Flying a satellite by a robot - Automated Station Keeping Maneuvers can replace the traditional commanding by human

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Abstract

The European Data Relay System (EDRS), also known as SpaceDataHighway, provides high speed data links between ground stations and satellites in low earth orbit. To cope with commanding of up to daily 400 optical links per two EDRS satellites, an automated system has been implemented as the classical operational concept of manual operations would have been impossible for that high commanding rate. During routine operations, several repetitive tasks need to be executed for EDRS-C, the second node of the EDRS system, on a regular basis. One of them is the station keeping maneuver (SKM), as is for all satellites in the geostationary orbit. This ensures keeping the satellite within the orbital slot. This paper shows how the already existing automated system will be used to realize an automated station keeping maneuver execution and which modifications are needed to achieve this automatization state. At first it will discuss how the SKM execution is initialized into the automated system. As the automated system was primarily designed for payload activities and the SKM operations are still performed by human operators, some small adaptions of the ground system have to be made to harmonize both. Furthermore, the porting of a traditional manual Flight Operations Procedure (FOP) to an automated FOP will be described. Amongst other adaptions, the human's ability of interpret needs to be handled by a logic within the FOP. It is also necessary to define how the system should react in case of an anomaly during automated execution. In addition, a solution to support the human interaction after such an anomaly will be shown.

Keywords: SpaceDataHighway, European Data Relay System (EDRS-C), automated operations, orbital station keeping

Acronyms/Abbreviations

European Data Relay System (EDRS), Station keeping maneuver (SKM), Telecommand (TC), Telemetry (TM), German Space Operations Center (GSOC), Procedure Tool Suite (ProToS), Flight Dynamics System (FDS), Flight Operation Team (FOT), Flight Operation Procedure (FOP), Geostationary Earth Orbit (GEO), Interface (I/F), Spacecraft (S/C), Payload (P/L), Versatile Propellent Estimation Routine (ViPER), Attitude and Orbit Control System (AOCS).

1. Introduction

The European Data Relay System (EDRS), also known as SpaceDataHighway, is primarily designed to greatly increase the amount of data transferred from a spacecraft in the low earth orbit to ground within a certain time period. It reduces the delay in transmission of these data and can provide a near real-time data transmission to earth. The system is composed of two geostationary satellites positioned over the Victoria Lake in Africa with ground stations in Europe. The first node (EDRS-A) is realized as a hosted payload on the *European Telecommunication Satellite Organization's (Eutelsat)* satellite EB9B and has been launched in January 2016. The second node (EDRS-C) is a dedicated spacecraft based on the SmallGEO platform developed by *OHB System* and was launched in August 2019. Both satellites are equipped with a Laser Communication Terminal (LCT) by *Tesat-Spacecom* to provide high speed optical links of up to 1800 Mbit/s [1].

