The RAXEM Tool on Mars Express - Uplink Planning Optimisation and Scheduling Using AI Constraint Resolution

Erhard Rabenau[(1)], Alessandro Donati[(2)], Michel Denis[(2)], Nicola Policella[(2)], Amedeo Cesta[(3)], Gabriella Cortellessa[(3)], Angelo Oddi[(3)], Simone Fratini[(3)], Guilio Bernardi[(3)]

[(1)] NOVA Space Associates Ltd
Bath, BA1 2AB, UK
name.surname@esa.int
[(2)] European Space Operations Centre
Robert-Bosch-Strasse 5, D-64293 Darmstadt, Germany
name.surname@esa.int
[(3)] ISTC-CNR
Via S. Martino della Battaglia 44, I-00183 Roma, Italy
name.surname@istc.cnr.it

Abstract

In recent years, software tools based on Artificial Intelligence (AI) have been introduced in the spacecraft operations domain that help to reduce operator workload and error and thus provide a means for cost-saving. This paper describes such an application, known as RAXEM, which has been developed to support the Flight Control Team of Mars Express in the daily planning task of uplinking telecommands to the spacecraft. The tool is part of the mission improvement activities within the team to move from a manually-oriented to a more tool-assisted and automated approach. A first AI-based system, MEXAR2, has been in operational use at ESOC since the beginning of 2005. The tool is based on AI constraint resolution techniques and was the first of its kind to be in operational use at ESOC. It has gained wide-spread acclaim in the mission planning and scheduling community. The operational experience and success of MEXAR2 and the similarity of the problem led to the requirements for an application to generate a detailed uplink plan and schedule. The paper presents the operations and mission planning constraints that influenced the requirements for the RAXEM planning tool. It further focuses on the tool and its operational usage, the iterative-prototyping approach from requirements definition to software development and operational validation, and the optimization and benefits for the Flight Control Team compared to the manual approach adopted up to the introduction of the tool. The paper will also address the issues raised by introducing so-called "clever" tools to help human operators and compare the consequences depending on the target user group, the planners (as for the downlink planning tool, MEXAR2) or the spacecraft engineers (as for RAXEM).

Introduction

In spacecraft operations engineers are always faced with the problem of consistent and timely preparation of the command data to be uplinked to the spacecraft and quick and thorough analysis of the telemetry data received. Very often during the preparation phase of the mission, these issues play a minor role because of the focus on preparation for launch and critical early orbit operations. Preparing for the uplink during routine operations is not perceived as an important task until actually faced with it. Very often it is down to the ingenuity of the engineers to come up with more or less sophisticated solutions. These may – in fact – be sufficient and meet the requirements to deliver the command data on-board safely and in a timely manner, unless certain constraints manifest themselves during testing and commissioning that impose restrictions on the planning process of the uplink. As a consequence, a fully manual approach that had been sufficient hitherto, now becomes labour-intensive, cumbersome and error-prone. Engineers will therefore look to find tools that will ease their workload without impacting on quality. These tools may be graphically-based for ease of operation, in the simplest case, or software applications which are more or less intelligent to perform the task at hand. Very often these add-on tools will be developed by the engineers themselves or as student projects using traditional and easy to implement programming techniques, e.g. PERL scripts, Visual Basic modules and, lately, JAVA applications.

In recent years, 'artificial intelligence' techniques have found their way into the missions operations domain. This

does not exclude other techniques and approaches that are used outside the space industries, e.g. operations research techniques. An AI-based tool, called MEXAR2, has been in operational use by the Mars Express (MEX) Mission Planning Group since 2005 to support the planning of the downlink of telemetry data, also referred to as solving the 'MEX downlink problem' in the publications. This tool was the first one to apply AI planning techniques to mission operations at ESOC. It gained international recognition when it won the 'best application' award at ICAPS 2007.

