SpaceOps-2023, ID # 308

AUTOMATION OF THE SENTINEL-5P ROUTINE PASS ACTIVITIES

D. Mesples[1], A Moore[2], V. Muzi[2], Ł. Brach[3]

[1]*European Operations Centre, Robert-Bosch-Strasse 5, 62493 Darmstadt, Germany*
[2]*Telespazio Germany GmbH, Darmstadt, Germany*
[3]LSE Space GmbH, Darmstadt, Germany

As part of Copernicus, ESA has developed, in collaboration with the Kingdom of the Netherlands a single satellite atmospheric chemistry mission: Sentinel-5P. Its mission objective is to provide high quality and timely information on the global atmospheric composition for climate and air quality applications. Since it was launched on the 13th October 2017 it has been successfully operated from the European Space Operations Centre (ESOC) located in Darmstadt, Germany. The operations are conducted via two visibility periods a day, 7 days a week, over a set of ground stations located in Svalbard, Norway; Kiruna, Sweden; and Inuvik, Canada. Telecommanding and telemetry reception takes place via S-band whilst science is transmitted via an X-Band link. The routine operations defined for each visibility periods consist of a set of highly repetitive tasks. It was decided in 2019 to pursue their automation in order to demonstrate the capability of the Flight Operations Segment (FOS) to evolve the operations concept towards an increase of automated, more 'hands-off' routine operations. The automation is two-fold, aimed at reducing the routine activities performed by the human operator (SPACON) in order to allow him/her to perform other tasks, while at the same time enable the capability to take routine TM/TC passes without man in the loop, i.e. outside the extended working hours of Copernicus/Sentinels. The SPACON continues to perform the daily and weekly activities under his/her responsibility and will also monitor the automation system during working hours, gaining experience for future unmanning of some passes. The SPACON will report any anomalous behaviour identified to the on-call Spacecraft Operations Engineer, SOE. This paper will describe the process, lessons learnt, advantages and disadvantages associated with moving from a human based satellite operations concept to one doing without a man/woman in the loop. It will provide details of the Sentinel-5P mission and its operations and the process of selecting the operations procedures suitable for automation including examples showing that a simple human procedure can become a complex software automated one. It will provide insights into the complexity of configuring the various elements involved in the automation chain and the process of validating them both on ground and with the actual spacecraft.

Keywords: automation, operations, Copernicus, Sentinel-5P, evolution

Acronyms/Abbreviations

DSL	Domain Specific Language
ESOC	European Space Operations Centre
FOS	Flight Operations Segment
HKTM	Housekeeping Telemetry
MATIS	EGOS Mission AutomaTIon System
S5p	Sentinel-5 Precursor mission
SOE	Spacecraft Operations Engineer
SPACON	Spacecraft Controller
TROPOMI	Tropospheric Monitoring Instrument
TT&C	Telemetry and Telecommand

1. Introduction

Since it was launched on the 13th October 2017, Sentinel-5P (S5p) has been successfully operated from the European Space Operations Centre (ESOC) located in Darmstadt, Germany. The operations are conducted via two visibility periods a day, 7 days a week, over a set of ground stations located in Svalbard, Norway; Kiruna, Sweden; and Inuvik, Canada. Telecommanding and telemetry reception takes place via S-band whilst science is transmitted via an X-Band link. The routine operations defined for each visibility periods consist of a set of highly repetitive tasks.

It was decided in 2019 to pursue their automation in order to demonstrate the capability of the Flight Operations Segment (FOS) to evolve the operations concept towards an increase of automated, more 'hands-off' routine operations. The automation is two-fold, aimed at reducing the routine activities performed by the human operator (SPACON) in order to allow him/her to perform other tasks, while at the same time enable the capability to take routine TM/TC passes without man in the loop, i.e. outside the extended working hours of Copernicus/Sentinels.

This paper will describe the Sentinel-5P mission operations and the process, lessons learnt, advantages and disadvantages associated with moving from a human based satellite operations concept to one doing without a man/woman in the loop. It will provide details of the Sentinel-5P mission and its operations and the process of selecting the operations procedures suitable for automation including examples showing that a simple human procedure can become a complex software automated one.

It will provide insights into the complexity of configuring the various elements involved in the automation chain and the process of validating them both on ground and with the actual spacecraft.

2. Copernicus and Sentinel-5P

As part of Copernicus, the joint initiative of the European Commission (EC) and the European Space Agency (ESA) to establish a European capacity for the provision and use of monitoring information for environmental and security applications, ESA has developed, in collaboration with the Kingdom of the Netherlands a single satellite atmospheric chemistry mission: Sentinel-5P. Its mission objective is to provide high quality and timely information on the global atmospheric composition for climate and air quality applications.