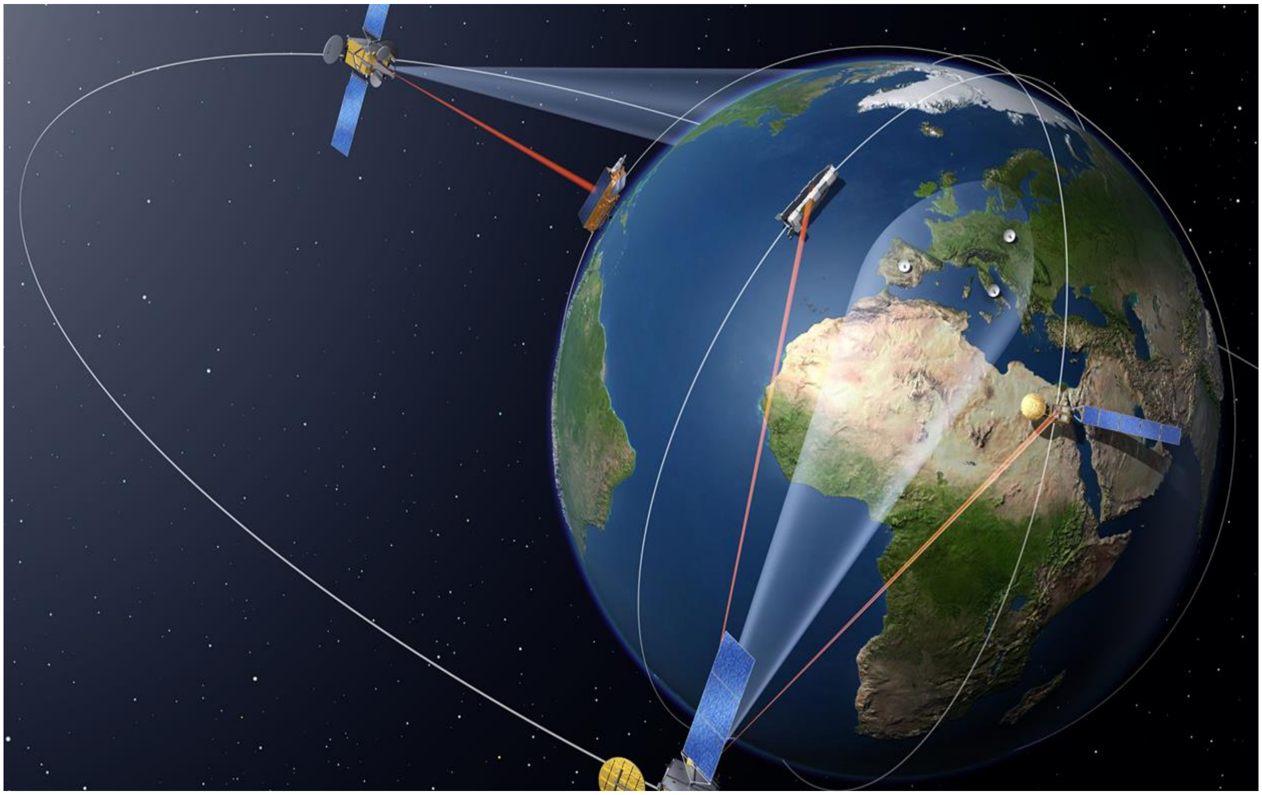

Fig. 1. Illustration of the SpaceDataHighway: EDRS satellites as geostationary nodes using an automated ground system for optical laser communication execution to support data forwarding from spacecraft on low Earth orbit to ground at near real-time.

To cope with commanding of up to 400 optical links daily per satellite, an automated system has been implemented as the classical operational concept of manual operations would lead to a high workload for the operators with repetitive tasks. Currently, this automated system is almost solely used to perform automated tasks associated to payload activities. In contrast to EDRS-A, which is a hosted payload on an *Eutelsat* satellite and therefore its platform operations are carried out by *Eutelsat's* control center in Paris, EDRS-C is a dedicated satellite with operations performed by the *German Space Operations Center (GSOC)* of the *German Aerospace Center (DLR)*. One of these operations is the station keeping maneuver execution, as necessary for all Geostationary Earth Orbit (GEO) satellites. This activity ensures keeping the satellite within its desired orbital slot. For EDRS-C, three dedicated SKMs have to be executed on a bi-weekly basis, which keeps dedicated members of the Flight Operation Team (FOT) occupied for roughly 2.5 hours each time. Already having a system for automated FOP execution in house and utilizing it to replace the traditional manual commanding of SKM operations would be a great benefit. With an expected life time of more than 15 years for a GEO satellite mission this approach promises to save substantial time resources of the Flight Operation Team.

This paper demonstrates how an SKM execution is introduced into the automated system. At first, section 2 will elucidate how the SKM execution will be initialized for EDRS-C. The section 3 will show which small adaptions to the ground system are needed to prepare the system for an automated SKM execution. The porting of a manual Flight Operation Procedure (FOP) to an automated FOP will be described in section 3. Also, how the human's ability of interpretation can be handled by a logic within the FOP will be outlined there. Section 4 describes the system's reaction to an anomaly scenario and how the interaction for the operator with the system can be supported in that case. Finally, a conclusion is drawn in section 5.

2. Initialization of a Station Keeping Maneuver execution into the automated ground system

For a SKM execution, several tasks have to be performed before the actual maneuver can be executed. This has to be done independent of whether the maneuver execution is performed manually by a person or automated by the system. Therefore, the general task of the maneuver execution is divided into a preparation the day before the SKM and the actual execution. Hereby, the SKM preparation consists of calculating and preparing information that is required for the orbit correction, followed by commanding the Attitude and Orbit Control System (AOCS) parameters to the spacecraft (S/C). By this action, the desired station keeping maneuver is prepared on-board, followed by configuration changes and maneuver execution of the S/C on the next day.

