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Flying a satellite by a robot — First Experiences of the Automation of Station Keeping Maneuvers of a Geostationary Satellite

Jan-Christoph Scharringhausen[a*], Kristina Lautenschütz[a], Mark Pfeiff[a], Viktor Schwarz[a]

[a] *German Aerospace Center (DLR), Space Operations and Astronaut Training, Münchener Str. 20, 82234 Weßling, Germany*

[*] Corresponding Author, jan-christoph.scharringhausen@dlr.de

Abstract

In 2019, the second geostationary node of the European Data Relay System (EDRS), also known as SpaceDataHighway, was successfully deployed into orbit. Considering that the control box of this EDRS-C satellite is confined to a sector of 0.05 degrees, rather than the standard 0.1 degrees, the frequency of required station-keeping maneuvers exceeds that of typical geostationary missions. To address these intensified operational activities, the EDRS control center harnesses the advanced capabilities of the ground system to automate operations. This functionality has been integrated into the ground system from the beginning of its design, because the substantial amount of commands necessary to establish up to 400 optical inter-satellite links daily surpasses the capacities of traditional manual operation systems. Consequently, an automated system had already been implemented that requires human intervention solely in instances of anomalies in either ground processing or the space segments. Building upon this automated system for payload operations and the pre-existing manual station-keeping procedures, an innovative methodology has been devised to execute maneuvers autonomously. This approach remains anchored in human-readable Flight Operations Procedures (FOPs), which is essential for maintaining situational awareness should any issues arise during execution. In the absence of issues, the concept foresees only periodic monitoring at specific points in the timeline by the operator. Following its implementation, the automated process underwent a six-month period of rigorous monitoring to attain validation. This extensive validation phase was required to identify very minor timing issues that are negligible when a human operator executes a procedure but pose a significant risk of stumbling for an automated system. Using the knowledge gained from the validation period, the automated FOPs were refined to address these minor issues, and the flight operations team received training to manage potential problems during automated execution. With only minor issues detected during validation, the approach has transitioned to operational status and is in routine use ever since. This paper delineates the design of the existing automated system within the Satellite Control Center (SCC) used to automate Station Keeping Maneuvers (SKM). In addition, the implementation and validation process is detailed, and the first 12 months of operational use are evaluated with respect to reliability and efficiency. With the station-keeping maneuvers of EDRS-C executed in a classical manual way for the first four years of operations, a comparison between the two methodologies is elaborated. This novel approach represents not only a significant innovative leap in systems for operational automatizing but also in optimizing the limited time of the operator. Therefore, the paper does not only focus on technical aspects but examine the operational advantages and challenges of this methodology for the control center's staff as well.
Keywords: Automatization, Station Keeping Maneuver, EDRS, Operations, Human Factor

Acronyms/Abbreviations

AFD	Automated File Distributor
AMC	Antenna Management Center
AOCS	Attitude and Orbit Control System
DLR	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
EDRS	European Data Relay System
FDS	Flight Dynamic System
FOP	Flight Operations Procedure
GOP	Ground Operations Procedure
LCT	Laser Communication Terminal
MOS	Mission Operations System
MPB	Mission Parameter Database
OMR	Orbit Maneuver Realization

ProToS	Procedure Tool Suite
SCC	Satellite Control Center
SKM	Station Keeping Maneuver
TC	Telecommand
TM	Telemetry
TPGT	Thermal Propellant Gauging Technique
ViPER	Versatile Propellant Estimation Routine

1. Introduction

Geostationary satellites are located in the equatorial plane at a distance of approximately 42,164 km from the center of the earth. In order to space the satellites apart on this ring, each satellite is restricted to a sector of typically 0.1 degrees. The flattening of Earth and the gravity of the moon and the sun cause a precision motion of the orbital plane. Additionally, the asymmetry of the earths gravitational field causes a longitude drift. These two distortions must be countered by station keeping maneuvers . In the frame of a mission analyses a strategy is developed to optimize between the necessary maneuvers to retain the satellites position within its control box and the amount of propellant used.