Sentinel-5P satellite carries a single payload instrument: TROPOMI (TROPOspheric Monitoring Instrument). The TROPOMI instrument was co-funded by ESA and the Netherlands. The main objective of the Sentinel-5P mission is to perform atmospheric measurements with high spatio-temporal resolution, to be used for air quality, ozone & UV radiation, and climate monitoring & forecasting.

The satellite's local time of ascending node crossing of 13.30 h has been chosen to facilitate the so-called loose formation operation with NOAA's Suomi-NPP spacecraft. This concept will allow the utilization of co-located, high resolution cloud mask data provided by the VIIRS (Visible Infrared Imaging Radiometer Suite) instrument on-board Suomi-NPP during routine processing of the TROPOMI methane product. This is illustrated in Figure 1.

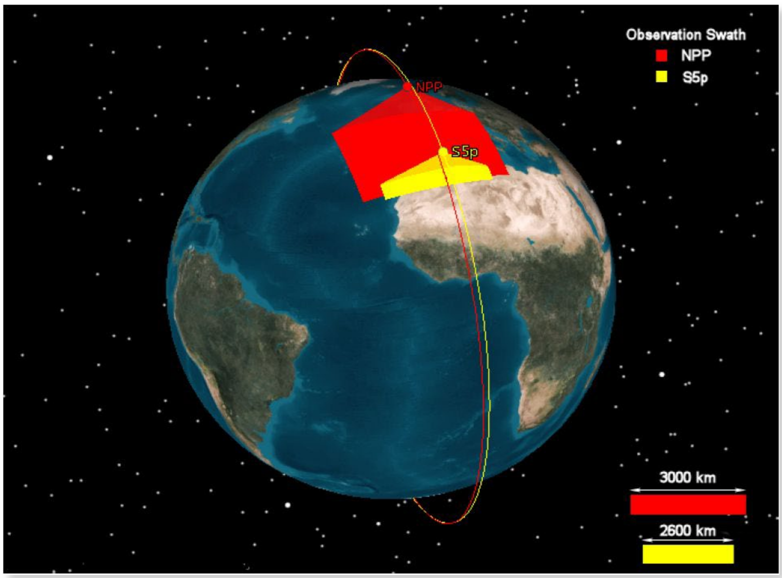


Figure 1 S/NPP and S5P Loose formation flight

3. Sentinel-5P Routine Operations

The sentinel-5P mission operations concept consist of a highly repetitive set of activities consisting of daily and weekly operations. The concept is driven by the mission requirements, in particular:

- Routine commanding tasks shall be limited to use of a single S-band ground station (eg. Kiruna TT&C station), and using a single pass per day.
- The satellite monitoring shall be based on processing of housekeeping and ancillary data downlinked via the S-band channel. The monitoring concept shall comprise all sub-systems, including the TROPOMI payload instrument.
- The operation of the TROPOMI instrument shall be in accordance with a set of pre-defined planning rules and constraints based on an instrument specific planning repeat cycle of 360 orbits.

The TROPOMI instrument performs measurements according to a pre-defined scheme which repeats every 360 orbits (24 'days' consisting of 15 orbits) as illustrated in Figure 2.