2.1 Preparation and data gathering

For EDRS-C, the basis of the maneuver execution is the SKM cycle plan. It is created automatically by the Flight Dynamics System (FDS) on a bi-weekly rhythm and consists of a set of maneuvers, their dedicated dates and the desired velocity changes per axis within the satellite body coordinate system [5]. These velocity changes have to be performed to prevent the satellite's orbit from deforming. However, this information cannot be commanded directly to the spacecraft as the SmallGEO platform of EDRS-C, developed by *OHB*, can only cope with information about the maneuver direction and requires the accumulated thruster set on-times besides further parameters. Therefore, this information needs to be extended, for instance with the actual S/C mass, the propellant tank pressures and other calibration parameters to calculate the required inputs for the telecommands of the SKM. This data is retrieved and partly calculated by a station keeping preparation tool named ViPER. It uses an interface (I/F) to the Satellite Monitoring System (Satmon) to collect S/C live telemetry via GSOC's Enhanced Command & Control System (GECCOS) [2][3]. A precise propellant consumption is calculated by this tool and S/C live telemetry information is prepared as input for the FDS. Afterwards, FDS calculates the required command parameters and creates the final commanding files. In parallel, several AOCS parameter updates are calculated by ViPER to allow a more accurate SKM execution. The file transfer is done in the background. Only the selection of the desired SKM from a dropdown menu and the preparation start is triggered by the engineer to start the data exchange with FDS.

2.2 Adaptions of the ground system to allow automated SKM execution

To allow the injection of an automated SKM execution into the ground system a few small adaptions were accomplished. The ground system of EDRS-C already provides the possibility of FOP request initialization for automated execution [6] as the automated payload operation activities were one of the core design objectives during the ground design phase and are used in daily service operation [8]. On this backend, no modification is necessary and the overall biggest modification affects the ViPER propulsion tool. For the manual SKM execution, this tool is only used for the interaction with FDS as described in section 2.1. Consequently, this tool was upgraded with a new tab within the Graphical User Interface (GUI) for the automated SKM execution and the feature to load the commanding files from the FDS, which are otherwise used directly within GECCOS for a manual SKM commanding [3].

Consequently, ViPER is upgraded with the possibility of writing FOP requests. Within a FOP request all parameter inputs for telecommands are contained. Furthermore, so-called procedure variables are provided to the automated system to structure the execution [6]. They are executed by the automated system just like a telemetry check with the difference that the value is not coming from the S/C as a telemetry value but as an input from ground.

This is the case for example to distinguish between the SKM execution direction. Thus, this information is included as TC input to command the execution direction to the S/C. At the same time, it is present in a FOP request as a procedure variable to guide the automated execution, for instance within an if-statement checking the respective procedure variable against a value, to determine which procedure step should be executed. All variable parameters for a FOP have to be part of the FOP request, all other fixed parameters are already part of the FOP itself and are extracted from a database [6].

Besides these modifications, a small submodule is created in ViPER and ProToS to exchange information that cannot be associated with a FOP. A periodical dual-side ranging is performed to determine the position and speed of travel to calculate the orbital elements. During the timeframe of a dual-side ranging, no commanding of the S/C is foreseen for EDRS-C and ProToS pauses its commanding module. Telemetry checks can still be executed, as the telemetry stream is not affected. For payload (P/L) activities these commanding pauses are negligible as the activities are not time critical and can be paused for this period of time or the commands are already uploaded to the S/C as time-tagged telecommands. Both solutions are not feasible for a station keeping maneuver in terms of safety. Therefore, a dual-side ranging is skipped by coordination with the Antenna Control Center, in case it collides with the timeframe of the maneuver execution. This is done for manual station keeping execution and has to be considered for the automated execution as well. To forward the information about a skipped dual-side ranging to ProToS and allow the software to continue commanding during a dedicated time frame, a software submodule was created. With these adaptions the ground system is feasible to fully perform an automated station keeping maneuver from ground system side.