The European Data Relay System (EDRS) consists of two nodes in geostationary orbit. While the first node (EDRS-A) is a piggy-back payload on Eutelsat's EB9B satellite, the second node (EDRS-C) is a spacecraft dedicated to the project. The system is owned by Airbus Defense and Space. The operations of both the EDRS-A payload and the EDRS-C satellite are subcontracted to the German Space Operations Center of DLR. EDRS delivers the service of relaying data received from satellites in low-earth orbit via an inter-satellite link, either using laser communication or via radio frequency signals, to ground stations. The system is designed to execute up to 200 inter-satellite links per communication channel per day, leading to a combined 600 links per day. This amount of operational activities is beyond the capability of a manual operational concept. Consequently, an automation-based approach has been developed for the control center [1]. Although the intention of this design has been to automate payload operations, the system is capable of automating any routine operational activity. This functionality has been used for limited tasks, such as upload of on-orbit propagator polynomials and synchronization of the on-board clock.

For EDRS-C the control box on the geostationary orbit is limited to 0.05 degrees due to a co-location with another satellite. To secure the position of the satellite in the control box, a 14 days SKM cycle with one maneuver in north/south direction to maintain the inclination and two maneuvers in east/west direction to control longitude drift rate and eccentricity has been defined. The execution of these maneuvers has been a manual operation at the begin of the mission. But with the automation system in place, a transition to an automated execution of the SKM has been foreseen in the course of the mission. This transition should leverage on the existing procedures and tools as much as possible, not only to limit the effort but also to rely on proven and validated components.

In this paper, first a description of the manual approach using the well proven system of the EDRS-C control center will be given in section 2. Afterwards the implementation of the new approach with its implementation of the FOP, its approach to ensure situational awareness, the changes to the system and the approach to bring all these changes into the system are described in section 3. Section 4 gives an review of the validation phase in live operations and section 5 discusses the effects of the approach in its routinely use on EDRS-C operations.

2. The proven baseline system

2.1. The manual execution of station keeping maneuvers

The defined SKM strategy for EDRS-C is a 14 days cycle long strategy with two east/west and one north/south maneuvers per cycle as shown in figure 1. The cycle starts on a Wednesday with the preparation activities for the two east/west maneuvers.

The preparation of an SKM is performed the day before the SKM execution by an engineer using a tool called Versatile Propellant Estimation Routine (ViPER). Three sources are required as input: the TM archive to retrieve parameters of the satellite, the maneuver cycle plan from the Flight Dynamic System (FDS), and configuration parameters from a Mission Parameter Database (MPB), reflecting the configuration status of the spacecraft and algorithm control parameters. The SKM tool exports maneuver preparation data which is transferred to the FDS.

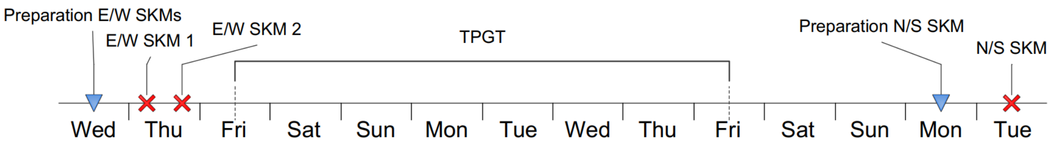

Fig. 1. SKM cycle

This data includes fuel and oxidizer pressure, latest S/C angular momentum (including TM generation timestamp), selected thrusters for orbit and attitude control (nominal/redundant), thrust ramp-up profile, and updated spacecraft mass. The data is archived and transferred to the FDS via an Automated File Distributor (AFD). The maneuver preparation data is used by the Orbit Maneuver Realization component of the FDS. This software calculates the necessary command parameters for the SKM execution and exports these in a command parameters file. This file is transferred back via AFD to the operational environment. Two FOPs are requested. One for the station keeping preparation and one for the execution of the SKM. The FOPs are executed based on the command parameters file from FDS and on the spacecraft configuration retrieved from the MPB. During the 14 days cycle, the Thermal Propellant Gauging Technique (TPGT) will be used to determine the remaining fuel and oxidizer masses on-board the spacecraft (cf. [2]) towards the end of life of the satellite .

