to new mission-specific requirements. Initially, there was some hesitation that standardizing parts of the operations bus would limit specialized missions. However, flexible, software-defined interfaces and customizable procedures allowed operators to support a wide range of mission goals without sacrificing uniformity in essential elements. For these purposes, new developments were done with feedback from the operations team, that further expanded the flexibility and configurability of the platforms, that allows the creation of further abstractions. These abstractions present as small frameworks that are reusable in their own context, for example the creation of an abstraction for sending commands over the scripting language used by the Onboard Data Handling Computer.

4.4 Continuous Improvement Through Iterative Processes

The fast-paced environment of satellite operations often reveals latent inefficiencies or misunderstandings in mission protocols. Iterative updates to processes, documentation, and training have been crucial in refining the operational framework. Implementing small, incremental changes frequently proved more effective than periodic major overhauls, as smaller adjustments were less disruptive to ongoing missions.

4.5 Resilience Requires Proactive Risk Management

Whether addressing hardware anomalies or unexpected mission changes, proactive risk management is a critical pillar of operating multiple spacecraft concurrently. Lessons from cross-domain missions emphasized the need for advanced planning in resource allocation, potential failure modes, and fallback architectures. The ongoing development of refined anomaly detection algorithms, coupled with continuous cross-training, allows EnduroSat to adapt quickly to any challenges.

5. Conclusions

EnduroSat's endeavor to make space accessible, flexible, and cost-effective for a diverse customer base creates a complex yet rewarding operational environment. The organization's choice to craft a modular, standardized operations bus, while encouraging active two-way knowledge transfer, has addressed many of the initial challenges. By implementing iterative updates to procedures, automations, and training, EnduroSat has maintained an adaptive and forward-looking approach.

The lessons gleaned from simultaneously operating different types of missions underscore the value of balancing standardization with domain-specific tailoring. From knowledge management practices to automated scheduling solutions, each innovation arises from real operational demands and benefits multiple stakeholders. As the company continues to scale its operations, the processes, tools, and collaborative culture serve not only as an internal advantage but also as a demonstration to the wider space community that accessible satellite operations need not compromise on complexity or ambition.

Ultimately, successful collaboration between the Mission Operations Team and customers from varying backgrounds highlights the feasibility of universal space access rooted in rigorous, yet flexible, operational frameworks. By continuing to embrace iterative learning and cross-domain expertise, EnduroSat positions itself, and its partners, on the leading edge of sustainable, inclusive, and ambitious space exploration.

Acknowledgements

We'd like to acknowledge all customers that have made EnduroSat what the success that it is, along with everyone who works at the company for their continued support.