2.3 Injection of an automated FOP into the ground system

ViPER was developed to allow an easy workflow for the operator to perform the SKM preparation. The next and last tasks for the user therefore are, to load the commanding files provided by FDS into ViPER by selecting the corresponding file and performing a last coherent check of displayed information. By loading the commanding files, and utilize the calculated data before, ViPER possesses all information that is needed for the SKM injection. After confirmation by the user FOP request files are created. One FOP request file is for the SKM preparation and the other FOP request file is for the SKM execution itself. It contains the identification number of the desired FOP, an execution time and parameter inputs for all procedure and sequence variables. Procedure variables give the opportunity to control the FOP execution itself while sequence variables possess telecommand parameter inputs.

All predefined information, like telecommands with fixed parameter inputs and telemetry checks are loaded by an automated ground system from a data base. The ground system already supports the injection of a Flight Operation Procedure (FOP) request to be automatically executed by the GSOC's developed Procedure Tool Suite (ProToS). It allows an execution of a FOP statement-by-statement and has the capability to perform telemetry checks, command TCs and perform further basic logical operations like If-Than-Else statements. More detailed information about the features and how the SKM FOP will be adapted is explained in section 4. At the time ProToS receives a FOP execution request, it instantiates the FOP with information from the FOP request file and the data base and directly starts its execution [6].

The telemetry retrieval and commanding of EDRS-C are realized by GSOC's Enhanced Command & Control System, which is the main application for S/C operations at the German Space Operations Center (GSOC). It is used for manual commanding and provides also an I/F for the communication with other software tools. This I/F is used by ProToS to have access to the S/C live telemetry stream and commanding capabilities [1].

3. Porting of a traditional Flight Operation Procedure (FOP) to an automated FOP

All routine flight operations should be performed according to validated Flight Operation Procedures. A FOP is used to conduct a series of actions in a certain manner to indicate the way of performing an activity. Usually, a FOP consists of telemetry checks, packet content checks, command statements (if applicable with parameter input), calls to other procedures and time references like the execution start time. Furthermore, there are comments and decision steps. Of that, the procedures that are executed at GSOC can include preconditions, if-than-else statements and switch cases [4].

Basically, the porting of a FOP designed for manual execution to an automated procedure can be done as commanding and telemetry statements can also be performed by a computer, the decision steps corresponds to the basic logical operations and the procedure is executed step by step and statement by statement. The remaining challenge is to transfer operations instructions and information from comments as well as the ability of human interpretation into an automatically executed FOP. Besides the traditional statements within a FOP for manual execution, an automated FOP should provide the capability of waiting-statements, while-loops and info- or alarm-statements to inform the operator in case of predefined error cases.

First of all, some general aspects were defined for the automated station keeping maneuver execution. It was decided to send telecommands (TC) "one-by-one", which means to wait for the successful on-board execution packet (PUS 1.7) for each telecommand before the next TC is sent to the S/C by the system. This is not a hard constraint and in dedicated cases the release of several TC without waiting for each successful on-board execution packet is also possible. However, the FOP execution by the automated system is much faster than performing the operation manually and therefore this configuration does not impose any problem. Furthermore, for every failed telemetry (TM) check the automated system needs to stop the execution, as it is also done for manual commanding.

All prepared steps that check the S/C systems for an unexpected state and in case command it back to the nominal configuration were replaced by telemetry checks for an expected state. If for instance the status of the Chemical Propellent Propulsion Subsystem (CPPS) pressure transducer is expected to be "ON", as this is the default S/C configuration, it is replaced as follows: Instead of checking the status to be "OFF" and if so commanding the pressure transducer to the status "ON", the TM check will be performed for the status "ON". This ensures that the S/C configuration is not changed unnoticed, so the operator is informed about any deviation from the expected state, even if the corrective action is already part of the manual commanding FOP. Instead of a complete removal of the corrective step, it would be possible to add a stop statement at the beginning of the step to pause the execution and ask the operator for confirmation. In case of a time-critical step, it could be useful to allow the automation to proceed with the corrective task without acknowledgment by the operator. However, the operator should be informed in any case.