The execution of the SKM is done by an AOCS sub-system engineer, together with a spacecraft operator. The FOP for station keeping preparation contains telemetry checks to be verified, check of the on board schedule content and the upload of the time-tagged command sequence as delivered as command parameters file by the FDS in the preparation step. It is being executed manually the day before the actual SKM. The second FOP for the station keeping execution includes the parking of the Laser Communication Terminal (LCT) in the case it is still in an un-parked position to prevent contamination of the optics of the terminal. With the parking of the LCT, the general purpose schedule is disabled in order to prevent undesired activities on the spacecraft. This is just a pre-caution. Nominally the parking is scheduled by the automated system for the LCT's link operations 664 seconds before the start of the maneuver. To prevent automated commanding, the telecommand (TC) release of the automation engine is paused during the SKM execution. The FOP further includes the opening of the latch valves of the selected thruster set. The set has been defined by the AOCS engineer during preparation of the SKM. Afterwards the AOCS mode changes and packet store managements are commanded. Within the FOP all relevant TM checks during the SKM execution are checked by the engineer manually on alphanumeric display pages and procedure pages. At the end, the downlink of the packet store is requested. The LCT will be un-parked by the automated system. With the FOP for the SKM execution being developed for all types of maneuvers (north, south, east or west), the flow through the FOP is rather complex. At numerous steps a branch must be selected and certain steps are not executed as can be seen in the flow diagram of the procedure (cf. figure 2).

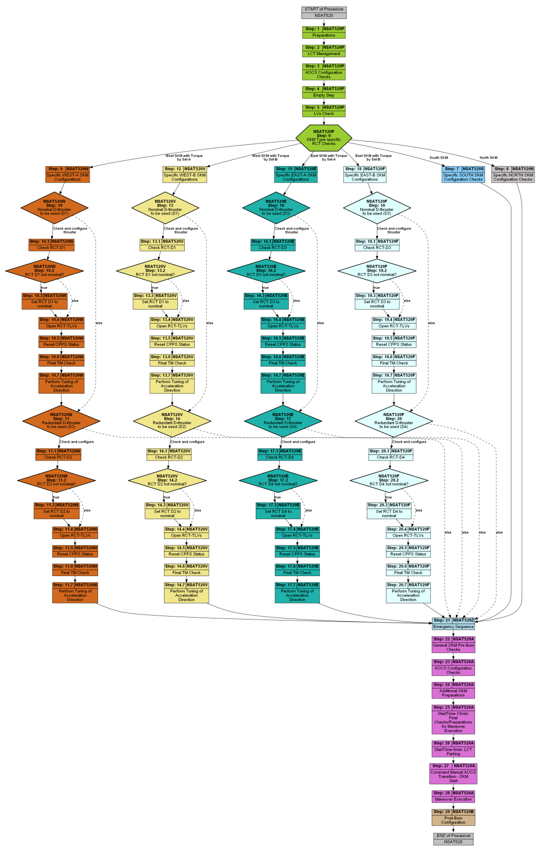

Fig. 2. SKM execution FOP flow diagram

The calculation of the time of the SKM is being made by the FDS to optimize fuel consumption and position security of the spacecraft. This leads to a required execution time not always during daytime. With the engineer needed on console latest two hours before the maneuver start time to start the procedure execution and the post SKM activities taking about one hour, more than three hours of work with a high level of concentration is required possibly in the middle of the night. Together with the high complexity of the FOP, this increases the risk to make a mistake.

2.2. The existing automation system

Two major components of the EDRS-C control center are involved in the automated SKM approach. The automation engine Procedure Tool Suite (ProToS), and the SKM and propellant calculation tool ViPER.

ProToS is the already established tool to automatically execute FOPs. The tool provides a semi automatic FOP execution for which an operator is interacting with the graphical user interface. With this it is possible to execute a loaded FOP either statement by statement, step by step, or the entire FOP automatically. The operator has feedback at all times which statement is currently executed and what the results of every statement are. The tool stops in case of failed TC or TM check waiting for the operator's input on how to proceed. For this semi automatic way no special development of the FOP is necessary because the operator is still completely in charge on what steps are executed and when. On the other hand, the fully automated execution of a FOP requires a different development of the procedure. No operator is involved in the execution. The request to exercise a FOP is given to ProToS in an XML file and the acknowledgments at the end of the execution are returned by file as well. For this kind of execution a certain focus needs to be taken during FOP development. Especially on timings the FOP must be more precise compared with one that is executed by a well trained engineer. An engineer knows how long to wait for a telemetry check to be verified. This might take a couple of seconds due to the time the actual change happens and due to the interval the parameter is checked and downlinked to ground. The automated system does not have such an experience and if no precise timing is given, the telemetry check might fail which causes the execution to be stopped. [3]

The second major tool is ViPER. This tool provides two functionalities: The calculation of the remaining lifetime based on propellant estimation, either by bookkeeping or by the TPGT, and the preparation of an SKM.

