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CHEOPS Automated Operations

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Abstract

CHEOPS (CHaracterising ExOPlanet Satellite) is ESA’s first S-class mission dedicated to study already-known exoplanets. It performs high-precision observations of bright stars to determine exoplanets size using the transit method. S-class missions are designed to be implemented quickly and on a small budget, having an impact on every aspect of the mission, such as the spacecraft or the ground segment design. CHEOPS ground segment is mainly divided into the Mission Operations Centre, responsible for the control and operations of the satellite, the ground stations used for communication with the satellite, both hosted by the Instituto Nacional de Técnica Aeroespacial in Madrid, and the Science Operations Centre located in Geneva. CHEOPS was launched in December 2019 into a sun-synchronous orbit at a height of 700 km with a Local Time of Ascending Node at 6:00 a.m. As a result of the orbit design and the ground stations’ location, there are between four to six short passes per day outside of regular working hours. Therefore, operations automation was considered from the very beginning of the project to reduce costs. The initial automation requirements called for the automation of passes where the Activity Plan was not uplinked to the satellite, and the automatic notification to the operators in the event of anomalies. Operators analysed the numerous activities that could be automated considering the automation capabilities of the Mission Control System and the Flight Dynamics System, and the initial requirements were already exceeded before the launch such that most of the routine activities were fully automated. During the commissioning phase, once the automatic uplink was verified, the automatic Activity Plan uplink was introduced. This was a significant breakthrough because routine passes no longer required manual intervention. Operators need to be present during passes only in order to respond in the event of non-routine activities or emergencies in the control centre or in the satellite. All in all, automated operations have shown to be reliable and useful for operators to efficiently control CHEOPS. Additionally, operators can concentrate on the analysis of the results and other activities that require a deeper understanding of the different subsystems by letting the automation system handle the repetitive tasks.

Keywords: CHEOPS, Satellite, Ground Segment, Operations, Automation

Acronyms/Abbreviations

Activity Plan (AP)
Collision Avoidance (CA)
CHaracterising ExOPlanet Satellite (CHEOPS)
Depth of Discharge (DoD)
European Space Agency (ESA)
Flight Dynamic System (FDS)
Ground Station (G/S)
In-Orbit Commissioning (IOC)
Mission Control System (MCS)
Mission Operations Centre (MOC)
Instituto Nacional de Técnica Aeroespacial (INTA)
On-board Computer (OBC)
Telecommand (TC)
Telemetry (TM)
Science Operations Centre (SOC)

Space Traffic Management (STM)

1. Introduction

CHEOPS (CHaracterising ExOPlanet Satellite) is a European Space Agency (ESA) mission dedicated to study already-known exoplanets. It performs high-precision observations of bright stars to determine exoplanets size using the transit method.

On December 18th, 2019, CHEOPS was launched to a dawn-dusk sun-synchronous orbit at an altitude of 700 km. The nominal mission lifetime was 3.5 years. Nevertheless, a first extension to the mission operations until the end of 2026, with an indicative second extension to the end of 2029, has been granted due to the exceptional quality of the science produced by the mission as well as the excellent satellite health status.

CHEOPS is the first small mission (S-class) in the ESA science program. As such, the budget and the development times were limited.

CHEOPS platform is an Airbus AS-250, and the payload, developed under the responsibility of Universität Bern, is a Ritchey-Chrétien telescope. In order to remain within the budget, the AS-250 platform was downgraded. Some units were removed from the design while others were replaced with cheaper equivalents that had performances closer to the requirements. Some of these modifications implied additional requirements in the control centre operations, which also had a limited budget.

The ground segment architecture is illustrated in the Fig. 1. The control and operations of the satellite are performed from the Mission Operations Centre (MOC) located at the Instituto Nacional de Técnica Aeroespacial (INTA) in Madrid (Spain). The Activity Plan (AP) generation with the activities to be executed on-board, and the science data processing, distribution and archiving are performed by the Science Operations Centre (SOC) situated in the Université de Genève (Switzerland). Then, INTA's ground stations (G/S) located in Madrid are used to communicate with CHEOPS during the nominal operations. Additionally, ESA's G/S network can also be used for emergencies.

