18th International Conference on Space Operations, Montréal, Canada, 26 - 30 May 2025.

SpaceOps-2025, ID # 32

Optimising *SMOS* payload operations: adapting auto-downlink strategies to evolving budgetary realities

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Abstract

Launched on November 2nd, 2009, the Soil Moisture and Ocean Salinity (*SMOS*) satellite monitors global soil moisture and ocean salinity to enhance understanding of Earth's water cycle, improve weather forecasts, and refine climate models. Operating in a Sun-synchronous polar orbit at an altitude of 763 km and with a 98.4° inclination, *SMOS* carries a single instrument —an *L* band interferometric radiometer named MIRAS— that measures "brightness temperature" images to produce soil moisture maps and ocean salinity data with high precision. It is a joint project between CNES-Toulouse, which manages the platform and flight dynamics operations, and ESA-Madrid (ESAC, European Space Astronomy Centre), which oversees control operations and data processing for the MIRAS payload. Initially intended as a five-year mission, *SMOS* has exceeded expectations, now operating in its sixteenth year with 99.8% efficiency. Notwithstanding this exemplary operational performance and scientific significance, the mission now confronts potential financial constraints, as impending budgetary reductions necessitate operational adaptations. A reduction scenario under consideration entails the prospective decommissioning of the ESAC-based *X* band acquisition antenna. This antenna currently manages four daily data passes and supports auto-downlink operations (automatic satellite-initiated data transmissions) critical for minimising data loss during onboard software resets. In the absence of this antenna, Svalbard —also an integral component of the *SMOS X* band downlink network— would necessarily assume the role of default downlink station, requiring modifications to MIRAS software and adjustments to the auto-downlink algorithm to avoid conflicts between automated downlinks and manual recovery operations. Onboard resets necessitate ground intervention during working hours to restore the payload configuration and must be handled with the auto-downlink function inactive. Reducing the across-track distance threshold from 1000 km to 700 km is a crucial parameter change that will enable a solution. This paper explores the modifications and testing of the onboard software that will enable Svalbard to serve as the default for auto-downlink. It also discusses the development of a ground-based emulator (called *S*ADE) that specifically simulates the auto-downlink to evaluate diverse parameter configurations. Output from *S*ADE will be fed into *SMOS* mission planning to identify the *X* band passes that will not activate the auto-downlink function, thereby providing advance information on safe reset-recovery slots.

Keywords: (downlink, Earth observation, ground segment, onboard software, space sustainability, *X* band operations)

Nomenclature

This work is based on [1], an internal ESA technical note intended for operational teams. Authors have abstracted it into this paper and tailored it for broader scientific audiences by removing excessive technical details while highlighting sustainability and scientific relevance. Therefore, in the interest of clarity, [1] is cited exclusively here.

Acronyms/Abbreviations

AAV:	Attitude and Angular Velocity
ANX:	Ascending Node Crossing
AOS:	Acquisition of Signal
CCU:	Correlator and Control Unit
CEC:	Calibration Expertise Centre
CMN:	Control and Monitoring Node
CNES:	*Centre national d'études spatiales*
CPU:	Central Processing Unit
DPGS:	Data Processing Ground Segment
EEPROM:	Electrically Erasable Programmable Read-Only Memory
ESA:	European Space Agency
ESAC:	European Space Astronomy Centre (ESA)

FOS:	Flight Operations Segment (ESA)
GO/NOGO:	Proceed with (GO) or halt (NOGO) the next phase of activities
GUI:	Graphical User Interface
ITL:	Internal TimeLine
LICEF:	Light Weight and Cost-Effective Front End
LLSW:	Low-Level Software
LOS:	Loss of Signal
MIRAS:	Microwave Imaging Radiometer using Aperture Synthesis
MIRASIM:	MIRAS Simulator
MM:	Mass Memory
MP:	Mission Planning
NIR:	Noise Injection Radiometer
OBSW:	Onboard Software
PROTEUS:	*Plateforme Reconfigurable pour l'Observation, les Télécommunications Et les Usages Scientifiques*
PVT:	Position, Velocity, and Time
RAM:	Random Access Memory
*S*ADE:	*SMOS* Auto-Downlink Emulator
SMOS:	Soil Moisture and Ocean Salinity
SOGS:	Spacecraft Operations Ground Segment (CNES)
Svalbard:	Svalbard Satellite Station
*X*BAS:	*X* Band Acquisition System

1. Introduction

The Soil Moisture and Ocean Salinity (*SMOS)* mission, operational since November 2009, has evolved into a cornerstone of Earth observation. As the second Earth Explorer mission, *SMOS* has demonstrated remarkable longevity, surpassing its initial three-plus-two-year design life through three successive mission extensions in 2014, 2017, and 2022. Having completed over fifteen years of service, and with the current operational mandate extending through December 2025 (with potential continuation until 2028), the mission faces significant budgetary constraints necessitating strategic operational adaptations to sustain its scientific output.

To adjust to these financial limitations while maintaining mission effectiveness, we examine in this paper essential modifications to *SMOS* operations, specifically addressing the anticipated decommissioning of the European Space Astronomy Centre’s (ESAC) *X* Band Acquisition System (*X*BAS), one of the ground segment antennas. Our analysis focuses on optimising auto-downlink operations (automatic satellite-initiated data transmissions) that will be required, proposing a comprehensive solution that designates Svalbard (also part of the *SMOS X* band downlink network) as the primary downlink station (currently this is ESAC) while implementing refined onboard algorithm parameters to ensure robust data recovery following frequent resets of the payload Correlator and Control Unit (CCU). The auto-downlink function serves as a pivotal mechanism for maintaining mission continuity in the wake of reset events. The proposed transition to Svalbard necessitates meticulous parameter optimisation to preclude operational conflicts between automated downlink procedures and manual recovery protocols. Operational impact, required modifications, and supporting simulation results are presented here. By emphasising resource efficiency and cost reduction, these optimisation efforts align with SpaceOps 2025 conference theme of "*Toward Space Sustainability*".

Understanding the *SMOS* mission's fundamentals is essential to address the operational challenges we presented in this paper. The following subsections provide context: Section 1.1 outlines mission objectives and orbital characteristics affecting downlink opportunities; Section 1.2 examines the platform architecture that enables auto-downlink operations; and Section 1.3 details scientific achievements and the frequent CCU resets necessitating the auto-downlink function. This framework establishes the constraints within which our proposed modifications must operate to maintain scientific data acquisition while adapting to new budgetary realities.

1.1 Mission overview

The mission performs global observations of soil moisture over land and salinity over oceans (see Fig. 1), contributing significantly to our understanding of Earth's water cycle and climate models, and it is the result of a collaborative effort between the *Centre national d'études spatiales* (CNES) and the European space Agency (ESA), with CNES managing platform (named PROTEUS) activities and ESA overseeing the payload (named MIRAS). Originally, ESAC's *X*BAS antenna was designed as the mission's sole *X* band downlink terminal, with Svalbard added later to meet near-real-time data requirements.

SMOS operates as a 3-axis stabilised satellite in a meticulously maintained dusk-dawn Sun-synchronous orbit at 763 km mean altitude. The orbital parameters, including an inclination of 98.4° and a local solar time of 18:00 descending node, facilitate optimal solar array illumination through precise attitude control. The spacecraft maintains local nadir pointing with a 32° track offset (axis X_A), while the solar panel axis remains collinear with the velocity vector (axis Y_A), ensuring maximum power generation efficiency (see Fig. 2).

Fig. 1. Artist's impression of the *SMOS* flight configuration, illustrating both the *Microwave Imaging Radiometer using Aperture Synthesis* (MIRAS) payload and the *Plateforme Reconfigurable pour l'Observation, les Télécommunications Et les Usages Scientifiques* (PROTEUS) platform. *(source: AOES Medialab, ESA)*

1.2 Platform architecture

The mission employs the PROTEUS bus (see Fig. 3), developed by Thales Alenia Space France. This sophisticated platform architecture —demonstrated successfully across multiple missions including *Jason2*, *Jason3*, *Corot*, and *Calipso*— incorporates dual process modules with both dedicated and shared components. The platform's exceptional reliability is evidenced by comprehensive system redundancy, sustained energy reserves, and substantial propellant margins. Regular station-keeping manoeuvres, executed quarterly, maintain accurate orbital parameters against atmospheric drag effects.