3. Implementation of the automated station keeping maneuver

The automated approach does make use of the already established manual approach as much as possible. Figure 5 presents the overall process activities (in yellow) and data (in grey) to be exchanged. While the FDS component OMR and the Automation Engine can remain unchanged, there are certain changes to the SKM tool ViPER as well as to the FOP required.

3.1. Development of the Flight Operations Procedure

The original manual FOP to execute an SKM consists of three parts: A preparation for the SKM, the monitoring of the SKM execution, and post SKM checks and configurations. With the automation in ProToS being based on the same human readable FOPs (cf. [3]), the first part is quite straightforward to be implemented as an automated procedure. The only adaptations needed have been setting up of timings between TCs and following TM checks, and adding notifications for the operator. These notifications are statements within the FOP that will trigger ProToS to send a message to the operator in case the FOP is executing a certain branch. With that, the operator who is usually not monitoring every step of the FOP's execution will be alerted and can take action the second an issue occurs. For some known possible contingencies, the FOP itself has reactions implemented. For example in case the laser communication terminal is not in its park position in order to prevent a contamination of its optic, the FOP will send a TC to reset the component which triggers its parking regardless of its current mode.

The second part of the FOP has been significantly more effort to be implemented. In the manual FOP a list of TM checks is defined to be monitored by the engineer executing the SKM. He/she is monitoring these TM values on alphanumerical pages and plots specifically designed for that purpose. The checks include status of the latch valves, attitude error angles, pressures and temperatures in the propulsion system, and occurrences of sudden drops in temperature. These checks are made by the engineer based on simple displays and plots of the parameters relying on his/her training. For an engineer a sudden drop in a temperature curve is visible. For the automated system it is not such an easy task. The automated FOP therefore implements a loop over all the parameters to be monitored during the SKM burn. This loop consists of seven different major steps each checking a different aspect. In case a single TM check in these steps fails the FOP will automatically switch into an SKM abort step that sends out a TC to stop the burn immediately. For certain checks it was necessary to develop synthetic parameters. These parameters are calculated within the mission control system on ground based on parameters received from the spacecraft. This is used for example to calculate the delta between two samples of the combustion chamber temperature in order to react in case the temperature does not rise at the begin of the maneuver, which would indicate a thruster not firing properly. With the entire loop taking about 20 to be executed, the loop is only entered in case the SKM burn is planned to take longer than the loop execution. Figure 3 shows the FOP view in ProToS at one of these major steps within the loop. As long as all TM checks in step 54.3 are green the *Then* branch is not entered and the step 54.4 with the TCs to abort the SKM and a notifications statement is not executed.