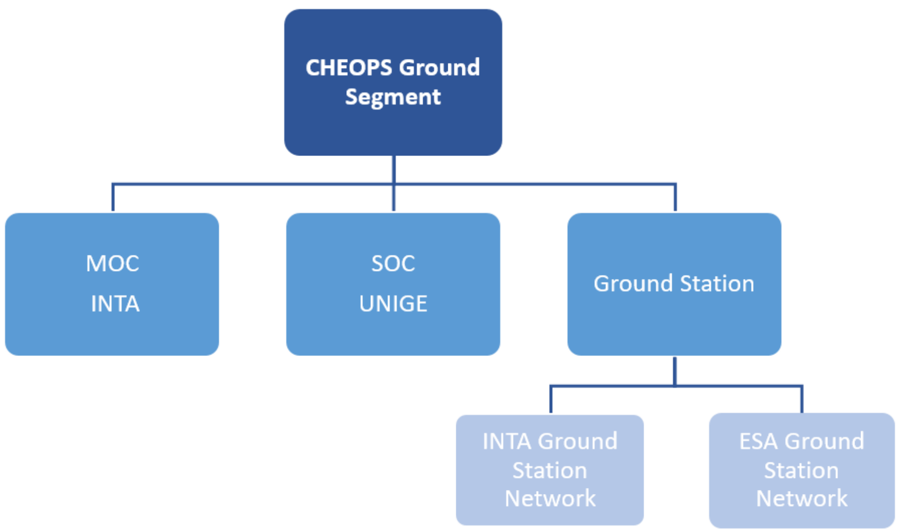


Fig. 1. CHEOPS ground segment architecture

Due to the orbit design and the G/S locations, the spacecraft is visible by the G/S approximately two to three times in the early morning, and two to three times in the late evening. To minimize the operator presence outside of working hours and thus reduce operational costs, the MOC automation was considered from the very beginning. Initially, the automation included the execution of the passes where the AP was not uplinked. Then, the automation was further improved to cover the vast majority of the routine activities, as well as some maintenance and contingencies activities. The current trend is to continue improving the automation system.

This paper offers a description of the CHEOPS MOC automation capabilities that enable the efficient and reliable operation of the satellite and highlights the effort to automate operations for an S-class mission intended to operate on a moderate budget.

Section 2 focuses on the automation capabilities of the different MOC subsystems. Then, the use of these automation capabilities by MOC operators to create automatic activities that enable passes and other routine activities to be executed automatically is detailed in Section 3. Section 4 covers the partial automation implemented to assist operators in activities that still need some human intervention because of their criticality. Finally, Section 5 presents the automation improvements foreseen in the near future.

2. CHEOPS MOC Automation capabilities

The MOC is composed of the different subsystems needed to operate the satellite (Fig. 2). To comply with the automation requirements, the MOC subsystems require some automation capabilities:

The **Mission Control System (MCS)** is based on ESA's SCOS 2000 tailored for the satellite mission requirements. The automation capability is provided through a library of Python modules generated by GMV that enables the interaction with MCS from Python scripts. These Python scripts are able to configure different MCS components and variables, read telemetry (TM), and send telecommands (TC).

The **Flight Dynamic System (FDS)** is built on the Focus software suite, a collection of flight dynamics modules developed by GMV. The automation capability is handled by an additional software component, **Autofocus**, which enables automated execution of FDS procedures that involve the sequential operation of multiple modules. This capability enhances operational efficiency and ensures consistency in the execution of complex flight dynamics processes.

The **Automation system** is based on GMV's Flyplan software. This tool enables automatic planning and execution of Python scripts that create or delete activities in the Flyplan schedule, MCS Python scripts, and Autofocus scripts, offering a comprehensive Ganttstyle visualization that provides insight into the schedule and reflects the execution status of all tasks.

Initially, the Automation System provided the capability of schedule time-driven activities. Later on, a new key component named **monitorCHEOPS** was included to provide the capability to be data-driven whenever necessary, permitting flexible and independent operations. It monitors a configurable list of path names to detect input files and then triggers the corresponding processing activity. Operators manually triggered the processing activities in Flyplan until the monitorCHEOPS component was validated shortly after launch.