The success of MEXAR2 and the identification of a similar constraint-based problem in the operations domain of MEX has led to the specification of requirements and the subsequent development of a second AI-based tool which is subject of this paper. The new tool supports the planning of the uplink activities to the MEX spacecraft. It is referred to as 'RAXEM' (which is MEXAR spelled backwards to show the relationship of the software) and has been in operational use since 2007. After successful demonstration of the problem solving engine, RAXEM recently was enhanced to provide a complete configuration management environment for managing, solving and documenting the uplink to the spacecraft. The technical implementation details on the algorithms used in both tools are not subject of this paper. The focus of the paper is on the operational use and experience gained from using the tools.

Definition of the Uplink Problem

"Why is artificial intelligence needed to uplink telecommands to a spacecraft?", one may be inclined to ask. There are ground station passes during which command data can be transferred to the spacecraft (uplink passes) and the satellite presumably has sufficient buffer capacity to retain the command data for execution at a later time. Thus, the solution would be to simply keep 'topping up' the command buffer, were it not for a number of constraints which are discussed below.

MEX is ESA's first mission to another planet. The constraints of the mission are manifested in the operations and mission planning concepts. MEX operates on a store-and-forward concept, where all data, uplink or downlink, is asynchronously stored on-board before either released for execution (in the command case) or dumped to the ground (in the telemetry case). Commands are generated on the ground with an execution time-tag, sent to the spacecraft during a ground station pass, where they reside in a time-ordered buffer and are released for execution driven by the time-tag. Commands need to be uplinked with sufficient time margin before execution to provide safe and coherent operations.

As defined in the MEX operations concept, most units on the spacecraft (payload, transmitters) are required to be switched OFF when not in operational use and the spacecraft needs to be pointed differently for science and earth communications. This results in the necessity to quantize the flow of telecommands into safe-bounded packages of commands which always leave instruments and platform in a safe status, should the flow be suspended for a longer period of time in case of problems on the ground or the spacecraft. This directly affects the telecommand timeliness problem for planning (generation of commands) and loading (uplinking of the commands).

The MEX spacecraft either supports communication passes where the spacecraft antenna is pointed to Earth or science and/or maintenance passes where the spacecraft antenna is not pointed to Earth any more (MEX does not incorporate a steerable antenna). Ground stations are allocated by the ESA Tracking Network (ESTRACK) and NASA's Deep Space Network (DSN). Typically, a total of 8 hours over ESTRACK and another similar amount of station time on DSN are allocated per day. This may vary as the ground stations have to be shared with other missions. At times there may be no uplink passes for up to 40 hours. Because of the incompatibility of Earth pointings and science observations (constrained by the spacecraft attitude as detailed above), science operations compete with the communication resource, a conflict that has to be solved during science planning. Additionally, eclipses, occultations, regular reaction wheel off-loadings and irregularly performed orbit correction manoeuvres will interrupt and split communication passes into several small windows. Some DSN passes may have to be shared with other spacecraft around Mars, in which case the pass may support downlink but not uplink. A typical communications scenario is shown in Fig 1.