Day within Cycle

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	D1	W1	O1	O1	D2	W2	O1	O1	D3	W3	O1	O1	D4	M1	O1
2	D1	W4	O1	O1	D2	W5	O1	O1	D3	W6	O1	O1	D4	O1	O1
3	D1	W7	O1	O1	D2	W8	O1	O1	D3	W9	O1	O1	D4	O1	O1
4	D1	W10	O1	O1	D2	W11	O1	O1	D3	W12	O1	O1	D4	O1	O1
5	D1	W13	O1	O1	D2	W14	O1	O1	D3	W15	O1	O1	D4	M2	O1
6	D1	W16	O1	O1	D2	O1	F1	F2	D3	O1	O1	O1	D4	O1	O1
7	D1	W1	O1	O1	D2	W2	O1	O1	D3	W3	O1	O1	D4	O1	O1
8	D1	W4	O1	O1	D2	W5	O1	O1	D3	W6	O1	O1	D4	O1	O1
9	D1	W7	O1	O1	D2	W8	O1	O1	D3	W9	O1	O1	D4	M3	O1
10	D1	W10	O1	O1	D2	W11	O1	O1	D3	W12	O1	O1	D4	O1	O1
11	D1	W13	O1	O1	D2	W14	O1	O1	D3	W15	O1	O1	D4	O1	O1
12	D1	W16	O1	O1	D2	O1	F3	F4	D3	O1	O1	O1	D4	O1	O1
13	D1	W1	O1	O1	D2	W2	O1	O1	D3	W3	O1	O1	D4	M4	O1
14	D1	W4	O1	O1	D2	W5	O1	O1	D3	W6	O1	O1	D4	O1	O1
15	D1	W7	O1	O1	D2	W8	O1	O1	D3	W9	O1	O1	D4	O1	O1
16	D1	W10	O1	O1	D2	W11	O1	O1	D3	W12	O1	O1	D4	O1	O1
17	D1	W13	O1	O1	D2	W14	O1	O1	D3	W15	O1	O1	D4	M5	O1
18	D1	W16	O1	O1	D2	O1	F1	F2	D3	O1	O1	O1	D4	O1	O1
19	D1	W1	O1	O1	D2	W2	O1	O1	D3	W3	O1	O1	D4	O1	O1
20	D1	W4	O1	O1	D2	W5	O1	O1	D3	W6	O1	O1	D4	O1	O1
21	D1	W7	O1	O1	D2	W8	O1	O1	D3	W9	O1	O1	D4	M6	O1
22	D1	W10	O1	O1	D2	W11	O1	O1	D3	W12	O1	O1	D4	O1	O1
23	D1	W13	O1	O1	D2	W14	O1	O1	D3	W15	O1	O1	D4	O1	O1
24	D1	W16	O1	O1	D2	O1	F3	F4	D3	O1	O1	O1	D4	O1	O1

orbit ID	interval	periodicity	name
O	1	360	orbit
D	15	24	daily
W	90	4	weekly
F	180	2	fortnight
M	360	1	monthly

Figure 2 TROPOMI Instrument measurement planning cycle.

3.1. Ground stations allocation considerations

Flight operations tasks are implemented in the Flight Operations Segment (FOS) of the Sentinels Ground Segment. It is based on a Core system, common to all Sentinels, and on specific extensions of the Core system to accommodate S5p mission-specific requirements, allowing for cost effective operations.

The resulting operational concept, adapted to align partially to the that of Sentinel-1 and 2, consists of taking two passes a day, seven days a week, to perform tele-commanding (TC) and check telemetry (TM). The amount of science data generated every orbit and the visibility duration available over Svalbard and Inuvik, see Figure 4, result in having to downlink via X-band once every orbit over one of these ground stations. Due to fact that the platform TM is not stored in the PDHU Mass Memory, a downlink of the OBC Mass Memory via S-band is scheduled in parallel to each X-band downlink, once every orbit over either Svalbard or Inuvik as illustrated in Figure 5.

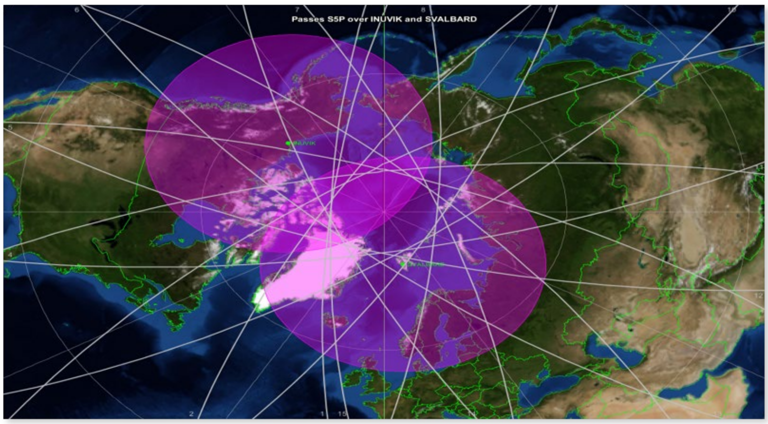


Figure 3 Overview of Sentinel-5P ground station passes over Svalbard and Inuvik

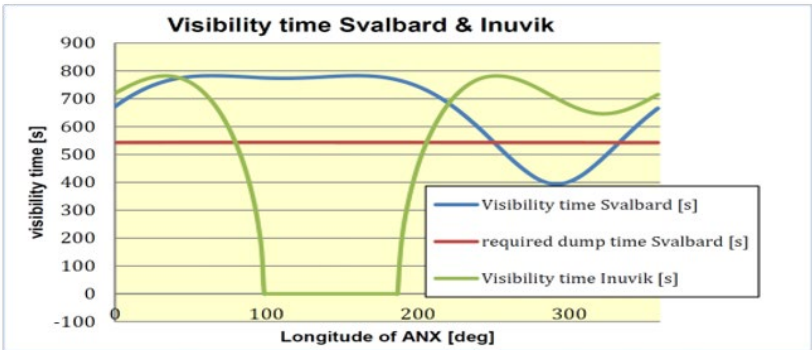


Figure 4 Sentinel-5P visibility duration over Svalbard and Inuvik ground stations

Mission planning is performed on a weekly basis, on Thursdays. It brings together the inputs from the X-band stations allocation provided by PDGS, the TROPOMI instrument scheduling and, the FOS TT&C station allocation.