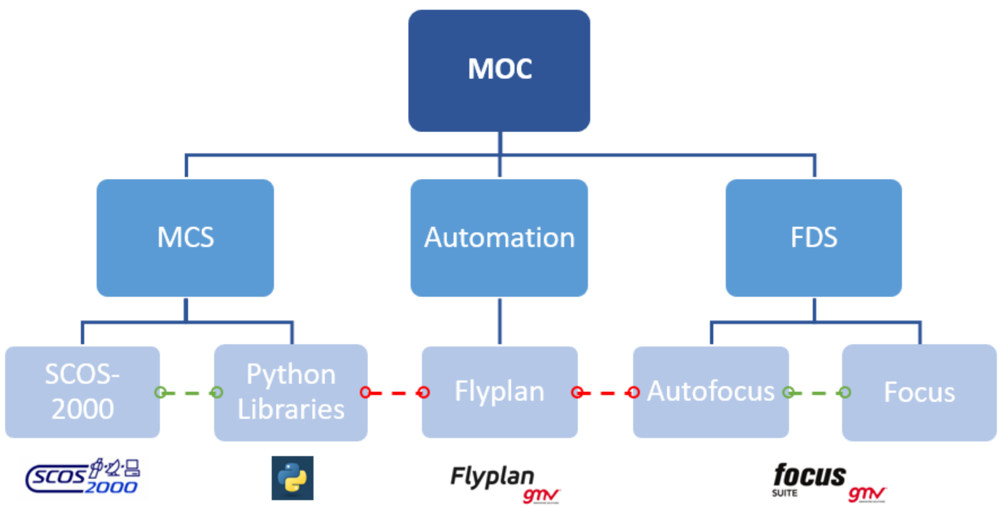


Fig. 2. MOC subsystems

3. CHEOPS MOC automation

The MOC responsibilities for CHEOPS mission encompass the AP uplink, the platform and instrument status monitoring and anomalies management, the orbit and attitude determination and control, and the satellite deorbiting.

The initial automation requirements included automation outside nominal working hours if needed to ensure the spacecraft safety and to meet downlink time requirements, and automatic notification in case of spacecraft and ground segment anomalies. These requirements had already been exceeded before the launch, and the automation has continued to be improved throughout the mission.

3.1 Pass automation

The pass automation is based on a series of activities scheduled in the Automation System for every pass. These activities are Python scripts that have the capability to interact with the MCS. Considering the initial requirements, the pass automation started with two activities that enabled the automatic pass execution and automatic warning to the operators in case of anomalies. Afterwards, to reduce the workload and prevent human error, the automation was enhanced before the launch by adding a number of activities that perform tasks that operators detected could be automated. Finally, an additional activity was developed in the routine phase when operators detected the need for the system to react under certain conditions.

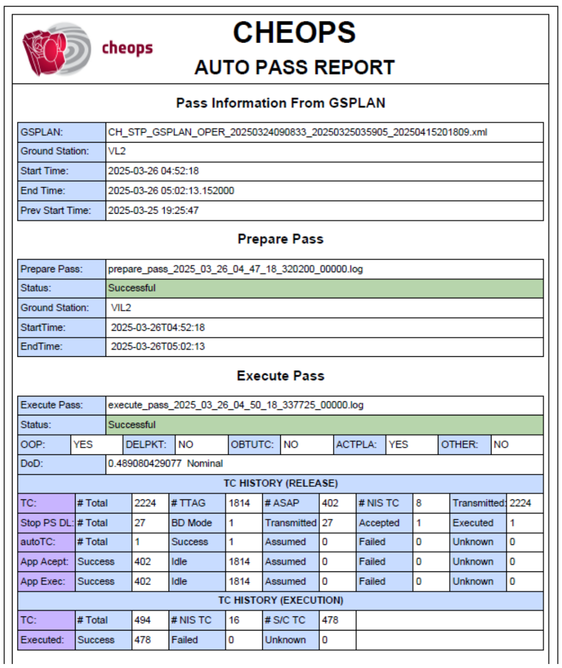
3.1.1 Initial pass automation

The initial activities created were the **execute_pass** and the **pass post-processing.**

The **execute_pass** activity performs the automatic pass execution including the connection between the MCS and the G/S assigned for the pass, the sending of pre-generated TCs, and the downlink of the TM recorded on-board.