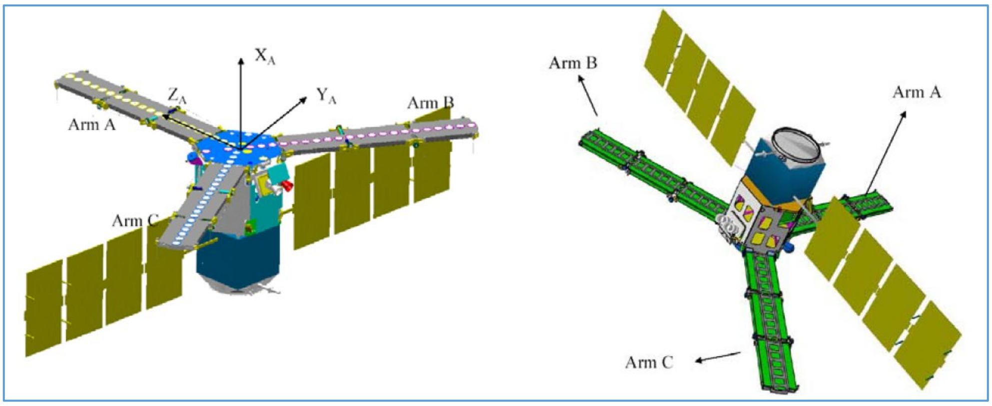


Fig. 2. *SMOS* axis orientation and arm nomenclature, showing the spacecraft's alignment for optimal solar array illumination and observation geometry. *(source: AirBus, ESA)*

PROTEUS provides navigational data (i.e., Position, Velocity, and Time [PVT] and Attitude and Angular Velocity [AAV] telemetry) for the MIRAS auto-downlink algorithm to determine satellite-to-station positioning and orientation.

1.3 Scientific achievement and evolution

SMOS has achieved unparalleled data availability, with successful acquisition and distribution rates exceeding 99.8%. This exceptional performance, a testament to robust payload design, stems from minimal payload and platform anomalies and seamless coordination between CNES and ESA operational teams. Nonetheless, frequent and unpredictable onboard software resets of MIRAS's CCU —caused by a low-level software (LLSW) anomaly discovered shortly after launch— impact operations and necessitate manual ground intervention during working hours.

The mission's *L* band interferometric measurements at 1.4 GHz have proven particularly effective in typifying soil moisture and ocean salinity through their influence on surface emissivity. Beyond these primary objectives, the extended operational lifetime has enabled the development of novel applications, including ice dynamics monitoring, frozen and thawed states of soil evolution, wind field mapping, and unique *L* band solar flux measurements contributing to space weather characterisation.

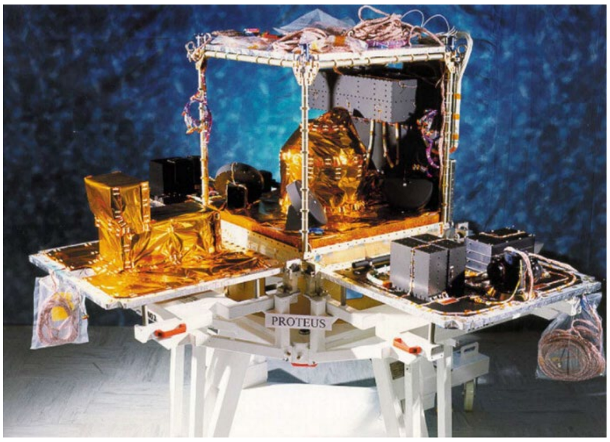


Fig. 3. The PROTEUS platform architecture, highlighting its modular design and redundancy features as used in the *SMOS* mission. *(source: Alcatel Space, CNES)*

2. *SMOS* ground segment operations

2.1 Operational architecture

The ground segment architecture encompasses two primary sites: SOGS (Toulouse) for PROTEUS operations and FOS/DPGS/CEC (Madrid) for MIRAS payload management. This dual-facility approach enables comprehensive mission control through integrated command and telemetry systems, with sophisticated planning and monitoring protocols. Spacecraft Operations Ground Segment (SOGS) manages platform operations (i.e., telecommanding, orbit and attitude processing, platform housekeeping telemetry monitoring, and *S* band network management for telemetry acquisition). Flight Operations Segment (FOS) coordinates payload activities (i.e., MIRAS commanding and health monitoring with both scheduled weekly activities and manual, unscheduled commanding for specific operations or anomaly recovery). Data Processing Ground Segment (DPGS) is a complete payload data ground segment which coordinates payload data reception —including management of the local *X*BAS hosted at ESAC—, data processing, reprocessing campaigns, product generation, and distribution to users. Calibration Expertise Centre (CEC) oversees data quality assurance, encompassing calibration, scientific

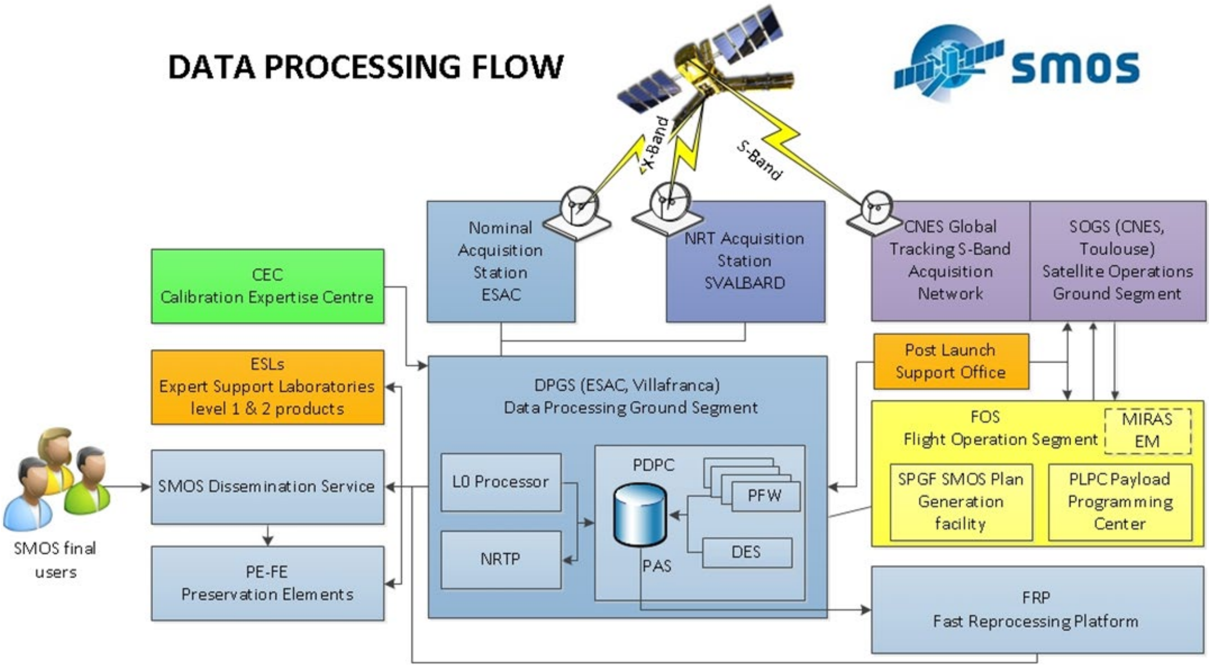


Fig. 4. Overview of the *SMOS* ground segment architecture, detailing key operational sites and their respective responsibilities for platform and payload management. *(source: DPGS Team)*

validation, quality control, trend analysis, and optimisation of processing systems' configuration and operation. See Fig. 4 for the principal ground segment systems.

A salient aspect of the *SMOS* operational architecture is the local integration of FOS with DPGS and CEC at ESAC. This co-location enhances collaboration between teams, streamlines communication, and facilitates expeditious decision-making. The proximity of operational teams allows for seamless exchange of telemetry and telecommand information during *S* and *X* band passes, significantly reducing response times to potential anomalies and —thus— enhancing mission performance.

2.2 Payload configuration

MIRAS [2] represents a technological breakthrough in Earth observation, featuring an *L* band, two-dimensional interferometric radiometer with a Y-shaped synthetic aperture antenna spanning eight meters in diameter. The system integrates 69 Light Weight and Cost-Effective Front End (LICEF) receivers, and three Noise Injection Radiometers (NIR), distributed across its three arms and central hub, maintaining precise thermal stability at approximately 22 °C through twelve independent control cycles (see Fig. 5). The *X* band transmitter antenna is located on the instrument side, tilted by 32°, and features a unidirectional beam with a width of 134°. This specific orientation optimises signal transmission toward ground stations without compromising the instrument's primary observation capabilities.