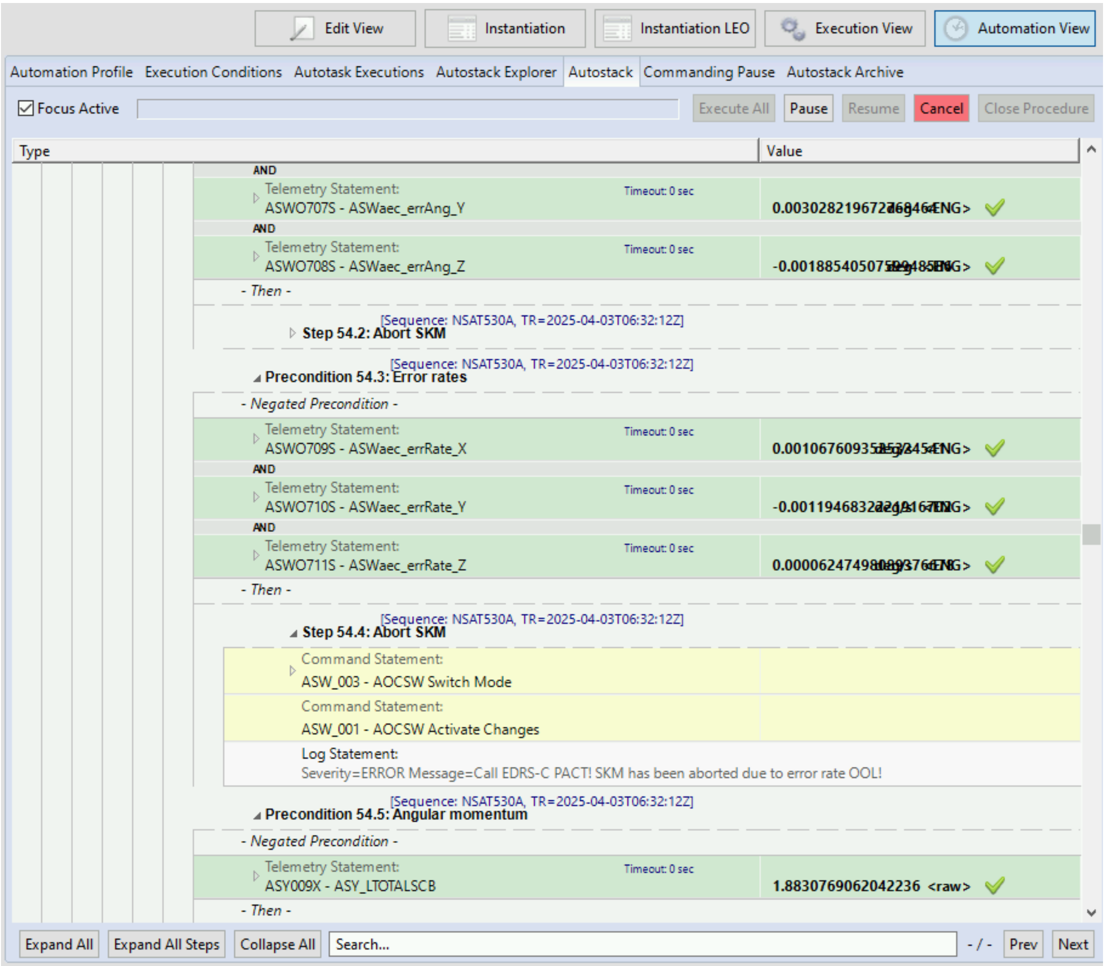

Fig. 3. ProToS at the SKM monitoring loop

Regardless if the SKM burn has been executed successfully or if it has been aborted in one of the previous steps, the last part of the FOP will be executed. This part is the post configuration of the spacecraft after the SKM and starts with a check of the latch valves to be closed. In case not all of the valves being closed, the FOP triggers a notification to the operator and retries automatically to close them. Afterwards all configuration made in the first part of the FOP are reverted back to the nominal on-station configuration. And TM that has been recorded on a high interval during the maneuver is dumped to the ground for analysis of the SKM performance.

3.2. Changes to the Mission Operations System

The changes on the Mission Operations System (MOS) have been quite limited. The tool ViPER has been modified in order to generate FOP request XML files that are distributed to ProToS to be executed. They are based on calculations that had been done by ViPER already beforehand. The request files are being transferred from ViPER to ProToS via the AFD that has already been in place and just needed to have an additional transfer being implemented.

To determine the position of the EDRS-C satellite a dual-side ranging is performed every three hours. The ranging itself is executed by the Antenna Management Center (AMC), which is independent from the SCC. But because of the carrier being changes from one antenna to another during the ranging, no TC shall be send during the ranging. Accordingly, ProToS is pausing its TC release during that fixed time. With the commanding of the SKM being critical, especially during the burn, the ranging is canceled in case it would fall into the execution time of the SKM FOP. Therefore, ViPER has been adapted to send out a message towards the AMC in case the FOP execution time and the time of a ranging overlap to prevent the ranging from being executed. At the same time ViPER sends out another message to ProToS in order to not pause the TC transmission for this now skipped ranging. Accordingly an adaption of the ProToS module for ranging pauses has been done.

3.3. Situational Awareness during the maneuver

One major concern for automating spacecraft operations is situational awareness [4]. While the automated system is executing a FOP in the background, no operator is monitoring it closely. It must be ensured that the operator is alerted in case of any issue, which is usually done by messages from the ground system, or by out-of limit alarms or alarm events from the spacecraft. In case of such an alert the operator must be in a position to gain awareness of the ongoing operations within a time frame as short as possible. To do so, ProToS provides an Automation View which displays the currently executed FOP in detail. In figure 4 the ProToS screen is shown at a point in time where the execution of the SKM FOP is halted to wait until two minutes before the SKM start time. The statement currently executed (in this case a waiting statement until the reference time TR - 2 minutes) is highlighted in red.