The **pass post-processing** activity is responsible for processing the recorded TM on-board and downlinked during the pass. It enables the provision of science and housekeeping TM to SOC, and the necessary TM to monitor the satellite status to MOC. The most relevant logs and reports from the pass are forwarded to the MOC operators so they can detect potential anomalies.

Additional tasks and checks have been included to the pass post-processing activity during the routine phase, such as the addition of the G/S information or graphs with out-of-limit TMs, the generation of TM reports for other subsystems, etc. The most significant improvement was the creation of a PDF that details the results of the different activities performed automatically during the pass, using a colour-coding system to display the results, along with a few warning messages in case of failure. The PDF has proven to be quite helpful to verify the execution status of the different activities and to detect potential anomalies quickly and efficiently (Fig. 3).



CHEOPS

AUTO PASS REPORT

Pass Information From GSPLAN

GSPLAN:	CH_STP_GSPLAN_OPER_20250324090833_20250325035905_20250415201809.xml
Ground Station:	VL2
Start Time:	2025-03-26 04:52:18
End Time:	2025-03-26 05:02:13.152000
Prev Start Time:	2025-03-25 19:25:47

Prepare Pass

Prepare Pass:	prepare_pass_2025_03_26_04_47_18_320200_00000.log
Status:	Successful
Ground Station:	VIL2
StartTime:	2025-03-26T04:52:18
EndTime:	2025-03-26T05:02:13

Execute Pass

Execute Pass:	execute_pass_2025_03_26_04_50_18_337725_00000.log
Status:	Successful

OOP:	YES	DELPKT:	NO	OBTUTC:	NO	ACTPLA:	YES	OTHER:	NO

DoD:	0.489080429077 Nominal

TC HISTORY (RELEASE)

TC:	# Total	2224	# TTAG	1814	# ASAP	402	# NIS TC	8	Transmitted:	2224
Stop PS DL:	# Total	27	BD Mode	1	Transmitted	27	Accepted	1	Executed	1
autoTC:	# Total	1	Success	1	Assumed	0	Failed	0	Unknown	0
App Acept:	Success	402	Idle	1814	Assumed	0	Failed	0	Unknown	0
App Exec:	Success	402	Idle	1814	Assumed	0	Failed	0	Unknown	0

TC HISTORY (EXECUTION)

TC:	# Total	494	# NIS TC	16	# S/C TC	478	
Executed:	Success	478	Failed	0	Unknown	0	

Fig. 3. Pass report

3.1.2 Additional pass automation

Before the launch, three additional activities were added to assist the operator: **status_sc_check**, **health_check**, and **checkODtrigger**. The first two activities use the capability to retrieve the value of specific TM from the MCS Packet Archive in real time.

The **status_sc_check** performs checks of the satellite high-level status and sends an email to the operator to quickly identify potential anomalies at the beginning of the pass.

The **health_check** checks the health status of different on-board units defined by the manufacturer.

The **checkODtrigger** activity scheduled at the end of the pass is responsible for scheduling additional activities in Flyplan in case certain conditions are met.

3.1.3 Pass automation during the routine phase

The pass activities described above have evolved throughout the mission with the incorporation of additional tasks. Furthermore, the **autoTC** activity was generated due to the necessity for the system to respond to certain conditions in real time. This activity enables the real-time generation and transmission of TCs to CHEOPS in response to specific TM values.

The Depth of Discharge (DoD) computation, which is a parameter that indicates the battery level of discharge, is computed on-board using an algorithm susceptible to drift. As a result, the reset of this drift is automatically performed on-board when the battery is considered to be charged. During the routine phase it was detected that this algorithm sometimes did not function as intended, and in consequence, the DoD reset had to be performed from ground. First, the TCs were manually prepared and sent to the satellite when this behaviour was detected, but with the generation of the **autoTC** activity, the misbehaviour is detected during the pass and the TCs for the reset are automatically generated and sent to the satellite.

This activity has proven to be of great help. Therefore, its functionalities have been expanded during the course of the mission. They are described below.