The hardware architecture exhibits a highly distributed design, wherein each arm is divided into three segments, each containing one Control and Monitoring Node (CMN) responsible for collecting data from six LICEF receivers. All twelve CMN units —nine across the three arms and three within the central hub— are connected to the CCU located in the hub. The CCU contains the instrument's Central Processing Unit (CPU), Electrically Erasable Programmable Read-Only Memory (EEPROM) banks, and Mass Memory (MM) units. The Onboard Software (OBSW) running on the CCU manages both the data flow from the LICEF receivers and thermal sensors via the CMNs, as well as controlling the *X* band transmitter positioned on the instrument hub.

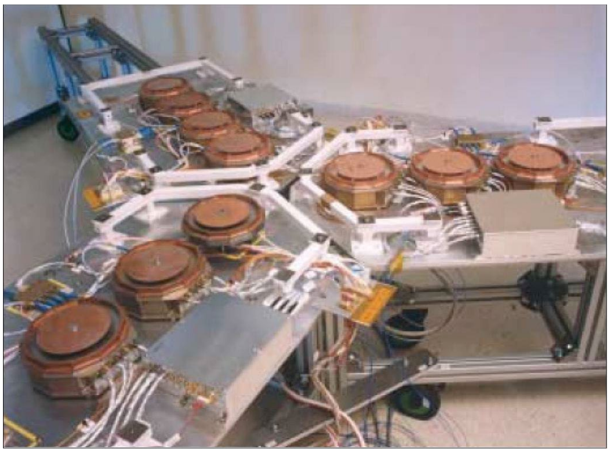


Fig. 5. Detail view of the MIRAS Y-shaped structure during assembly, showing the distributed arrangement of LICEF receivers and NIRs across its arms and central hub. *(source: ESA)*

2.3 Downlink strategy

2.3.1 X band satellite data acquisition system

The current *X* band operational framework employs a dual-station approach [3]. ESAC's *X*BAS typically acquires four daily passes, whilst Svalbard provides comprehensive orbital coverage with at least one pass per orbit for near-real-time data products. Due to the 06:00 Ascending Node Crossing (ANX, i.e. orbital plane orientation), ESAC receives passes either during early morning (ascending, northward) or late evening (descending, southward). Svalbard receives data during any of the fourteen daily orbits, apart from those operationally excluded due to ad hoc ESAC selection.

2.3.2 Technical specifications of ESAC's XBAS

ESAC's *X*BAS (see Fig. 6) features a 3.5 m Cassegrain antenna operating in the *X* band frequency range (8025 –8400 MHz) for data reception. The system utilises an X/Y positioner with ±85° travel capability in both axes, enabling efficient tracking of low elevation passes with 0.15° root mean square accuracy. The antenna assembly incorporates a modular design featuring a central aluminium interface surrounded by eight carbon fibre panels, optimised for structural rigidity under high wind conditions (operational up to 75 km/h, with survival capability up to 160 km/h in stow position). The receiving system supports selectable right- and left-hand circular polarisations, facilitating optimal signal reception across varying atmospheric conditions, with comprehensive environmental specifications ensuring reliable operation from -30 °C to +55 °C.

Fig. 6. View of ESAC's *X*BAS antenna, illustrating its design features, tracking capabilities, and environmental specifications for *X* band data reception. *(source: DPGS Team)*

2.3.3 Transition strategy for X band operations

To effectively manage the dual-station *X* band acquisition system, a structured operational framework has been established to optimise data reception and processing [4]. On Mondays, FOS coordinates the weekly *X* band schedule distribution (DPGS and Svalbard), as well as the service configuration file provision to SOGS. This file contains the external calibration manoeuvres, and the set of *X* band passes over ESAC. On Wednesdays, FOS submits to SOGS payload telecommands to switch on/off the *X* band transponder, along with calibration commands. All telecommands are uplinked by SOGS on Thursdays and stored on the onboard Internal TimeLine (ITL) for execution the week after. While this workflow has served the mission effectively, evolving budgetary realities necessitate adaptation. Consequently, the suggested optimisation strategy positions Svalbard as the primary downlink facility, supported by enhanced auto-downlink algorithms to maintain robust data recovery capabilities while achieving operational cost efficiencies. This approach leverages Svalbard's capability as the only commercial ground station able to provide all-orbit support (14 out of 14 orbits/day) to polar orbiting satellites, enabling more comprehensive and continuous data acquisition. In the following section we examine the auto-downlink mechanism's role in mitigating data losses due to the frequent CCU resets that have characterised *SMOS*'s extended mission lifetime.

3. Auto-downlink operations and payload resets

During nominal operations, MIRAS *X* band downlink acquisitions are executed through onboard telecommands provided by FOS on a weekly basis [5]. This routine will only be interrupted in cases of unforeseen collision avoidance or orbit correction manoeuvres not included in the original planning skeleton files furnished by SOGS [6]. In such instances, the onboard ITL queue is suspended from ground, preventing the execution of telecommands that would activate/deactivate the *X* band transmitter. During Mission Planning (MP) contingency operations, FOS may activate the MIRAS OBSW auto-downlink algorithm, which halts the payload onboard ITL and enables the MIRAS OBSW to autonomously initiate *X* band data transmission whenever the spacecraft traverses a predefined ground station —currently ESAC— by interpreting PVT/AAV telemetry from the PROTEUS platform.

The auto-downlink function activates automatically following instrument initialisation or OBSW resets, as these events clear all ITL commands residing in Random Access Memory (RAM). This mechanism ensures continuous science data preservation, as MIRAS resumes data accumulation and storage in MM immediately following a restart. With a maximum MM storage capacity of 26 hours, the auto-downlink function over ESAC prevents memory overwrite and guarantees data continuity. The maximum potential ground latency is 12 hours (the longest interval between consecutive *X* band passes over ESAC) from morning to evening acquisitions. The default auto-downlink station is defined in an EEPROM variable that can be set to any of four predefined stations: ESAC, Kiruna, Svalbard, and Toulouse. Since mission inception, ESAC has consistently served as the default station.

Frequent MIRAS CCU resets [7], attributed to a complex LLSW anomaly, result in ITL queue clearance and subsequent automatic activation of the auto-downlink mode targeting ESAC [8]. These CCU resets defy advance prediction and exhibit no discernible correlation with external events; nonetheless, 98% of all reset events observed throughout the mission's duration have occurred during *X* band passes.

The MIRAS CCU architecture incorporates dual CPUs —prime and redundant— each equipped with two EEPROM banks. Since mission commencement, the redundant CPU has been designated as the operational unit. OBSW is stored in both EEPROM banks, which function as prime and redundant units. Bank 2 of the redundant CPU is configured as the default memory bank, ensuring that following a CCU reset, OBSW code from this default bank is loaded into RAM. In cases where memory checksum errors are detected in the default bank, code is alternatively loaded from the redundant bank. Due to configuration discrepancies between the default OBSW stored in EEPROM and the current operational configuration of the instrument, SOGS flight control team must manually intervene after a CCU reset to restore the instrument to its nominal configuration. Following a CCU reset, MIRAS defaults to an obsolete operational configuration, generating basic housekeeping telemetry packets. This post-reset reconfiguration process includes, among other things, uploading a revised *X* band downlink schedule.

The established operational protocol between CNES and ESA stipulates that instrument recovery procedures occur exclusively during standard working hours, including weekends and public holidays. An additional critical constraint mandates that these recovery operations never coincide with *X* band transponder activity. The *SMOS* satellite's dusk-dawn orbit with a 06:00 ANX results in auto-downlink passes over ESAC occurring outside European standard working hours. This timing arrangement facilitates unimpeded instrument recovery operations. Fig. 7 illustrates the distribution of *X* band passes for the two stations during three consecutive operational weeks, with working hours highlighted in yellow. As demonstrated in this figure, the potential redesignation of Svalbard as the default station could result in numerous *X* band passes occurring during standard working hours, thereby increasing the probability of conflicts between instrument recovery operations and *X* band transponder activity. This potential operational conflict necessitated comprehensive analysis to evaluate the operational implications of establishing Svalbard as the new default auto-downlink station.