	Day Within Planning Cycle															
X-Band Pass #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL
2	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL
3	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL
4	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL
5	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL
6	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL	SVAL
7	ISSF	ISSF	SVAL	SVAL	SVAL	ISSF	ISSF	SVAL	SVAL	SVAL	ISSF	ISSF	ISSF	SVAL	SVAL	SVAL
8	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF
9	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF
10	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF
11	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF
12	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF
13	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF	ISSF
14	SVAL	ISSF	ISSF	ISSF	ISSF	SVAL	ISSF	ISSF	ISSF	ISSF	SVAL	SVAL	ISSF	ISSF	ISSF	ISSF
15					SVAL					SVAL						SVAL

Figure 5 X-Band downlink allocations over the 16 day repeat cycle.

An overview of the main operational relevant events is shown in Figure 6. As can be observed, S-band downlink is not performed over the PDGS station during orbits where the FOS performs TT&C activities.

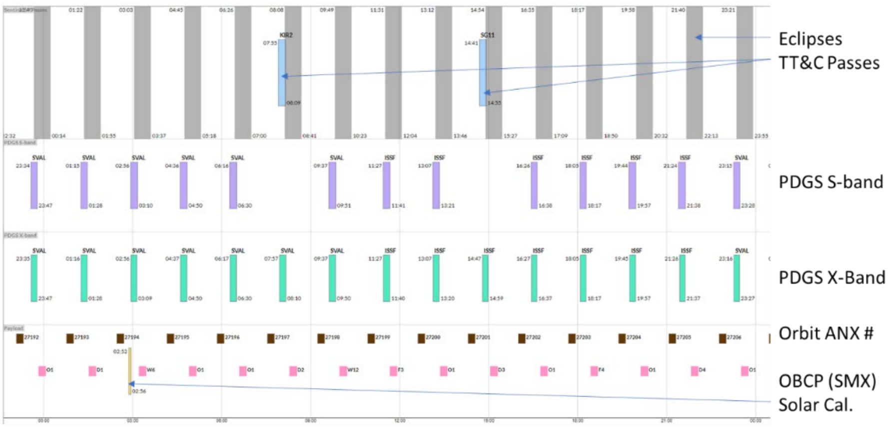


Figure 6 Sentinel-5P 24 hour operations overview

3.2. Daily Operations activities

Flight operations consist of:

- Nominal operations i.e. routine or special operations that are executed in order to exploit the mission objectives and maintain the satellite in a healthy state.
- Diagnosis and recovery of on-board failures
- Check of timely arrival of various files needed to support operations

Monitoring and control activities are performed using a combination of immediate and time-tagged commanding. The routine mission activities are generated by the MPS and programmed in the on-board Mission Timeline (MTL), i.e. activities are scheduled by ground via time-tagged telecommands stored on-board in the MTL queue.

Routine activities are defined in procedures to be performed by a SPACON and consist of monitoring the status of both the MCS and the satellite, and sending of telecommands to it.

A routine pass consists of the following activities:

Activity	FOP Reference	TC[1]	Comments
Connect TM and TC links to ground station	MSP_SPA_002 *MSP_SPA_101*	N	Only Pass tasks will be automated. Daily and weekly tasks will continue be performed by SPACON.
Check Acquisition Of Signal (AOS)	MSP_SPA_102 *CRP_SYS_001* *CRP_SYS_800*	N	
Check Spacecraft Status	NOM_SYS_100 *MSP_SPA_102*	N	Check will be executed within a loop throughout the station visibility period.
Request System Log downlink	NOM_SYS_100 *MSP_SPA_103* *CRP_TMR_235*	Y	Packet Store 5
Request Packet Store TM downlink	NOM_SYS_100	Y	Packet Stores 1, 2 and 3
Routine PS1 content deletion	NOM_SYS_110	Y	Daily Packet Store deletion.
Disconnect TM and TC links	MSP_SPA_002	N	

Table 1 Routine Pass Activities Operator Tasks

Note that CRPs and MSP_SPA_1xx procedure deal with contingency cases and are listed above for reference to allow definition of criteria to identify HKTM and other checks required for pass activities monitoring.