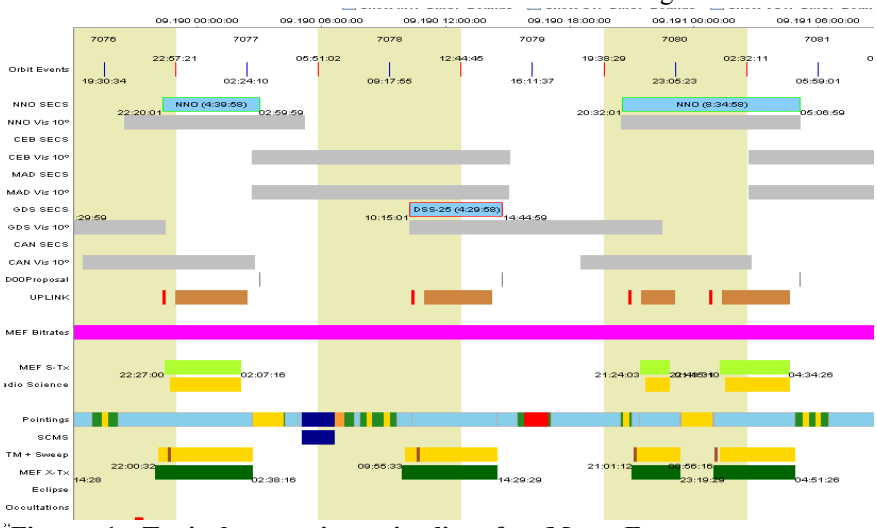

Figure 1. Typical operations timeline for Mars Express. Ground station allocations are depicted in light blue, a separate line for each station complex, e.g. New Norcia, Goldstone. The uplink opportunity windows to the spacecraft are shown in brown. The transmitter switch-on times are depicted in dark green.

During commissioning and early routine operations it transpired that certain constraints had to be observed when uploading commands in order to preserve the integrity and – more importantly – the safety of the spacecraft: the 'top-up' of the command buffer cannot be performed without observing rules that define boundary conditions that are considered safe for operations. Such conditions, or valid end states, include the spacecraft always being left in Earth pointing mode, the transmitter remaining switched on in order to guarantee communications (except in eclipse season where the transmitter is left off in order to preserve power), no downlink of telemetry data ongoing and all instruments switched off. The telecommand (TC) buffer on-board the spacecraft (MTL) holds a limited amount of command data (3000 TC).

Because of these constraints the mission planning process for MEX was set up to generate the command products by type from the very start of routine operations, e.g. pointing, transmitter, dump, instrument A, instrument B, etc. The output products are the MTL Detailed Agenda Files (MDAF). As planning is performed for a whole week at a time, MDAFs can contain several thousand TCs. These large files need to be further split into manageable segments observing the valid end state conditions. The size of the segments is determined by

a) the size of an uplink window determining the volume of data that can be uplinked and
b) the number of TCs that fit into the MTL which is determined by the number of the command executions between two subsequent uplink slots.

Experience has shown that a typical MDAF contains about 250 to 300 TCs. The splitting of the MDAFs is performed by an automated process. Per planning week, more than 30 separate MDAFs are produced that require to be uplinked.

Uplink Rules and Philosophy

The delivered MDAFs are independently checked by a member of the Flight Control Team responsible for the uplink process for continuity, split point consistency and completeness. Software tools help to ease the tasks. The following rules have been established to uplink the command data:

a) uplink according to execution time (default case), i.e. the files with the earliest execution time are uplinked first
b) uplink according to type, i.e. to be invoked if uplink according to execution time is ambiguous (each type has been allocated a priority, e.g. pointing and transmitter MDAFs have a higher priority than science)
c) uplink with full confirmation (default case), i.e. each uplink operation is fully confirmed on ground after having arrived on-board, been processed and inserted in the MTL
d) uplink without full confirmation, i.e. in certain seasons when long one-way light times occur (up to 42 min per 'hop') or uplink windows are small (as may be the case during eclipse seasons when MEX operates in a reduced mode in order to save power), an uplink window may not be long enough to provide the full confirmation, in this case it is acceptable if at least the reception of the file transfer on-board can be confirmed before loss of signal occurs
e) the uplink should always be planned with a full backup window preferably on a different ground station – this is to ensure that the commands can get on-board even if a station pass is lost because of ground station problems.

The uplink time required is one telecommand per second release time from the Mission Control System and one telecommand per second insertion time into the MTL on-board the spacecraft. Including the two-way light times, a full confirmation requires two times the number of telecommands (in seconds) plus the two-way light time.

It is the aim of the process to uplink command data as early as possible in order to be independent of ground station outages or control system problems and to keep the MTL as full as possible at all times.