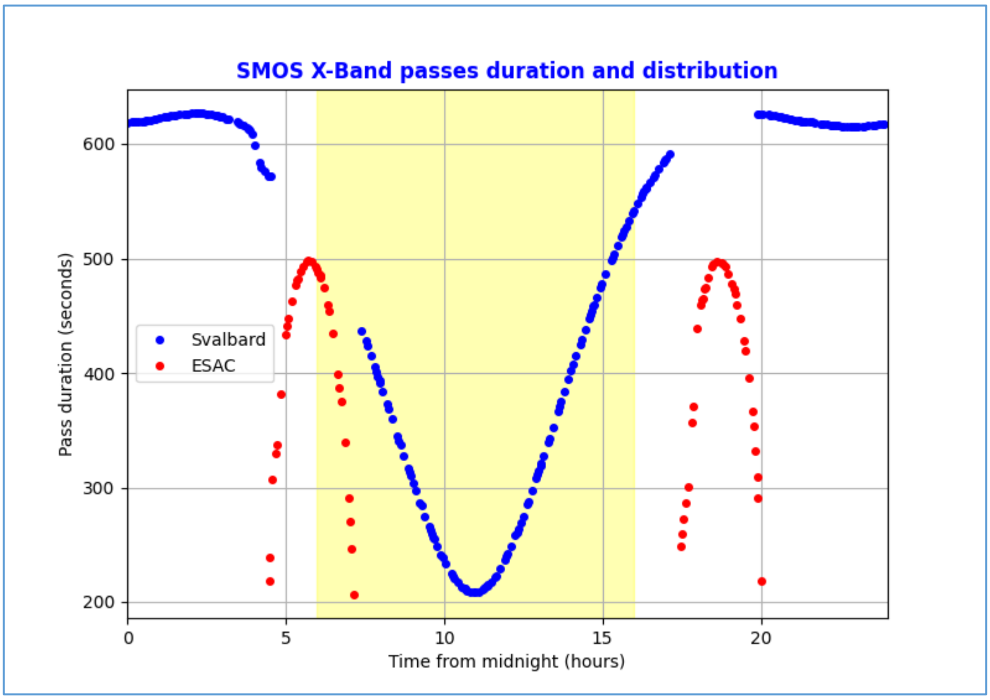


Fig. 7. Nominal distribution and duration of *SMOS X* band passes over ESAC and Svalbard during a representative three-week period. ESAC passes occur in early morning and late evening hours, while Svalbard provides coverage throughout all daily orbits. Normal working hours are highlighted (yellow) to illustrate potential operational conflicts. *(source: [1])*

3.1 Description of the auto-downlink algorithm

The auto-downlink algorithm constitutes an indispensable operational safeguard, autonomously restoring *X* band data transmission following CCU software resets to ensure uninterrupted science data downlink despite ITL queue clearance [9, 10]. Given the recurrent nature of these resets, the algorithm’s capacity to substantially diminish reliance on manual ground interventions remains pivotal to mission continuity.

Operating as an integral component of the auto-downlink OBSW, the algorithm executes at a frequency of once per second, continuously processing PVT/AAV telemetry from the PROTEUS platform. This real-time navigation data is essential for determining whether the spacecraft is within the visibility footprint of the pre-configured default ground station. While this configuration can be modified dynamically in RAM via telecommand, any such modifications are lost during a CCU software reset, reverting the system to its default parameters. These default parameters cannot be modified dynamically during operations and require a software update for permanent changes to the OBSW. The algorithm employs geometric criteria based on satellite elevation above the ground station and across-track distance (formally defined in Section 5) to evaluate transmission activation conditions, ensuring that *X* band downlink is triggered only under well-defined parameters.

The decision logic follows a structured sequence: first, the algorithm retrieves PVT/AAV telemetry to ensure current spacecraft position and velocity data; it then verifies whether the satellite is within the expected coverage area of the ground station and whether all geometric constraints are satisfied. Upon meeting these conditions, the *X* band transmitter is activated, enabling science data downlink without ground intervention. Once triggered, transmission continues until either the spacecraft exits the station's footprint, or all stored data has been downloaded.

Due to the OBSW architecture described previously, the default ground station following a CCU reset must be preselected in EEPROM, with any modification to this default configuration requiring a software patch. Additionally, the across-track distance threshold represents a critical parameter determining auto-downlink function activation frequency. Precise modulation of this value is essential to ensure algorithm efficiency, preventing unnecessary activations while maximising data return. The auto-downlink emulator was validated against actual spacecraft telemetry scenarios, demonstrating accuracy within one second compared to real operations.

By automating the downlink process and minimising the risk of prolonged data gaps, the auto-downlink function enhances mission resilience, ensuring valuable science data recovery following CCU resets. However, as its behaviour is governed by fixed onboard parameters, adjustments must be meticulously planned and validated to maintain operational stability. Emerging budgetary constraints necessitate reconfiguring this system since the *X*BAS antenna faces potential decommissioning. This transition presents challenges because the algorithm's parameters —particularly across-track distance thresholds— were originally optimised for ESAC's location. In Section 4 we examine how these ground segment changes impact auto-downlink functionality, and outline modifications needed to establish Svalbard as the new default station for autonomous transmissions.

4. Ground segment evolution and budgetary constraints

The dismantling of the *X*BAS antenna would necessitate several key operational changes within the *SMOS* ground segment. These changes will include designating Svalbard as the new default station for all X-band downlink operations, modifying onboard software parameters to accommodate this shift, updating MP procedures and software tools accordingly, and carefully evaluating impacts on onboard MM management. Each of these adaptations carries distinct operational implications that must be addressed comprehensively to ensure continued mission effectiveness.

4.1 Operational impact

MIRAS CCU stores its OBSW in two redundant EEPROM banks. Modifying the OBSW involves updating these EEPROM banks through well-established procedures. Due to inherent risks associated with direct memory patching, industry partners will perform these modifications by updating OBSW source code variables, recompiling the code, and delivering a fully validated new OBSW version for upload.

4.1.1 OBSW modifications

Various critical onboard parameters require modification:

- **Default ground station** sets default auto-downlink station.
- **Across-track distance threshold** modulates permissible across-track distance.
- **Acquisition of Signal (AOS) elevation** tunes minimum elevation angle required to commence transmission.
- **Loss of Signal (LOS) elevation** tunes minimum elevation angle required to terminate transmission.
- **Orbit path flag** defines whether transmissions occur during ascending, descending passes, or both.

These parameter changes are essential to ensure that auto-downlink activations do not conflict with manual CCU recovery operations, particularly during European working hours.

4.1.2 MP software adjustments

Transitioning from ESAC to Svalbard as the primary downlink station requires corresponding updates within existing MP tools and procedures:

- **High-Level Plan file**: Currently, this file includes scheduled ESAC passes used for coordination between ESA and CNES teams. With Svalbard becoming the primary station, this file must be updated accordingly. Given that reducing the across-track distance threshold effectively eliminates auto-downlink passes during typical European working hours, it may also be possible to remove *X* band pass information entirely from this file if operational teams determine it unnecessary [5].

- **FOS MP tool configuration**: The existing MP template ("ESAC+SVAL") currently used by FOS operators must be updated. Initially, during a transitional phase when both *X*BAS antenna and updated OBSW coexist operationally, the existing dual-station template can remain in use. However, once *X*BAS is fully decommissioned, a new template exclusively referencing Svalbard ("SVAL-only") must be implemented.

These updates will ensure smooth integration of operational changes into routine weekly planning processes without disruption or confusion.

4.1.3 MIRAS MM management

The adjustment of onboard parameters, particularly the reduction of the across-track distance threshold, will influence MIRAS mass memory management by altering the timing and frequency of downlink opportunities. This operational change will result in slightly longer intervals between consecutive downlinks compared to current operations, but given MIRAS's onboard storage capacity, it is expected that data continuity and latency requirements will remain comfortably within acceptable limits. A detailed analysis of the impact of these longer intervals is further elaborated in Sections 6.1 and 6.3.

Considering MIRAS's nominal data generation rate (approximately 41 telemetry packets per second following resets), the total accumulated data after a maximum gap period would require seven to eight minutes of continuous downlink at nominal rates (around 4400 packets per second). This duration corresponds closely to one or two consecutive *X* band passes over Svalbard, like current operational conditions with ESAC. Therefore, despite minor shifts in MM usage patterns resulting from these operational adjustments, no significant negative impacts on data continuity or latency are anticipated.

5. Development of an auto-downlink emulator

To comprehensively analyse and refine the auto-downlink algorithm, we developed a dedicated ground-based software emulator (*SMOS* Auto-Downlink Emulator, or *S*ADE) [11]. This emulator enables engineers to simulate the onboard logic by utilising externally provided orbital prediction files, thus eliminating dependence on real-time spacecraft telemetry. *S*ADE serves as an essential tool for validating algorithm performance under diverse operational scenarios, facilitating controlled testing of parameter modifications without the constraints imposed by spacecraft hardware or live operations.