The automated system has proven its reliability over years. Nevertheless, with the SKM being a critical operation it shall not be completely unmonitored by the operator. Therefore a Ground Operations Procedure (GOP) has been developed to guide the operator through the monitoring of the automatic SKM. It starts three hours before the burn and instructs to check in ProToS if the automatic SKM FOP execution has started and is waiting at a certain step . It also includes instructions to check the canceling of a dual-side ranging if one would be interfering. The time frame of three hours is considered enough for on-call engineers to do a minor fix or to take over the execution in case an issue prevents the FOP from being executed. At 15 minutes before the burn start the GOP instructs the operator to monitor the execution more closely and on how to react in certain predefined anomalies.

3.4. Assembly, integration and verification approach

In order to implement the automated SKM execution into the operations of EDRS-C several steps have been conducted:

1. Validation of the FOP
   Like every other operational procedure, the FOP had to undergo a validation. For EDRS-C a representative satellite simulator is available on a simulation chain with all automation components. With the FOP having numerous branches for the different maneuver directions and especially for the possible abort criteria, not only one but 19 different validation scenarios have been defined, summing up to 198 validation steps. The FOP was thereby validated with the automation of ProToS to have a representative scenario.

2. Verification of component changes
   The changes of ProToS and ViPER have been verified on component level using representative test cases on unit level.

3. Change process
   After all components including the FOP had been verified and validated on component level, the formal process to bring the change into the system started. An Engineering Change Request on the SCC system has been raised and discussed in a Configuration Change Board with all relevant stakeholders.