- Telemetry gaps retransmission: at the beginning of the mission, small uplink and downlink signal losses were observed of the order of one per month during some low elevation passes. The first solution was to change the nominal G/S to a redundant one with higher gain. As a result, the number of TM losses was reduced, but some still occurred. Therefore, it was periodically necessary to retransmit those TM intervals that had not been properly received on ground. This process involved the presence of an operator acting manually during the pass to disable the automatic TM downlink and manually command the downlink of the TM gaps, checking that one downlink had been completed before starting the next. This human intervention went against the idea of the automated operations concept. For this reason, this procedure was automated in such a way that the only manual intervention needed was for the operator to enter the information required for the retransmission before the pass.
- Star Tracker diagnostic TM request: this task performs the TM request when the star tracker electronics report the existence of a minor error.
- On-board Computer (OBC) memory check: the platform OBC has a mechanism to detect and correct memory errors. When a satellite reconfiguration occurred at the beginning of the In-Orbit Commissioning (IOC) phase, this mechanism was disabled, and the OBC needs to be reset to enable it again. To avoid the risk that this would entail, a task to perform the detection and patch of corrupted memory addresses every week from ground was included in the autoTC.
- On-board Packet Utilization Standardization services configuration request: recently, a new task has been introduced that requests the configuration every week for its comparison with the previous status to detect any unexpected changes.

Operators review the execution of the automatic operations and the status of the spacecraft based on the information generated by the Automation system every day. They only have to attend the passes in the case of non-routine operations or contingencies in the control centre or in the satellite. In those cases, the system report includes useful information to evaluate the criticality of the problem or even identify the faulty component without accessing the MOC.

3.2 Flight Dynamics System automation

Originally, the FDS activities were not planned to be automated, but having gained experience in automation, operators used the Autofocus tool capabilities to fully automate the following routine FDS activities: the orbit determination and attitude monitoring, the processing of auxiliary data files, and the generation of the satellite visibilities with the G/S and the predicted orbit. This layer of automation implied that operators could manually trigger the diverse FDS automated activities in Autofocus.

The automation was then further enhanced so that the Automation system was the one that initiated the execution of the FDS automated activities. Some activities were integrated into the **checkODtrigger** activity (section 3.1.2) that schedules them in the Automation system at the corresponding times. Others were incorporated into the **monitorCHEOPS** activity (section 2) so they are triggered by the Automation system upon the detection of specific files.

The **orbit determination** activity includes the estimation of the satellite's position and velocity using the Doppler measurements from the G/S, and the subsequent products generation. It should be mentioned that the operational orbit, which contains the orbit from the entire mission, is updated after each orbit determination.

Normally, modern spacecraft carry a GPS receiver for the spacecraft to determine its position and velocity. In the case of CHEOPS, the GPS unit was not included in the satellite to reduce costs, but this information is needed by the Attitude and Orbit Control subsystem software for orbit propagation. This implies that the satellite position and velocity must be uplinked to the satellite periodically before the on-board propagator accuracy drops below the requirements. Thus, one of the products derived from the orbit determination is a satellite state vector in the future.

At the beginning of the mission, this state vector was included in a TC and uplinked manually to the satellite. However, once the automatic passes were validated, the automation was further improved to enable the automatic conversion of the state vector into a TC and its uplink in the following pass.

The **attitude monitoring** procedure compares the simulated attitude computed when the AP is received from SOC and processed in the FDS (section 3.4) against the real attitude retrieved from the TM in order to detect differences.

The **auxiliary data files processing** activity updates the FDS database with the information included in those files (Earth orientation parameters, solar and geomagnetic activity, etc.) with the objective of improving the orbit determination and propagation.

Finally, the **orbital events generation** activity is responsible for propagating the operational orbit with the aim of generating two products: the G/S visibilities for the G/S scheduling, and the predicted orbit for SOC needed for the AP generation.

The orbit determination and the attitude monitoring activities are planned in the Automation system after the last morning and evening passes because they are based on information generated or retrieved during them. Moreover, the orbital events generation activity is planned once a week to feed the scheduling task. These three activities are triggered by the checkODtrigger activity. On the other hand, the auxiliary data files processing procedure is triggered by the Automation System upon detection of the files (normally once a day).

An illustration of the Flyplan schedule on a Sunday evening is provided in Fig. 4. The first event is the auxiliary data file processing triggered when the corresponding file is detected. On the other side, the orbit determination, attitude monitoring, and orbital event generation have been planned by the checkODtrigger after the pass execution.