An important part of the SPACON routine activities involves identification of spacecraft anomalies via TM and execution of dedicated procedures involving anomaly specific telecommanding. Automation of the recovery activities to simple, re-occuring anomalies will also be implemented, but only once significant operational experience has been gained with the automation of routine "anomaly free" operations.

3.3. Routine Pass Operations Automation Concept

Automation is two-fold aimed at reducing the routine activities performed by the SPACON in order to allow him/her to perform other tasks, while at the same time enabling the capability to take routine TM/TC passes without human interaction, i.e. outside the extended working hours of Copernicus/Sentinels. The SPACON will continue to perform the daily and weekly activities under his responsibility and will also monitor the automation system for the automation during working hours, gaining experience for future unmanning some passes. Some of the SPACONs off-line daily/weekly tasks, eg checks related to the arrival of files will also be automated. The SPACON will report any anomalous behaviour identified to the on-call SOE.

No existing external operational data interfaces will be affected by the introduction of the automation system.

3.4. Impact on Spacecraft Operations

[1] Procedure contains spacecraft telecommands

The automation of the routine pass activities does not modify the nature of the monitoring and control operations performed by the ground in terms of spacecraft telecommanding and consequently no impact on spacecraft operations is expected. Nevertheless, certain improvements or re-organisation of activities in view on enabling the automation of processes may need to be undertaken.

4. Sentinel-5P Mission Control System

The Sentinel-5P Mission Control System (MCS) is based on ESOC infrastructure. It is a delta development on top of the Earth Observation MCS Kernel. Its main subsystems are:

- TM Monitoring System, Spacecraft Commanding System, PUS Services
- Mission Planning System (MPS)
- On Board Software Maintenance System (OBSM)
- File Transfer System (GFTS)
- Data Archive System
- Data Disposition System
- Network Interface System (NIS)
- Mission Automation System (MATIS)
- Offline Mission DB Editor

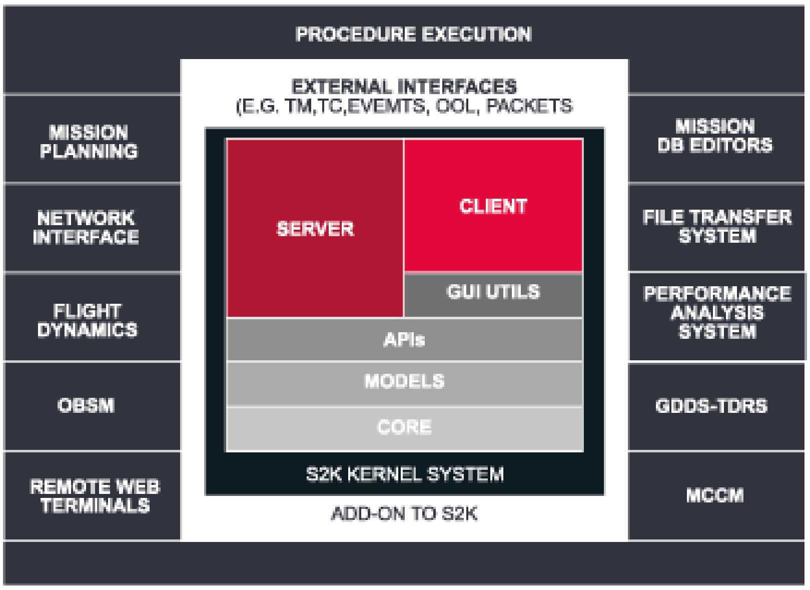


Figure 7 Overview of a mission control system based on SCOS-2000

4.1. MATIS

The EGOS Mission AutomaTIon System (MATIS) is an element in ESA's evolution towards ground and space segment operations automation. The MATIS system supports operations automation for elements of a mission ground segment within the ESOC mission operations activities.

The core functionalities of the MATIS application are:

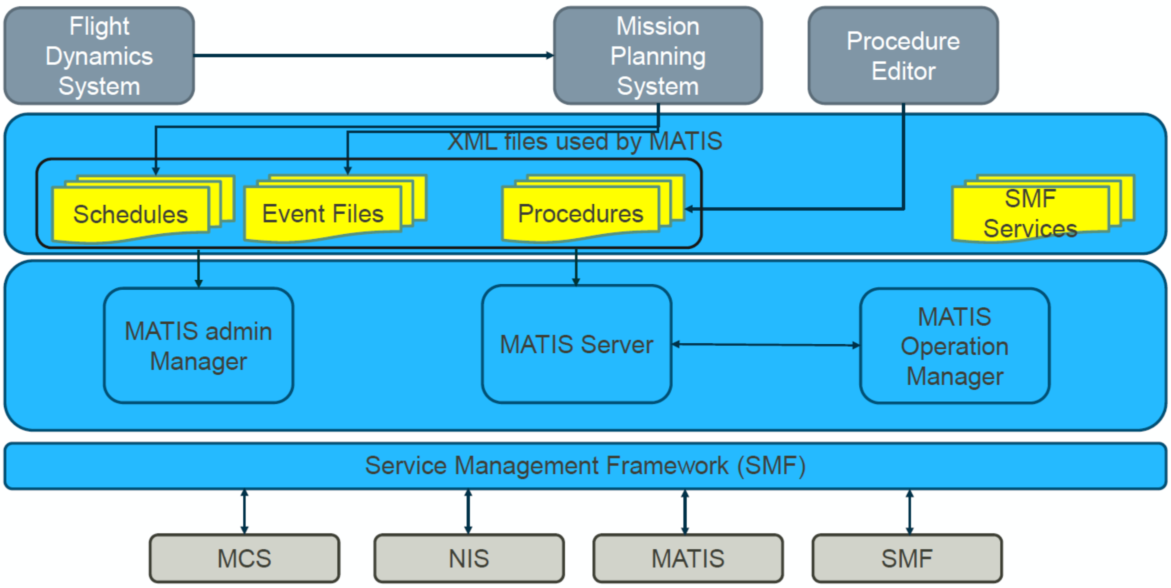
- Mission operational activities automation: The core of the automation functionality is typically driven by the need to help operations in reducing risks by eliminating human errors

17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

and/or controlling routine interactions with the mission. Most missions today have enough self-saving capabilities that spacecraft health and safety do not have to be responded to in real-time. For such missions there is no need for automation to provide real-time spacecraft responses.

  - Most of these missions can automate passes using scripting and notifications to control the up-linking to spacecraft of activities and schedule activities dedicated to monitoring capabilities built into their mission control system.
  - The primary response that is desired is to assure successful completion of passes, with automatic final reporting highlighting the completion of the desired pass production.

- Disturbance and anomaly handling control: Disturbance can be considered a less critical condition than anomaly. Disturbance is the condition where minor anomalies can occur and can be tolerated with properly designed automatic corrective actions. Anomalies are more critical conditions which could require first automatic intervention from the system and then proper human intervention.
- Automation of housekeeping processes: In many missions there is the need to perform reporting, data maintenance and in general housekeeping procedures. A term used within MATIS is "standing orders management" or the capability of the user to submit routine procedures to be executed repeatedly according to predefined period execution criteria. The medium and, of course, long term goal of MATIS is then to provide a flexible tool where the mission operations team can express the different automation needs and processes through the different mission phases.



The MATIS system includes the following components

- MATIS Designer
- MATIS Operation Manager
- MATIS Server
- MATIS Central Repository

Those components are foreseen to be deployed into the following working environments.

- Preparation Environment

- Test and Validation Environment
- Operational Environment

Overall, the Designer is used to edit and maintain the Automation Model (which contains the procedures and schedules) within the Preparation Environment. The Operational Manager is used to monitor and control the schedules running on the MATIS server, which is itself a background process. The Automation Model, prepared by the Designer and consumed by the Server, is version controlled by the Central Repository within the Preparation, Test and Validation Environments.

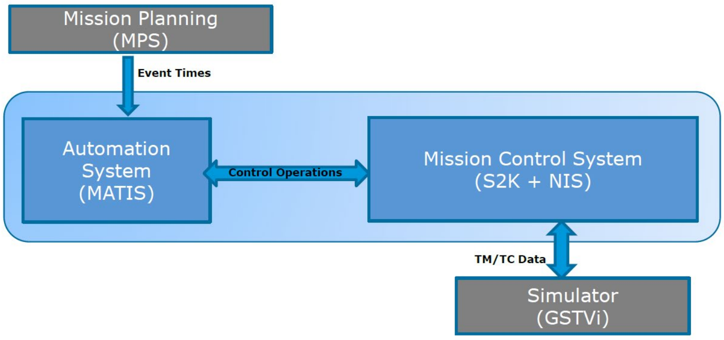


Figure 8 MATIS and Test and Validation Environment

MATIS interfaces overall with the following systems.

- Service Management Framework (SMF)
- Mission Planning System (MPS)

During the execution of the automation, MATIS interacts with SMF to control and monitor the system under control. The Mission Planning system provides schedules and events to MATIS via file exchanges, either before or during the automated operation.

SMF is a service provision middleware infrastructure designed to be generic. It can be tailored to expose the services of different software systems. It has a scalable and flexible architecture and run time environment. It ensures 'transparent' access to a service i.e. independence of underlying implementation.