During our initial validation attempts using MIRASIM (the Mission's MIRAS simulator), we identified certain limitations arising from spacecraft attitude definitions. To overcome these constraints, we incorporated targeted enhancements into the emulator design, ensuring robust validation capabilities aligned with the proposed operational modifications.

*S*ADE processes orbital prediction data supplied by SOGS, comprising satellite position and velocity information at one-minute intervals. From these input data, the emulator calculates PVT parameters along with AAV through rigorous mathematical transformations —including reference frame conversions and quaternion computations— to accurately replicate spacecraft attitude and positional states at each simulated instant. These computed parameters closely reflect actual onboard telemetry conditions encountered during flight operations.

Leveraging these calculated inputs, *S*ADE faithfully replicates the auto-downlink algorithm logic, evaluating dynamically at each simulation step whether conditions necessary for initiating *X* band downlink transmissions are satisfied. Unlike traditional pass-based simulations that rely on predefined ground station contacts, this approach ensures continuous evaluation of downlink feasibility throughout each simulated orbit.

Several key parameters within the emulator configuration are user-adjustable, allowing precise control over downlink activation criteria. Among these parameters are *AOS_ELEVATION* and *LOS_ELEVATION*, which respectively define minimum elevation angles required to initiate and terminate transmissions. Adjusting these thresholds enables engineers to optimise downlink timing —ensuring transmissions commence promptly upon entering visibility range and conclude appropriately as signal quality deteriorates or visibility is lost—.

Furthermore, across-track distance emerges as a critical geometric parameter governing downlink activation decision. Defined as the projection of the station-to-satellite position vector onto the orbital plane normal (aligned with satellite angular momentum vector **h**; see Fig. 8), across-track distance quantifies ground station offset relative to optimal satellite alignment. The sign convention adopted indicates whether the station lies in the direction (positive) or opposite direction (negative) of vector **h**.

Within the auto-downlink algorithm logic, two symmetrical thresholds constrain this across-track distance:

- ***DISTANCE_MAX***: Applicable when across-track distance is positive, defining maximum permissible offset beyond which auto-downlink activation is inhibited.
- ***DISTANCE_MIN***: Applicable when across-track distance is negative, similarly restricting downlink activations beyond a specified negative offset threshold.

Because the across-track distance can assume both positive and negative values, the corresponding thresholds are established symmetrically: *DISTANCE_MAX* is always defined as a positive value, whereas *DISTANCE_MIN* is correspondingly negative. For example, setting *DISTANCE_MAX* to 1000 km implies that *DISTANCE_MIN* is set to -1000 km, thereby delineating a symmetrical corridor of 2000 km within which the satellite must reside for the auto-downlink function to be activated.

At zenith passage (across-track distance = 0 km), no constraints impede downlink initiation; however, as ground station offset increases in either direction from this optimal alignment, these thresholds effectively delineate a permissible corridor within which auto-downlink activation remains feasible.

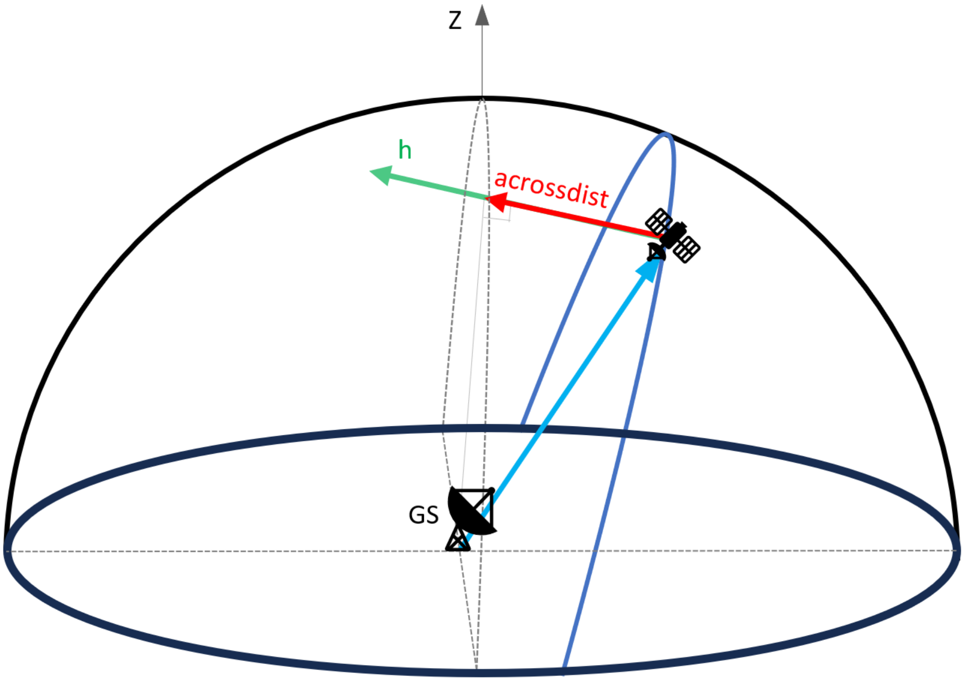


Fig. 8. Illustration of the across-track distance parameter, which quantifies the ground station's offset relative to the satellite's orbital plane. This parameter helps determine whether the satellite is optimally positioned for a downlink, with the sign indicating on which side of the plane the station is located. The angular momentum vector of the satellite, denoted as **h**, defines the normal to the orbital plane and serves as a reference for calculating this offset. *(source: this work)*

By systematically adjusting these parameters, we assessed the sensitivity of the auto-downlink algorithm to various geometric constraints, optimising its performance to achieve an effective balance between data recovery efficiency and operational robustness. Beyond validating algorithm performance, *S*ADE provides a structured environment for testing potential operational improvements. It enables mission planners to simulate modifications to auto-downlink parameters and thoroughly evaluate their effects on transmission timing and continuity prior to onboard implementation. Given that permanent real-time parameter adjustments are not feasible within the existing onboard software architecture, these ground-based simulations are essential for thorough characterisation and validation of proposed changes before deployment.

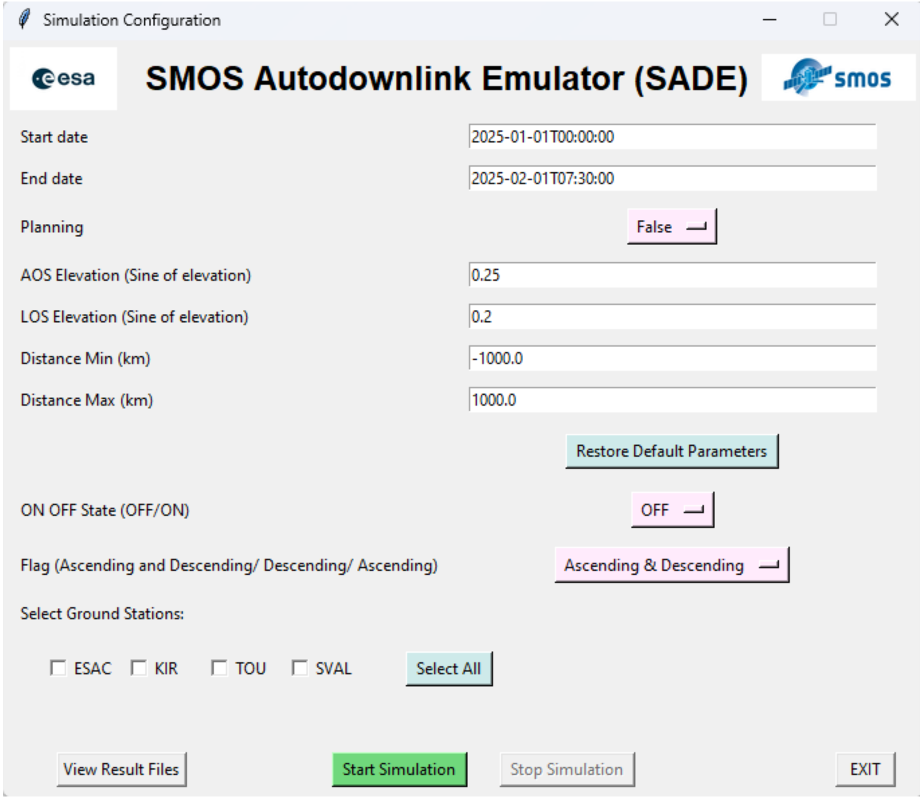
Algorithmic validation efforts provided by this emulator are complemented with a Graphical User Interface (GUI) to facilitate intuitive parameter configuration and comprehensive result visualisation. This interface allows dynamic adjustment of input criteria —including elevation angle constraints, across-track distance limits, and ground station selection— thereby providing flexibility in testing diverse operational scenarios (see Fig. 9).