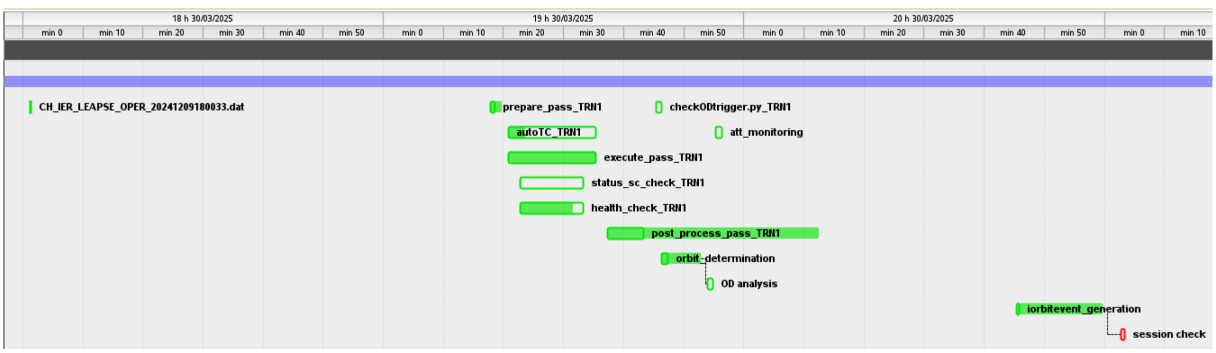


Fig. 4. Sunday evening Flyplan schedule

The automation of the aforementioned FDS activities was already done before the launch. During the routine phase, additional FDS activities have been automated to reduce operator's workload and human errors.

3.3 GSAvailability file processing automation

Every Sunday evening, the INTA G/S scheduling office receives the CHEOPS G/S visibilities from the FDS. They use this information, in addition to pass requests from other missions, to generate a conflict free solution for the use of the INTA G/S network. Then, they generate the **GSAvailability** file that includes the details of the G/S contacts assigned to CHEOPS for the following three weeks. It should be noted that this file is not only received by MOC, but it is also provided to SOC so that they can include the pass related activities in the AP.

The GSAvailability file provides the information to schedule the pass activities in the Automation system at the corresponding times (section 3.1), to generate the directory structure for the passes, and to create the routine pass TCs (MCS-G/S connection and recorded telemetry downlink) at their corresponding execution time. Then, these routine pass TCs are assigned to the corresponding pass directory for their automatic uplink.

MOC operators created an MCS Python script to automate the processing of the GSAvailabity file upon detection by the **monitorCHEOPS** component of the Automation system. This automatic activity performs the tasks outlined above without the need for operator intervention.

Additionally, an FDS activity is triggered by the Automation system upon detection of the GSAvailability file in order to further reduce the TM losses in the passes that are most likely to have them (section 3.1.3). This activity analyses the assigned passes to generate an EVENT file that includes a request for the G/S to increase the transmitted power for passes below a defined elevation.

3.4 Activity Plan processing automation

SOC is responsible for the weekly AP generation using the observation requests from the scientists, and the products received from MOC. These products are the predicted orbit computed in the orbital events generation activity (section 3.2), and the GSAvailability file (section 3.3). The AP normally lasts one week.

The first activity upon the AP reception from SOC requires the use of the FDS. The satellite attitude is simulated in order to ensure that the operational constraints are not violated.

The payload thermal stability requirements are very stringent and the temperature fluctuations on the payload radiator should be minimized. Aside from using a sunshield, the angle between the telescope's line-of-sight and the Sun must be smaller than 60º (Fig. 5). The FDS predicts the attitude and verifies that the SOC planning does not violate the Sun Exclusion Angle threshold (120º). Recently, this angle has been relaxed to 117º in order to extend the exposure time for certain targets and enable CHEOPS to observe part of the Kepler field.