Even if the Mission Control System is seen by MATIS as a system under control like the others. The SCOS-2000 infrastructure has a double role for the MATIS system.

- It is a service provider, as its services are accessed through SMF by MATIS;
- It acts as a deployment environment as MATIS can be deployed integrated within SCOS-2000. In this way, SCOS can provide basic services like, logging, task management, roles & privileges.

The MATIS execution system is modelled as a four layer system, which includes:

- A calendar management layer in charge to schedule Planned, User and Event schedules for execution;
- A schedule execution layer in charge of running Planned and User schedules, and scheduling the execution of procedures referenced by those schedules;
- A procedure execution layer in charge to execute procedures;

- An activity and external events execution layer in charge of invoking external entity services referenced by a procedure and forwarding events raised by the external system to procedures and schedules.

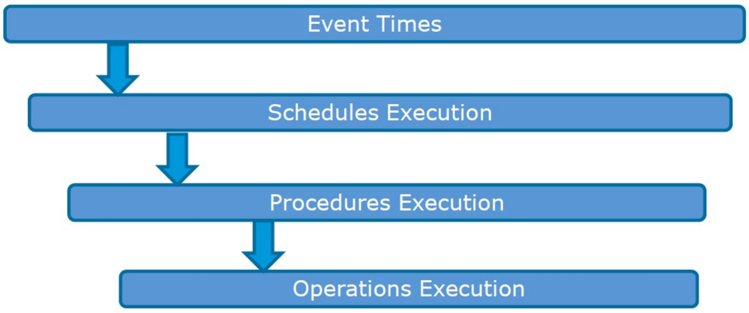


Figure 9 MATIS Execution System Layers

Figure 8 illustrates a typical routine pass activities. The Processing and Commanding activities performed are listed in Table 1.

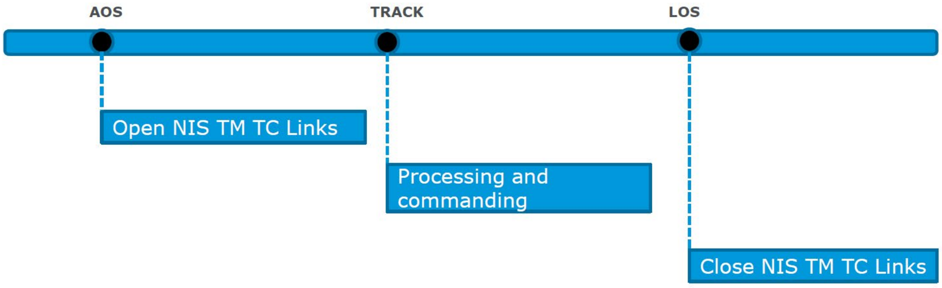


Figure 10 Routine pass activities schematic

4.2. Automation Model

The MATIS system is all about creating, managing and executing one or multiple Automation Models. An Automation Model defines all elements which specify how the MATIS system shall automate the systems under control for a specific purpose.

The Automation Model is fully user defined and is meant, as a conceptual model, to help understand, and interacts with the subjects the model represents; in this case, the user specification of how MATIS will act and react.

An Automation Model is composed of the following abstract elements.

- System Elements
- Activities
- Reporting Data
- Events

An activity is a monitoring and control function. The term activity is introduced to refer generically to procedures, telecommands and ground services provided by the underlying system under control (e.g. a printer request, sending an e-mail, transferring a file using ftp). Activities are defined inside Activity Procedures by the user using a simple computer language.

*4.2.1.*The MATIS Procedure Language

The MATIS procedure language is a Domain Specific Language (DSL) designed specifically for defining EGOS Mission AutomaTIon System (MATIS) Automation Procedures. The procedures are intended to be written in the MATIS Designer application and executed in the MATIS Operations Manager application. The MATIS procedure language is compliant to the ECSS-E-ST-70-32C (E32) standard (Test and operations procedure language) and its syntax is derived from the Standard Annexes (aka. PLUTO syntax). The ECSS-E-ST-70-32C Annexes define a Domain Specific Language (DSL), which domain is specified by ECSS-E-ST-70-31C (E31) - Ground systems and operations - Monitoring and control data definition.

5. Automation Process

The goal in automating an operational system in this case was to reduce the amount of time needed for human operator to monitor the spacecraft health, in view of allowing the operator to spend more time on other tasks, either monitoring one or more spacecraft or performing more intellectually challenging activities, i.e. less repetitive and more complex and thus less prone to being automated.