For the automated FOP, another structural change was established to take account of different station keeping maneuver execution durations. Depending on the maneuver direction, the duration of on-board thruster activation differs significantly. Maneuvers in north- or south-direction last several minutes, while especially maneuvers in west-direction have a thruster activation duration of close to zero seconds. In general, the monitoring of this critical operations step is essential. However, depending on the update rate of the TM packets which are generated on-board it could happen that it is simply impossible to perform telemetry checks, since no telemetry update is received on ground during the actual thruster activation time, or there are just not enough telemetry updates received to judge on the parameter changes. An operator who performs this kind of short SKM is faced with the same challenge. Since there is not enough information available or the time is too short respectively, it is not possible to perform dedicated telemetry checks in this case. That is obvious for an operator, but for the automated SKM execution this monitoring step needs to be performed differently. Determined by the foreseen SKM duration length, different cases should be executed containing a full or reduced set of telemetry checks to avoid false alarms during the execution of very short station keeping maneuvers.

Telemetry checks without an exact definition like “check for value to be near zero” or “check for temperature increase” pose another challenge. TM checks for values near a predefined fixed value need an explicit definition of the limits. These limits should be defined from previous operation experience with the satellite. To compare expected value changes against a fixed threshold new ground parameter were created for EDRS-C. These synthetic parameters calculate the difference between the last value received and the current value received with every new telemetry sample update. This differentiation shows the values’ rate of change and can be checked against defined thresholds to assess the speed of increase or decrease.

Some other adaptions for the automated FOP are applied to have a clean mathematical logic of the procedure. It is common practice to have TM checks for the nominal equipment or the redundant equipment as if-statements. For instance, some telemetry from the AOCS board side-A should be checked if the dedicated board side is ON. If the AOCS board side-B is ON, the dedicated telemetry checks for the corresponding side should be performed. For an operator it is obvious that one of the boards must be ON, however not so for the automation engine. The automated FOP is adjusted with extended else-statements for all these cases to raise an error notification if none of the boards are online. However, this guarantees that no important actions of the procedure will be skipped.

Telemetry checks that should be repeated as long as the thruster action is on-going are realized by a while-statement. For the manual procedure it is indicated to the operator to periodically perform the check and abort the station keeping maneuver if any of the TM checks fail. This is solved by adding negated if-statements within the while-loop checking for values outside the desired range. For instance, if the temperature of an equipment gets too high, the if-statement entry condition is fulfilled and the statement will be executed. The consequence is that the automated system will command the abort of the SKM. With the abort of the SKM also the condition for the while-loop is not given anymore and the automated system exits the while-loop. Combining similar telemetry checks in if-statements enhances the structure of the procedure and makes it easier for the operator to understand the decision made by the system. It is important that the automated execution does not stop here and continues the execution of the FOP starting with the next foreseen step to be performed after thruster activation end. This ensures that the S/C is configured back to the nominal configuration, for example checking closed thruster valves and that the P/L service can continue.

4. System reaction in an anomaly case

A station keeping maneuver activity is a more critical operation compared to payload operations as it could have an impact on S/C safety in case of an on-board anomaly. Therefore, it is important that the automated system reacts in the same way as an operator would handle the issue. As shown in Fig. 2, the automation engine provides a GUI for the operator to inform him about the current execution state. Also, a small set of interactions of the operator with the automated system are foreseen, for instance the operator is allowed to pause and continue the automated execution and to acknowledge errors [7].