Upon execution of simulations via this GUI tool, detailed predictions of downlink passes are generated and made available for analysis in both tabular format (Fig. 10) and graphical Gantt chart representations (Fig. 11). The tabular output offers precise timing information for AOS/LOS events, pass durations, elevation angles attained during passes, and associated ground stations, enabling meticulous inspection of individual pass characteristics. Conversely, Gantt chart visualisations provide an immediate overview of temporal distributions of downlink opportunities across multiple stations, facilitating rapid assessment of parameter configurations' effectiveness.

Through integration of orbit computing capabilities with visualisation tools, *S*ADE significantly enhances usability for FOS operators, supporting informed decision-making processes critical to maintaining operational excellence amidst evolving mission constraints.

5.1 Simulation analysis and parameter optimisation

To systematically assess impacts resulting from variations in across-track distance thresholds and elevation angle constraints on auto-downlink behaviour, we conducted extensive simulation analyses using *S*ADE. The primary objective was to identify optimal parameter configurations that maximise available downlink opportunities while simultaneously ensuring transmissions do not conflict with standard European working hours —a crucial consideration given Svalbard's geographical position relative to ESAC operations—.



Start date 2025-01-01T00:00:00
End date 2025-02-01T07:30:00
Planning False
AOS Elevation (Sine of elevation) 0.25
LOS Elevation (Sine of elevation) 0.2
Distance Min (km) -1000.0
Distance Max (km) 1000.0
ON OFF State (OFF/ON) OFF
Flag (Ascending and Descending/ Descending/ Ascending) Ascending & Descending
☐ ESAC ☐ KIR ☐ TOU ☐ SVAL

Fig. 9. *S*ADE’s GUI, designed to facilitate parameter configuration and visualisation of auto-downlink simulation results. *(source: this work)*

Across-track distance thresholds were methodically varied from 1000 km downward to 300 km in incremental steps of 100 km; concurrently, adjustments in *AOS_ELEVATION* and *LOS_ELEVATION* values were evaluated for their influence on pass durations and frequencies.

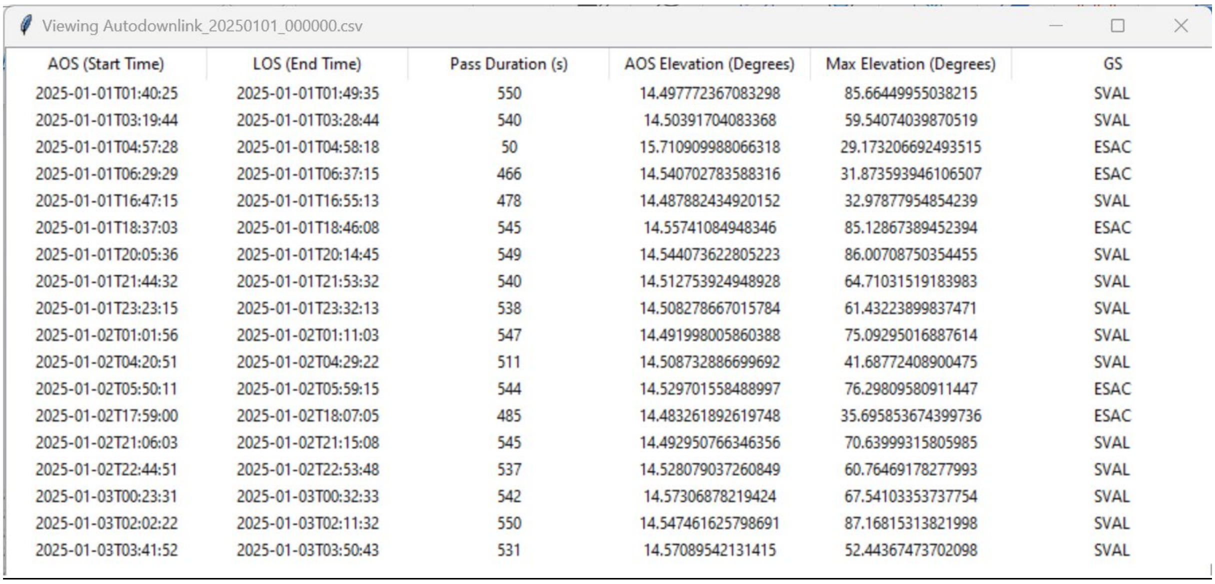
Our simulation outcomes revealed that elevation angle adjustments influenced individual pass durations without significantly altering overall pass frequencies unless extreme —and operationally undesirable— threshold values were employed. For instance, lowering the *AOS_ELEVATION* threshold extended total transmission time, while increasing it reduced pass durations. Conversely, incremental reductions in across-track distance thresholds directly impacted the number of available downlink passes by progressively eliminating those occurring within European working hours while preserving evening/night opportunities unaffected (i.e., for nearly all cases, individual pass duration was maintained).

Considering these findings alongside operational imperatives to avoid daytime conflicts between auto-downlinks and manual CCU recovery procedures following payload resets, we determined an across-track distance threshold value of 700 km to be optimal. This setting effectively eliminates *X* band passes coinciding with standard European working hours while preserving maximal evening/night transmission opportunities, thus ensuring continued efficient science data retrieval with minimal operational disruption under revised ground segment arrangements necessitated by budgetary constraints.

*S*ADE provides the methodological foundation for the algorithm analysis in Section 6, enabling controlled simulation of auto-downlink behaviour without risking flight software modifications. The simulation-derived optimum of 700 km for the across-track distance threshold formed the foundation for operational impact analyses and implementation strategies. This progression from emulator development to operational validation demonstrates a methodical approach that maximises scientific return while minimising risks during the transition from ESAC to Svalbard.

6. Algorithm analysis and modifications

The anticipated dismantling of the *X*BAS terminal at ESAC will significantly influence payload operations. Consequently, rigorous testing must be conducted to verify that the proposed modifications —specifically, reducing the default across-track distance threshold from 1000 km to 700 km and changing the default auto-downlink ground station from ESAC to Svalbard— will ensure that auto-downlink activations occur exclusively during the first and last passes within the selected daily time windows. Following successful validation against the MIRASIM simulator, a new OBSW version incorporating these parameter adjustments shall be implemented. Given that these OBSW modifications will be expected to preclude auto-downlink activations during standard European working hours, it may also become feasible to entirely remove *X* band pass information from the High-Level Plan file currently employed to alert SOGS of potential MIRAS CCU recovery operations.



AOS (Start Time)	LOS (End Time)	Pass Duration (s)	AOS Elevation (Degrees)	Max Elevation (Degrees)	GS
2025-01-01T01:40:25	2025-01-01T01:49:35	550	14.497772367083298	85.66449955038215	SVAL
2025-01-01T03:19:44	2025-01-01T03:28:44	540	14.50391704083368	59.54074039870519	SVAL
2025-01-01T04:57:28	2025-01-01T04:58:18	50	15.710909988066318	29.173206692493515	ESAC
2025-01-01T06:29:29	2025-01-01T06:37:15	466	14.540702783588316	31.873593946106507	ESAC
2025-01-01T16:47:15	2025-01-01T16:55:13	478	14.487882434920152	32.97877954854239	SVAL
2025-01-01T18:37:03	2025-01-01T18:46:08	545	14.55741084948346	85.12867389452394	ESAC
2025-01-01T20:05:36	2025-01-01T20:14:45	549	14.544073622805223	86.00708750354455	SVAL
2025-01-01T21:44:32	2025-01-01T21:53:32	540	14.512753924948928	64.71031519183983	SVAL
2025-01-01T23:23:15	2025-01-01T23:32:13	538	14.508278667015784	61.43223899837471	SVAL
2025-01-02T01:01:56	2025-01-02T01:11:03	547	14.491998005860388	75.09295016887614	SVAL
2025-01-02T04:20:51	2025-01-02T04:29:22	511	14.508732886699692	41.68772408900475	SVAL
2025-01-02T05:50:11	2025-01-02T05:59:15	544	14.529701558488997	76.29809580911447	ESAC
2025-01-02T17:59:00	2025-01-02T18:07:05	485	14.483261892619748	35.695853674399736	ESAC
2025-01-02T21:06:03	2025-01-02T21:15:08	545	14.492950766346356	70.63999315805985	SVAL
2025-01-02T22:44:51	2025-01-02T22:53:48	537	14.528079037260849	60.76469178277993	SVAL
2025-01-03T00:23:31	2025-01-03T00:32:33	542	14.57306878219424	67.54103353737754	SVAL
2025-01-03T02:02:22	2025-01-03T02:11:32	550	14.547461625798691	87.16815313821998	SVAL
2025-01-03T03:41:52	2025-01-03T03:50:43	531	14.57089542131415	52.44367473702098	SVAL