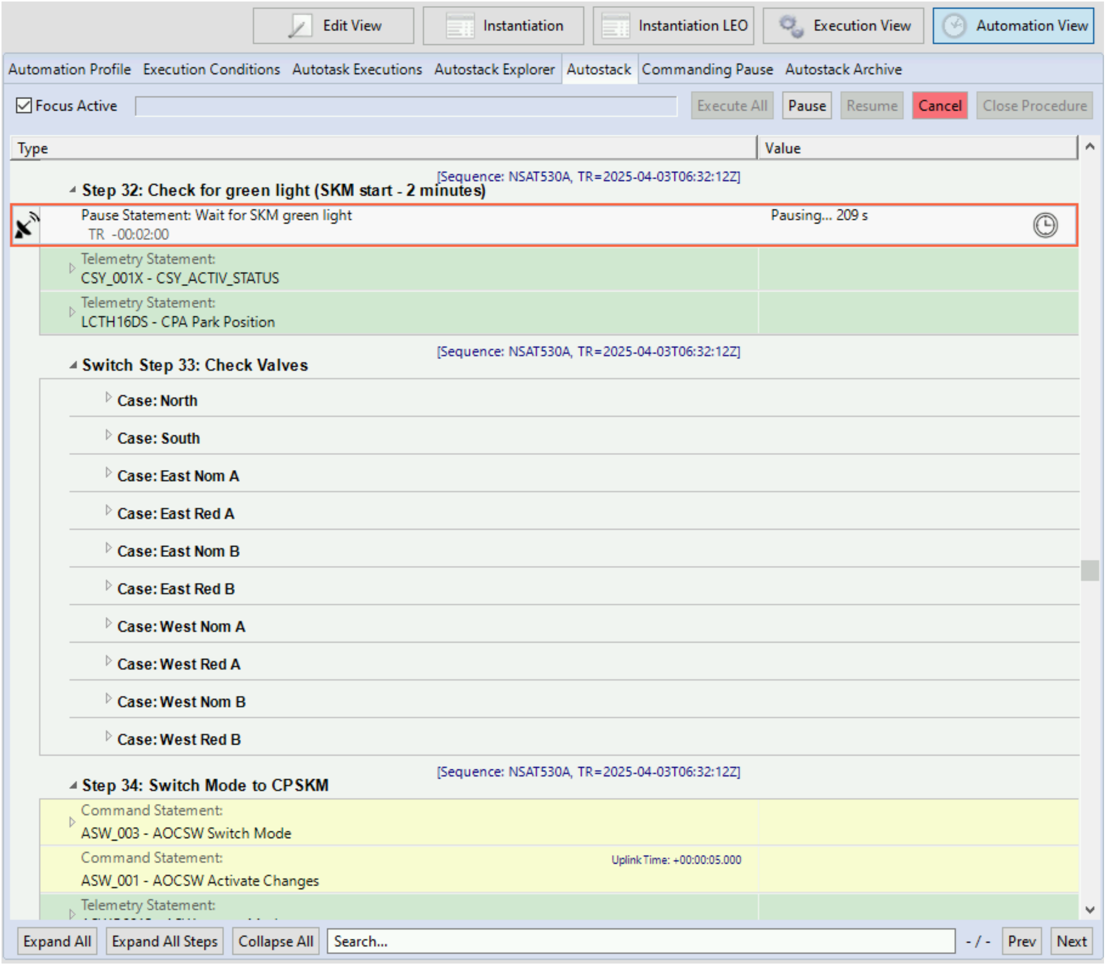

Fig. 4. ProToS automation view at a waiting statement 2 minutes before the SKM burn starts

4. Live validation
   After the changed components have been rolled out on the system, a six month operational validation had been performed. In this phase the automated SKM execution has been used, but under a strict monitoring of an engineer of the Flight Operations Team. This long validation period was defined in order to sort out timing issues that are occurring under very specific circumstances and are not realistically simulated on the spacecraft simulator. They cannot be found in only one validation run because their occurrence is random and rare.

5. Test Review
   After the half year test phase, the decision to end the phase and to bring the automated SKM into routine use was taken in a Test Review Board together with the customer.

4. Operational validation

During the six month validation in live operations a total of 33 automated maneuvers have been executed. It was expected to have observations of timing issues during these tests. On the other hand, it has been essential to not disturb the SKM execution by issues caused by the validation. To handle this the validation engineer had to pause the TC emission by ProToS at an exact point in the procedure at the SKM burn start. With this TC emission pause ProToS remained going through the FOP as long as only TM checks are to be executed. With the only TCs in the burn loop of the FOP being for the SKM abort this measure provided the security of not stopping the SKM by the automation while it kept running the SKM burn check loop. In addition a manual dispatch has been added to the TCs. With this measure the sending of these TCs would have had to be acknowledged.

Two observations have been made during the validation. One has been a TM check timing issue. The check has been timed and executed shortly before the parameter downlinked from the spacecraft has been received on ground. Therefore the check has been flagged as failed and the automation executed the SKM abort step. Thanks to the precaution the commands had not been send out and the SKM has been executed nominally. The second observation has been on one of the temperature drop checks. For this one the limits to trigger the check to fail have been to tight. No range had been defined to prevent the check being triggered due to fluctuations of the temperature. With one sample 0.1 degrees lower than the previous sample, the check had been failed. After some closer analysis it has been decided that this fluctuation still shall be considered nominal, therefore the values in the TM check have been increased so that only a sudden temperature drop would trigger this check. All other timing steps, e.g. maneuver start or latch valve opening checks, worked flawlessly in all 33 maneuvers. The trigger of these two checks had the positive side effect that the notifications to the operator were able to be validated as well.

5. Comparison of manual and automated approach in routine use

Since February 2024 the automated SKM execution is in routine use for EDRS-C. Since that point in time all SKMs have been flown automatically and not a single issue occurred for the SKM itself. But, with the devil being in the detail of very sharp timings, after more than one year in March 2025 a TM check failed due to a timing issue. This check has been the verification of thruster closure after the SKM being executed shortly before all thruster have been reported closed. This issue itself would not have caused an issue because the FOP is setup in a way it would close the thruster in such a case, inform the operator and continue with the FOP. But, with the thruster closing shortly after the TM check and before the FOP triggered closing, the upcoming TM check failed and the FOP stopped at this moment. With this happening after the burn the SKM has still been successful. But this occurrence shows that even after extensive tests very small deviations can still pose challenges to an automated execution which would not be an issue for a well trained engineer.

From a team organization point of view the automated approach pose significant benefits. In the last full year of manual SKM execution a total of 42 SKMs have been at least partly out of normal office hours. Five of them on public holidays. Not only is this an inconvenience for the team members, it also invokes additional costs and unavailability of staff for other activities. Concerning the reliability the approach still must show its benefit compared with the manual execution. Up until writing of this paper the previous described issue has been the only one, while in the first 4 years of operations three SKMs have been not executed due to different human mistakes.