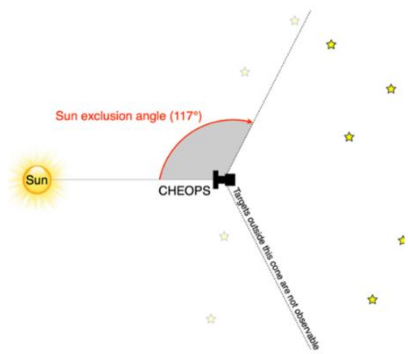


Fig. 5. CHEOPS Sun Exclusion Angle

The second activity consists of AP conversion into a stack of TCs for its uplink to the satellite.

The automatic AP processing upon reception from SOC was implemented before the launch. Once the AP is received from SOC, the monitorCHEOPS component of the Automation system detects the file and triggers the FDS activity responsible for the attitude check. If the previous check is passed, the second activity, which consists of an MCS Python script that converts the AP into TCs, is triggered.

The initial automation requirements did not include the automatic AP uplink and at the beginning of the mission, operators needed to be present once a week for the manual AP uplink. During IOC phase, once the automatic uplink was validated, an extra activity was added to enable the automatic AP uplink. This activity consists of an MCS Python script in charge of allocating the AP stack to the next pass with enough time for it to be automatically uplinked to the satellite.

The deployment of this last automated activity was a breakthrough in the operations concept because it eliminated the need for any manned pass for routine operations.

Fig. 6 illustrates that the number of passes requiring manual intervention is significantly low, and that operators only need to attend the passes in the event of non-nominal operations.

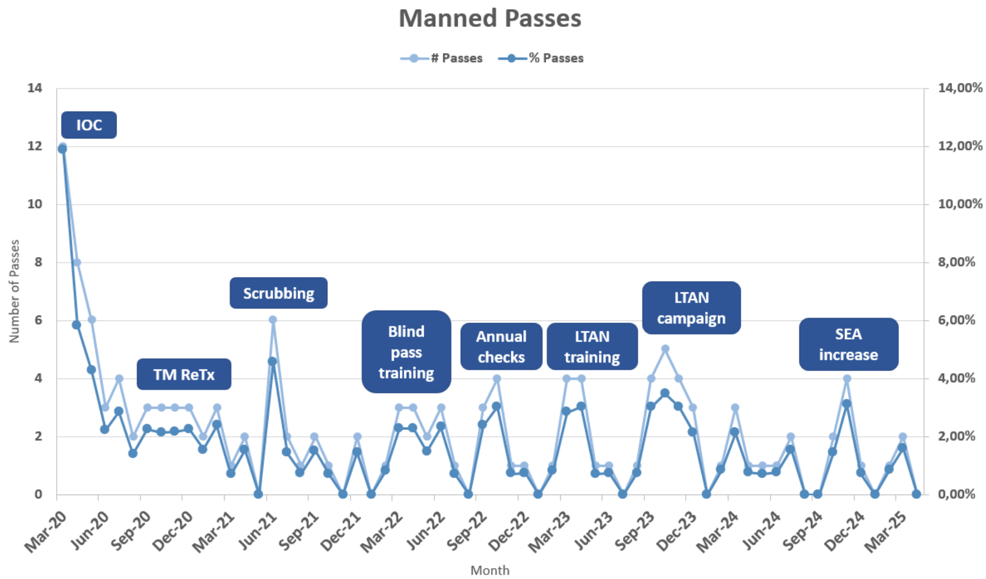


Fig. 6. Number of manned passes per month

4. CHEOPS MOC partial automation

Partial automation has been implemented to assist operators in certain non-routine and contingency activities that need to be performed multiple times but still require some manual intervention because of their criticality. These activities are the **collision avoidance (CA)** procedure and the **Annual Checks**.

CHEOPS is located in a very populated orbit and as a result, every now and then, collision warnings with other objects are received from the Space Traffic Management (STM) provider. On a routine basis, the orbital products derived from the orbit determination are forwarded to the STM provider so it can perform the screening of potential collisions. If the collision probability is above the defined threshold, the **CA procedure** is triggered.

This procedure consists of the products generation needed by the STM providers to perform the screening considering the scenario with and without manoeuvre, the generation of TCs to configure the satellite for the manoeuvre and to resume the scientific activities, and the generation of the manoeuvre TCs.

At the present time, this procedure is almost fully automated, with the exception of an operator manually triggering the activity that generates the TCs. The reason is that when these TCs are generated, they are automatically allocated to the next pass folder for its uplink, and at this stage, human control is still desired.