Fig. 10. Tabular output generated by *S*ADE, providing detailed predictions of downlink passes, including AOS/LOS times, pass durations, and elevation angles for analysis. *(source: this work)*

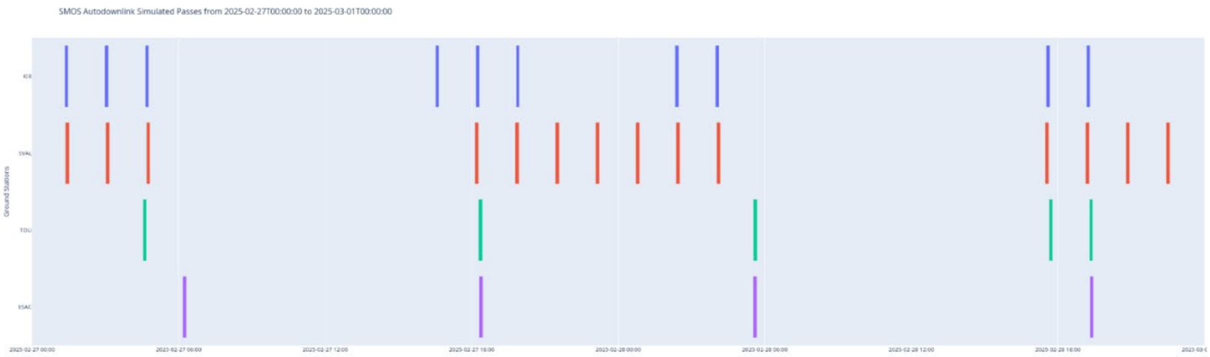


Fig. 11. Gantt chart output from *S*ADE, offering a visual representation of downlink opportunities across multiple ground stations over time for rapid assessment of configurations. *(source: this work)*

6.1 Initial tests

Our initial validation activities involved extensive simulations using *S*ADE to evaluate satellite passes over Svalbard spanning 149 consecutive days —corresponding precisely to one complete *SMOS* orbital repeat cycle (hereafter referred to as a simulation cycle)—. Each simulation cycle replicated the satellite's trajectory over Svalbard, ensuring identical spatial positioning at consistent local times upon completion of each cycle. By systematically applying various across-track distance configurations within these simulations, the analysis assessed how parameter variations influenced auto-downlink activation patterns. Particular attention was given to identifying the timing of the last morning pass and the first evening pass, as these events define the daily gap period without satellite visibility (see Fig. 12). This iterative approach generated comprehensive datasets encompassing all potential downlink opportunities throughout the observation period.

Key aspects of this analysis included:

- **Precisely determining the timing** of both the latest morning pass and earliest evening pass, thereby establishing clear boundaries for daily periods lacking downlink opportunities.
- **Comparing various across-track distance threshold settings** to quantify their effects on downlink availability and assess whether proposed parameter adjustments yield operational benefits.

- **Evaluating whether the proposed reduction** of the across-track distance threshold from 1000 km to 700 km significantly restricts valid auto-downlink opportunities or adversely impacts operational efficiency.

6.2 Results and observations

Our simulation results indicated that with an across-track distance threshold set at 1000 km, the latest morning pass occurred at 05:21:11, while the earliest afternoon pass commenced at 16:41:50. This configuration resulted in a daily gap period without satellite visibility over Svalbard lasting approximately 11 hours, 20 minutes, and 39 seconds.

When reducing this threshold to 700 km, however, simulations revealed that the latest morning pass shifted earlier —to 04:26:49— and the earliest afternoon pass was delayed —to 17:34:54— thereby extending the daily gap period without downlink opportunities to approximately 13 hours, 8 minutes, and 5 seconds. This represents a 16% increase over the current ESAC-based gap period yet remains within MIRAS’s 26-hour MM capacity.

These findings demonstrate that lowering the across-track distance threshold notably extends intervals without available auto-downlink passes. Although this increased gap duration may influence overall data transmission efficiency, further analysis (presented subsequently in Section 6.3) confirms that such extended intervals remain comfortably within MIRAS's onboard mass memory capacity limits. Therefore, despite longer intervals between consecutive downlinks resulting from stricter geometric constraints, no significant negative impacts on data continuity or latency are anticipated.

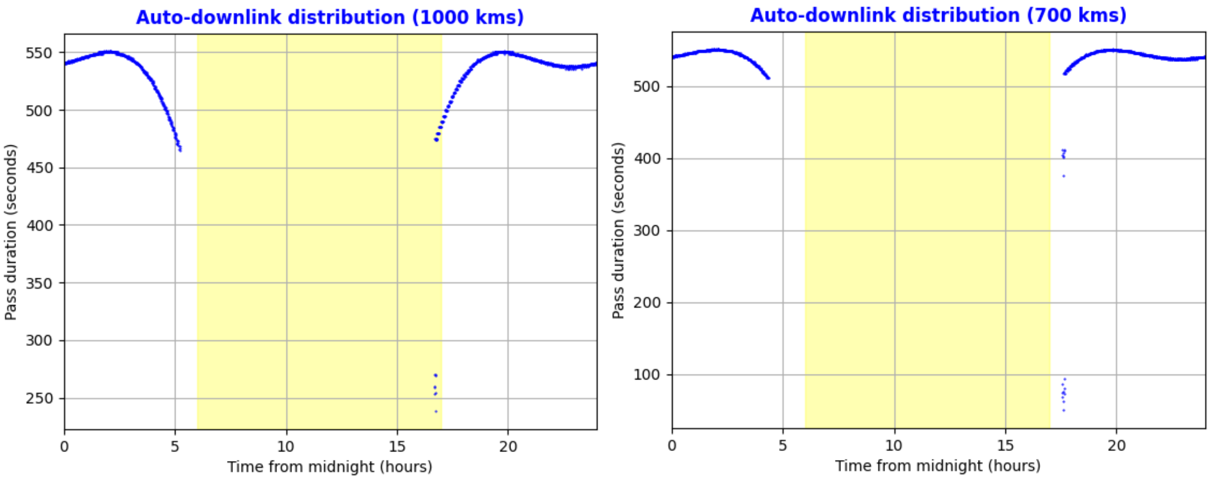


Fig. 12. Influence of across-track distance threshold modifications on satellite pass timing relative to standard European working hours (highlighted in yellow). Progressively stricter constraints effectively shift available downlink passes outside typical working periods, thereby eliminating potential operational conflicts. *(source: [1])*

6.3 MM latency

The reduction of the across-track distance threshold from 1000 km to 700 km will necessarily introduce an extended interval devoid of auto-downlink opportunities, potentially lasting from early morning until late evening. This longer interval between consecutive downlinks raises important considerations regarding onboard MM management and data latency.

The MIRAS instrument continuously generates science data packets at a stable rate following payload resets. After a reset event, the instrument typically produces telemetry at an estimated rate of 41 packets per second. Considering the maximum possible duration without downlink opportunities —spanning some 13 hours— the total volume of accumulated data onboard could reach slightly over 1.9 million telemetry packets.

Given MIRAS's onboard MM capacity (about 26 hours of continuous data storage), this extended gap remains well within operational limits. Even in the worst-case scenario —where a reset occurs immediately after the last available morning pass— the onboard storage would remain significantly below full capacity by the time of the first available evening pass.

Once downlink opportunities resume, the nominal *X* band transmission rate of approximately 4400 packets per second will ensure rapid download of accumulated data. At this transmission rate, the complete acquisition of all telemetry accumulated during the maximum gap period would necessitate merely seven to eight minutes of continuous transmission. This duration aligns closely with typical pass durations available at Svalbard, meaning that stored data can be reliably retrieved within one or two consecutive passes.

From an operational standpoint, this scenario closely mirrors current conditions experienced with ESAC-based operations, where similar intervals between morning and evening passes occur regularly. Consequently, no significant negative impacts on mission data continuity or latency are anticipated due to these operational changes. Reducing the across-track distance threshold will slightly alter onboard storage usage patterns by increasing the duration between consecutive downlinks, yet MIRAS's MM capacity and *X* band transmission rates will ensure continued data retrieval without adverse effects on overall mission performance.

7. Schedule

The implementation schedule for transitioning *SMOS* operations in response to the potential dismantling of the *X*BAS antenna is structured into four distinct phases (see Fig. 13). Each phase is contingent upon the final decision regarding the decommissioning of this ground segment asset, with preparatory activities designed to ensure seamless adaptation to the proposed operational changes.