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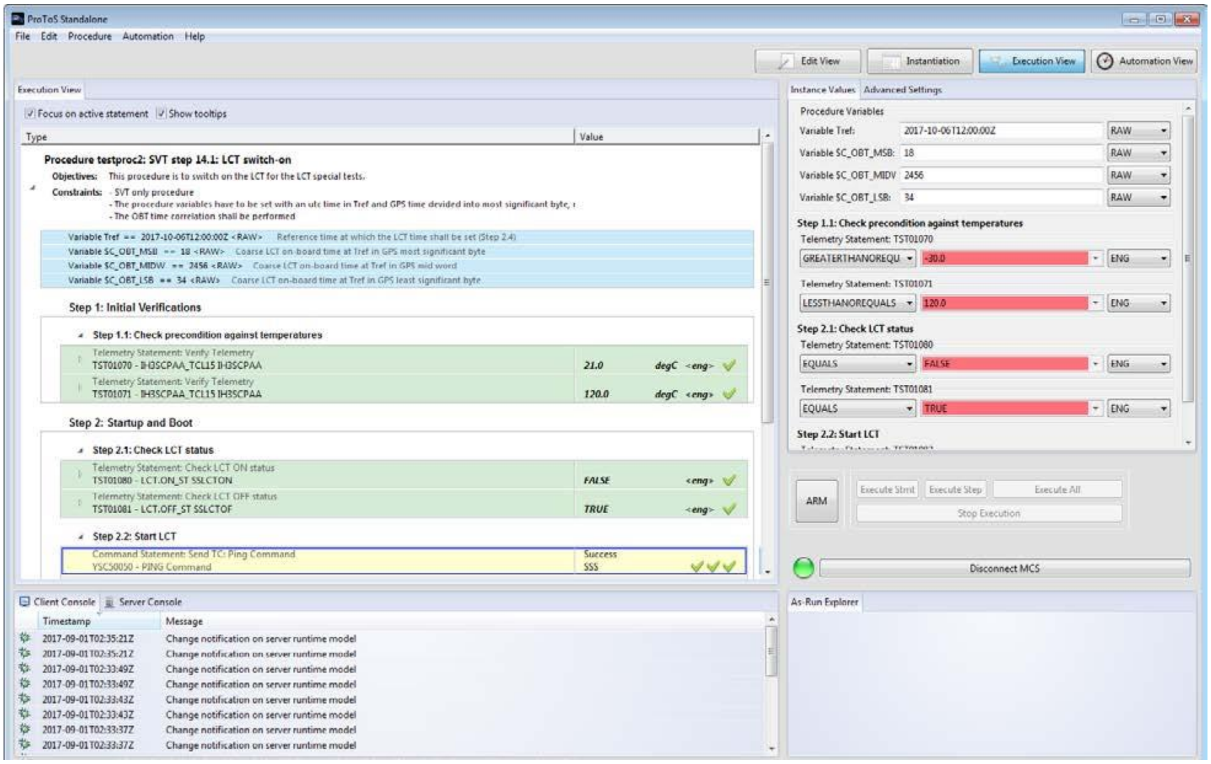

Fig. 2. Execution view in ProToS of an on-going automated flight operation procedure (FOP) execution.

For all detected discrepancies from the expected state, even if contingency operations are already part of the FOP, the operator will be informed. They are asked for acknowledgment for non-time-critical activities before the automated system is allowed to continue the procedure execution. These stop- or info-statements contain some helpful information for the operator to support their interaction. At the very least it indicates why the operation was stopped at this point. Even better, it guides the operator to the next steps that need to be performed. This support can be enhanced by a dedicated ground procedure with follow-up information that is referenced by a stop- or info-statement. For time-critical activities, like failed telemetry checks within the while-loop during thruster activation, that the automated system should react on its own and should abort the thruster activation but still continues the execution of the FOP until at least a safe S/C state is reached or even until the payload service is re-established. For instance, in case that the station maneuver execution needs to be aborted on-board due to any deviation from a TM check during thruster activation, the maneuver will be aborted automatically and the FOP will be further executed until procedure end. At the time of commanding the SKM abort, the operator is advised to inform the Flight Director about the anomaly and to check that the execution is performed until a dedicated step (safe S/C state) is reached.

5. Conclusion

The presented methods can be used to implement an automated station keeping maneuver execution for a S/C which was initially designed for manual commanding. Due to the fact that FOPs are usually executed statement-by-statement and consist of basic logical decisions, an automated FOP execution system can be realized within the ground system. For the porting of a traditional FOP into an automatically executed procedure, some adaptions at FOP level are needed. Primarily, this is driven by the need to establish a FOP with a fixed logic that eliminates any kind of interpretation. Furthermore, necessary information is shown to the operator for the interaction with the automated system in contingency cases. For EDRS-C, it has already been shown that the automated system can successfully execute station keeping maneuvers against the Dynamic Spacecraft Simulator with this approach. After the currently on-going validation phase has ended, it will be used to demonstrate the first fully automated SKM execution of the spacecraft and will be used during routine operations afterwards.

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