Another non-routine activity that is partially automated are the **Annual Checks**. Following the manufacturer's indications, the status of some redundant units that are normally switched off has to be checked annually. Operators created a series of Python scripts that read satellite TM in real time, display them using a colour code based on the result, and request the operator's authorization to send the corresponding TCs. Once a year, operators manually launch these scripts during a pass to perform the Annual checks. They have allowed this operation to be performed more quickly and efficiently.

5. Future automation improvements

INTA's operations team is continuously working on enhancing the MOC automation. Below is a description of the most significant improvements to be implemented in the near future.

The first improvement is the partial automation of the safe mode recovery following the same approach as for the Annual checks. Whenever this contingency occurs and the recovery has been approved, operators will only need to run some Python scripts that send the appropriate TCs after operator's authorization and print the corresponding TMs in real time.

The other improvement will enable full automation of the TM gap retransmission (section 3.1.3). Until now, the missing telemetry information included in the autoTC activity has been provided by SOC since the science TM is not processed at MOC. A new tool has been developed by the MCS provider to detect TM gaps after every pass without requiring the input from SOC. This tool is under testing, and once it is verified that the TM gaps match the ones detected by SOC, INTA operators will enhance the TM retransmission task to avoid any manual intervention.

6. Conclusion

CHEOPS is the first ESA mission focused on the study of exoplanets. As an S-class mission, the tight budget and development times had an impact on the platform design and the control centre operations. Because of the pressing need for cost reduction, CHEOPS operations automation was contemplated from the very beginning, and it has been facilitated by the adaptability of the various MOC subsystems and the compatibility of satellite commanding with automated operations.

The initial automation requirements included automating passes outside of regular business hours and automatically alerting the operator in the event of satellite or ground segment anomalies. Due to the CHEOPS orbit and the G/S' location, nearly every pass is outside of nominal working hours.

The automation of passes marked the beginning of the automated operations. After then, the automation was enhanced over time to the extent where practically all of the routine activities were automated before the launch. The AP uplink automation during IOC, which was not considered at the beginning, was key because manual intervention was no longer required for routine passes.

At present, the automation is used for all routine operations, with the exception of assessing the satellite status and reviewing the outcomes of automated activities. In addition to reducing the workforce demands, this lowers the probability of human error while also ensuring consistency in the execution of complicated activities. As a result, operators can concentrate primarily on analysing the results, executing non-routine manual operations that need expert knowledge of the various subsystems, and further improving the automation system to satisfy the needs.

The current automation enables a very efficient operation of the MOC by the INTA operations team. However, being aware of the potential knowledge loss that the automation of activities may entail, operators conduct regular training sessions and perform tests against the spacecraft simulator for every non-routine activity.

All in all, after five years of successful operations, it has become apparent that the automation enables the fulfilment of the mission's operational requirements without compromising any of its aspects. In particular, it has proven to be very robust and useful in extreme situations such as the COVID-19 pandemic.

CHEOPS operations strongly focused on automation can serve as inspiration for future missions. Even though bigger space missions' operations would seem more difficult to automate, CHEOPS experience shows that few issues can be expected with enough validation prior to actual operations, and the majority of them would also be faced in manual operations.

Acknowledgements

The MOC team sincerely express their gratitude to each and every member of the CHEOPS team. This forward thinking operational concept based on automation would not have succeeded without the effort and commitment of those who have contributed to the ground segment development and maintenance, and their constant openness to explore new approaches. We would like to express our heartfelt appreciation to the ESA team for their invaluable expertise in missions operations at the European Space Operations Centre, the instrument team at Universität Bern for their extensive instrument knowledge and ongoing dedication to the mission management, the Science Operations team in the Université de Genève for the tireless effort to ensure a seamless interface between the scientific community and the satellite control centre, and Airbus D&S in Madrid for their endless support to the spacecraft maintenance throughout the mission. We gratefully acknowledge Richard Thomas Southworth from ESA for his vital contribution to mission operations based on his wide experience, and José Ramiro Peñataro from GMV for his ceaseless technical assistance. Their guidance has proven essential to the success of the operations. Lastly, the CEIT G/S and IT Network teams deserve special recognition for their contributions, which have been the basis of the MOC.

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