7.1 Onboard manual tests

The first phase will involve conducting manual onboard tests to cross-check the necessary modifications to the auto-downlink algorithm. These tests will validate changes previously simulated using MIRASIM and include the preparation of telecommand files for execution on the spacecraft. Spanning 14 working days, this phase can proceed even before a formal decision on antenna decommissioning is made. Its results will determine whether the proposed modifications receive a GO/NOGO decision, paving the way for subsequent OBSW implementation by industry partners.

7.2 OBSW implementation and validation

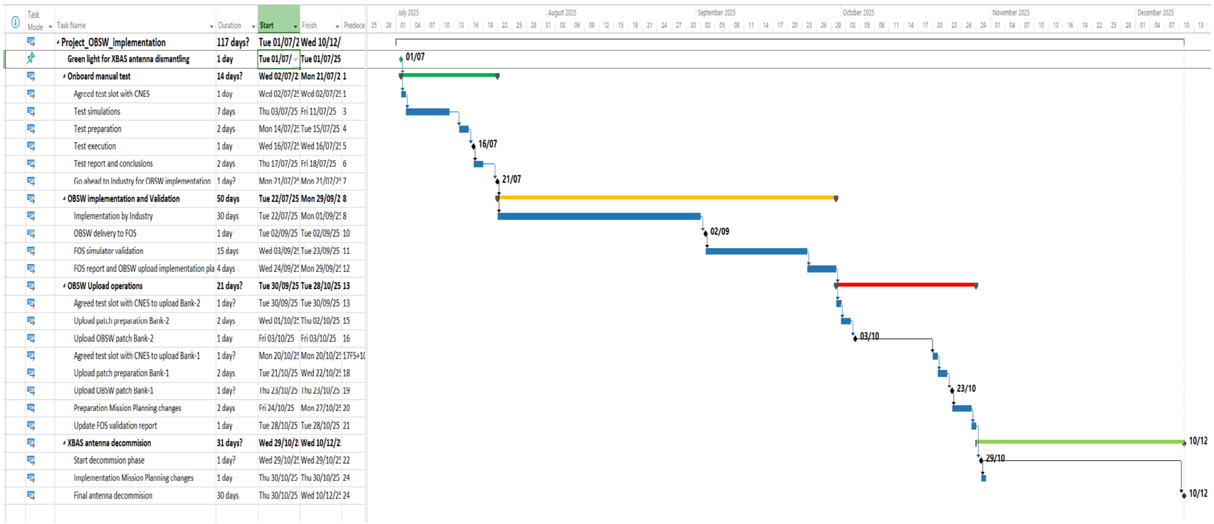
The second phase will encompass the development and delivery of a new OBSW version by industry, incorporating the required auto-downlink modifications [12, 13]. This phase also involves rigorous testing and formal acceptance of the updated software using the MIRASIM simulator. The anticipated duration for this phase is 47 working days, during which FOS teams will ensure that all modifications meet operational requirements and maintain system robustness.

7.3 OBSW upload and trial period

The third phase will focus on uploading the new OBSW patch to the two EEPROM banks onboard. A two-week trial period between uploads will allow for thorough verification of the new software's reliability and to identify any potential regression issues. Concurrently, additional validation will be conducted using MIRASIM simulations over several consecutive cycles. At the conclusion of this phase, all necessary updates to FOS MP software will be completed and ready for deployment. This phase is expected to last at least 21 working days.

7.4 XBAS antenna decommissioning

The fourth and final phase will involve the physical dismantling of the *X*BAS antenna. While this activity will not directly impact FOS operations, all preparatory work related to MP software updates must be completed prior to its commencement. This phase is anticipated to take approximately one month, during which Svalbard will serve as the sole *X* band downlink station. The key milestone for FOS during this phase will be ensuring that all MP software changes are operational at its outset.



Task Mode	Task Name	Duration	Start	Finish	Predece
	Project_OBSW_implementation	**117 days?**	**Tue 01/07/2**	**Wed 10/12/**	
	Green light for XBAS antenna dismantling	**1 day**	**Tue 01/07/**	**Tue 01/07/25**	
	Onboard manual test	**14 days?**	**Wed 02/07/2**	**Mon 21/07/2**	**1**
	Agreed test slot with CNES	1 day	Wed 02/07/2	Wed 02/07/2	1
	Test simulations	7 days	Thu 03/07/25	Fri 11/07/25	3
	Test preparation	2 days	Mon 14/07/2	Tue 15/07/25	4
	Test execution	1 day	Wed 16/07/2	Wed 16/07/2	5
	Test report and conclusions	2 days	Thu 17/07/25	Fri 18/07/25	6
	Go ahead to Industry for OBSW implementation	1 day?	Mon 21/07/2	Mon 21/07/2	7
	OBSW implementation and Validation	**50 days**	**Tue 22/07/25**	**Mon 29/09/2**	**8**
	Implementation by Industry	30 days	Tue 22/07/25	Mon 01/09/2	8
	OBSW delivery to FOS	1 day	Tue 02/09/25	Tue 02/09/25	10
	FOS simulator validation	15 days	Wed 03/09/2	Tue 23/09/25	11
	FOS report and OBSW upload implementation pla	4 days	Wed 24/09/2	Mon 29/09/2	12
	OBSW Upload operations	**21 days?**	**Tue 30/09/25**	**Tue 28/10/25**	**13**
	Agreed test slot with CNES to upload Bank-2	1 day?	Tue 30/09/25	Tue 30/09/25	13
	Upload patch preparation Bank-2	2 days	Wed 01/10/2	Thu 02/10/25	15
	Upload OBSW patch Bank-2	1 day	Fri 03/10/25	Fri 03/10/25	16
	Agreed test slot with CNES to upload Bank-1	1 day?	Mon 20/10/2	Mon 20/10/2	17FS+1
	Upload patch preparation Bank-1	2 days	Tue 21/10/25	Wed 22/10/2	18
	Upload OBSW patch Bank-1	1 day?	Thu 23/10/25	Thu 23/10/25	19
	Preparation Mission Planning changes	2 days	Fri 24/10/25	Mon 27/10/2	20
	Update FOS validation report	1 day	Tue 28/10/25	Tue 28/10/25	21
	XBAS antenna decommision	**31 days?**	**Wed 29/10/2**	**Wed 10/12/2**	
	Start decommsion phase	1 day?	Wed 29/10/2	Wed 29/10/2	22
	Implementation Mission Planning changes	1 day	Thu 30/10/25	Thu 30/10/25	24
	Final antenna decommision	30 days	Thu 30/10/25	Wed 10/12/2	24

Fig. 13. Timeline outlining the implementation phases of OBSW modifications and validation activities, highlighting key milestones critical for ensuring a smooth transition in payload operations following the decommissioning of the *X*BAS antenna. *(source: [1])*

8. Conclusion

The *SMOS* mission, originally conceived for a five-year operational lifetime, has transcended initial expectations to become an indispensable cornerstone of Earth observation and climate research. Now in its sixteenth year of operations, the mission faces new challenges driven by evolving budgetary realities. A critical scenario under consideration involves the potential dismantling of ESAC's *X*BAS antenna, a key element in the current ground segment infrastructure.

In this paper we have examined the operational implications of transitioning *SMOS* payload auto-downlink operations from ESAC to Svalbard. Through careful analysis and targeted simulations, we have demonstrated that designating Svalbard as the default auto-downlink station will be both feasible and operationally robust. Adjustments to onboard software parameters —particularly reducing the across-track distance threshold from 1000 km to 700 km— will effectively mitigate potential conflicts between automated downlinks and manual recovery procedures following frequent onboard resets.

Comprehensive validation conducted through *S*ADE has affirmed that these parameter modifications preserve data continuity without appreciable adverse effects on mass memory management or data latency. Furthermore, proposed updates to MP software ensure smooth integration of these operational changes into routine ground segment processes.

By adapting payload operations to evolving fiscal realities, *SMOS* demonstrates exemplary operational flexibility and mission resilience. The strategic optimisations described in this paper not only preserve the mission's exceptional scientific output but also exemplify cost-effective sustainability in long-term Earth observation missions. These strategic optimisations exemplify *SMOS*'s commitment to sustainable space operations, aligning with SpaceOps 2025's imperative to harmonise scientific excellence with fiscal responsibility.

Acknowledgements

Authors thank B.J. Duesmann (ESA), V. Rodríguez González (Telespazio Vega UK), and E. Uranga Sáez (ISDEFE) for insightful discussion.

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