It shall also be noted that a complete relying on the automated system shall not be considered. The members of the AOCS sub-system team are still trained to fly an SKM manually and the proficiency on this is shown regularly.

6. Conclusions

The automation of the SKM flown by EDRS-C has been a significant effort to be implemented. While the system changes can be neglected thanks to the already existing tools, the development of the FOP has not been a minor task. Especially the validation of the FOP in 198 validation steps is a time consuming activity. However, the system has shown its reliability and its benefits for the flight operations team.

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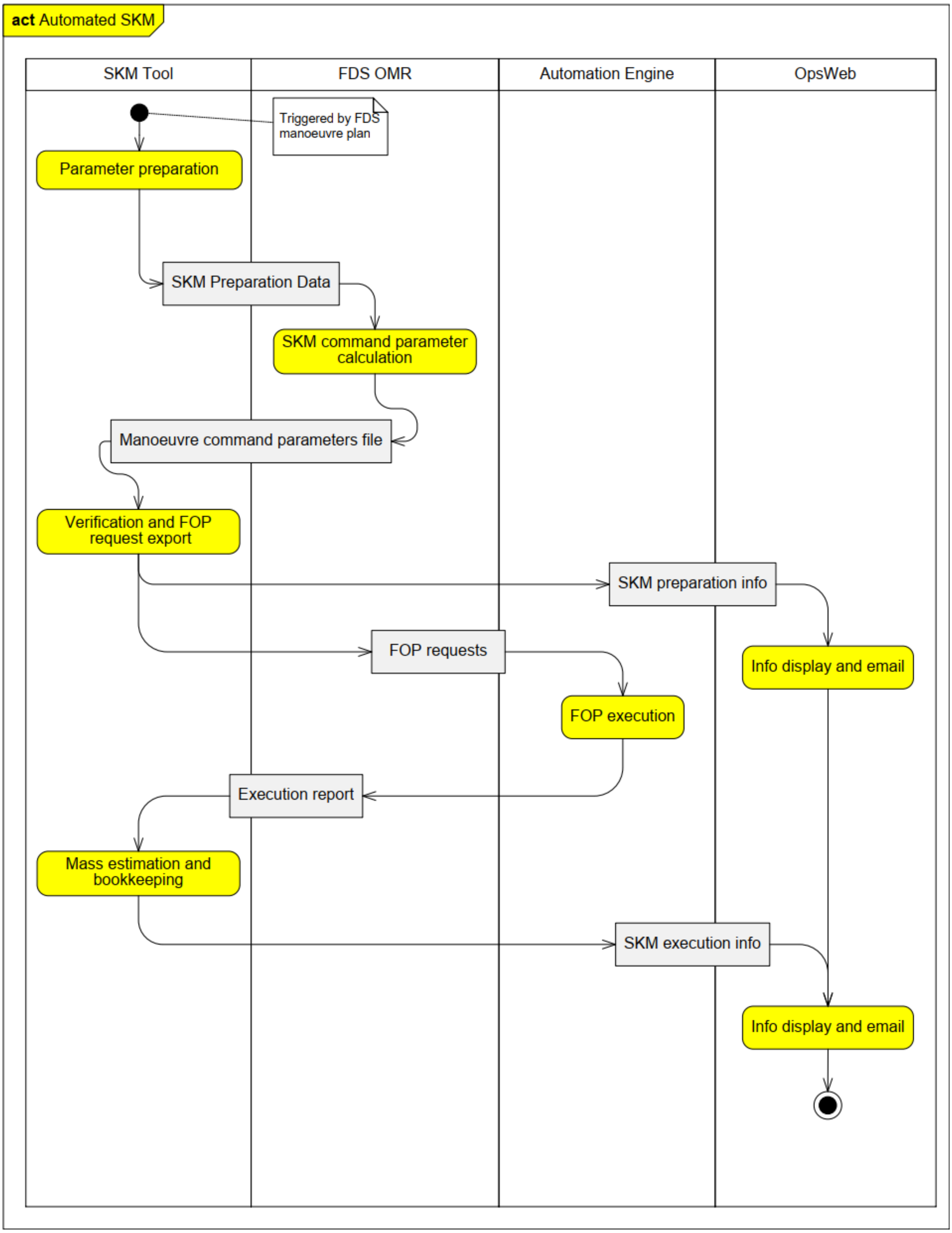

Fig. 5. SKM process diagram