A stepwise approach was followed addressing the automation of the following activities in terms of priority:

1. Ground Station connection and link status checks
2. Spacecraft TM checks and operator notification
3. Connection Test TC uplink and verification
4. System Log (Packet Store 5) downlink request and verification
5. Recorded TM (Packet Store 1, 2 and 3) downlink request and verification
6. Packet Store 1 deletion request and verification

The general concept is that each step involving commanding is executed ONLY if the previous step is successful. Any failure TC uplink for verification will cause the automation to stop any further commanding activities, and the SPACON or SOE would resume control.

5.1. Automation Phases and Experience

The process consisted of 3 major phases:

- MATIS SMF tailoring
- Procedure Development and testing
- Operational Validation

At each phase a number of iterations were necessary, and involved a learning curve, in particular in the area of the user familiarisation with the various MATIS elements.

Although the S5p MCS is based on a core ESOC software infrastructure, specific modifications implemented to the Earth Observation mission needs meant that some the SMFs did not function as expected and needed to be modified. Using the MATIS Procedure Language syntax to encode the manual operations into automated one took significant time as the logic for the implementation of certain checks and logic proved not to be simple for persons who although having been exposed to software were not trained computer programmers. In some cases usage of calls to external scripts used to perform complex operations on Telemetry proved to be simpler than using the MATIS Procedure Language.

In the area of TM monitoring, it quickly became obvious that a computer function can much more reliably and efficiently check the spacecraft health, in parallel to sending Telecommands to the spacecraft, by implementation of logic checking key TM before and after each Telecommand. At the same time, the user had to resist the temptation of including additional non-essential checks, just because it was possible.

A non-trivial aspect of the procedure writing was the reflection on what to include in terms of logging to trace potential errors and unexpected behaviour. For this a scheme was introduced to enable two levels of logging, one for debugging and the other for routine operations. Logging needs to be performed both for successful execution as well as for reporting of errors.

When automating some offline checks, the SPACON/SOE needs to be aware that the lack of an alert message could be interpreted as either all checks were nominal OR that the automation system has failed. Some sort of heartbeat reporting can provide a means to check that the automation system is functioning correctly. Alternatively, the operator needs, via dedicated procedures to actively check that this is the case.

The testing was performed in two stages. The Mission Control System of each Satellite consists of operational servers connected to a suitably segregated operational network and other servers used for development connected to another network. The verification tests of any new procedure or software function are first performed on the development environment with the satellite simulator. Contingencies involving major spacecraft failures were injected, in order to verify that the automated procedures were correctly interrupted and that the MATIS system did not interfere with the ensuing return to operator driven operations. Once this is completed, the new procedures and software functions are deployed onto the operational servers. Although a lot of effort is put into making the development environment as representative as the operational one, for practical reasons some differences remain, which occasionally lead to new issues being identified once testing is performed in real time operations.

Automation, driven by a need to re-allocate human resources, will necessarily result in shift in responsibilities. The impact of this needs to be carefully assessed to ensure that nothing is missed. As this will result in some tasks no longer being performed by the operator, regular refresher training should be foreseen in order to ensure that the operators remain proficient and able to support contingency activities when the automation system is suspended.

The shift to a new operational concept of course requires the production of new procedures and training material. All in all this results in overall increase in the teams workload for a significant time period and should be factored in when considering the long term intended reduction in human resources.

5.2. Software evolutions and pandemic issues

Over the course of the automation process, fixes to identified MCS software issues led to problems with the MATIS and SMF components which proved to be difficult to reproduce and resolve, last but not least as a result of the difficult restrictions put in place during the COVID-19 pandemic. The focus shifted to implementing solutions to ensure continuation of operational activities whilst minimising on-site presence. This resulted in a long pause in the operational validation of the Sentinel-5P routine pass activities automation which was then exacerbated by the loss of key personnel. As a result, at the time of writing of this paper, the routine pass operations continue to be carried out by a human operator, but validation testing is continuing and it is planned to perform man-free routine pass operations some time over the course of 2023.

6. Conclusions

Automating spacecraft operations of a flying mission is a time consuming and complex process and the resources required should not be underestimated. In particular careful assessment of what should be automated plays a key role in the overall process. In the short to medium term, the process results in additional load on resources, with benefits being achieved only in the longer term.

Although standardisation has allowed to increase the commonality in the software used to monitor and control satellites, a number of disparities remain and each of these result in additional software development and associated verification and validation, resulting in additional resources. The drive to more standardisation, especially in the space to ground interfaces must continue.

When designing future missions, machine executable procedures for all routine and repetitive activities and software functions supporting their scheduling and execution should be considered, not as nice to have add-on, but as a baseline.