Uplink Planning Before the Introduction of AI

When routine operations first started and the uplink constraints became apparent, as detailed in the previous chapter, the MEX flight control team planned the uplink in a fully manual fashion. The number of telecommands that could be uplinked to the Spacecraft was determined by the remaining number of TCs in the MTL provided by the Onboard Queue Manager of the Mission Control System and the availability of a ground station pass. Secondary uplink windows were taken into account, in case the primary window could not be used. The uplink planning process was eventually refined by introducing a Gantt chart-style representation manually drawn on paper, also internally referred to as the 'Olligram' (after the engineer in charge of the process), as depicted in Fig. 2. The chart basically linked the uplink time with the execution time of the MDAF. Instructions to the Spacecraft Controller (SPACON), in charge of the uplink, were written by hand specifying MDAF(s) to be uplinked, primary and

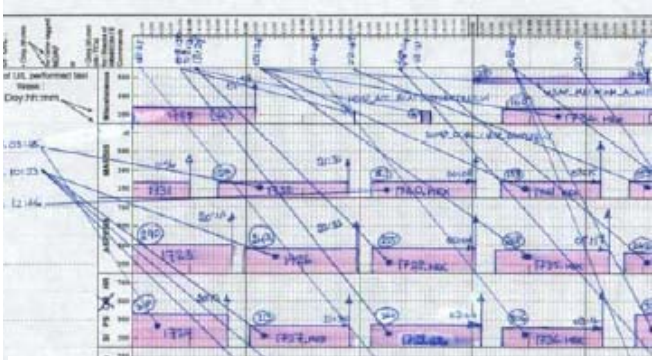

Figure 2. Example of the 'Olligram'. Lines connect the uplink time with the on-board execution bars, thus providing a visual overview of the uplink plan and spacing

secondary uplink windows extracted from the master timeline and re-calculated for full confirmation. Mainly because of the lack of requirements, want of better tools and change of the operations concept after launch, this way of working survived for 3 years, even though it was a cumbersome and time-consuming process, error-prone and not optimised to keep the MTL as full as possible. Having to re-plan an uplink plan because of short-term ground station changes proved to be a very time-consuming task.

Uplink Planning Process as Supported by RAXEM

The AI-based algorithm, together with the look and feel of the interface tailored to the human approach to a problem, are the key features of MEXAR2 as experienced by the MEX mission planning team. Based on the experience and confidence in using AI-based algorithms operationally, it was proposed that the AI technology could also be beneficial in automating the uplink planning process. The requirements for the new tool were largely based on the functionality and experience of the manual process described above (including the graphical representation of the 'Olligram'). The subsequent development of the RAXEM application was performed by the same team that developed MEXAR. This proved beneficial in several ways: a) the development team was familiar with the MEX operations and planning concepts b) they very much supported the fast prototyping approach c) they had shown their competence in the field of AI tool development. The algorithms employed, however, differ greatly. While MEXAR relies on a workflow-based approach, RAXEM uses a different algorithm largely because the problem is constrained and therefore requires fewer alternatives to find a solution.

The first prototype of RAXEM was delivered in 2007 and transitioned quickly into an operational tool. As was the case with MEXAR, the tool soon showed its superiority over the manual process, even though there were still some limitations and shortcomings. But these were fixed in a continuous iteration cycle between the operations team and the developer. Initially the tool only provided the uplink solution engine with some graphical display support (MTL buffer contents and MDAF execution timeline). The SPACON Instruction Forms (SIF) had to be generated by a separate tool developed by the Flight Control Team that took the RAXEM solution file as input. The initial RAXEM and the SIF generator together improved the generation of uplink plans but the activity was still quite time-consuming.

A new enhanced version of RAXEM (RAXEM2) has recently been deployed that supports the entire life cycle of uplink activities and keeps a historical record in an uplink database. RAXEM2 comprises two modules: the AI-based solver and a module to manage the uplink planning and interaction with the user. The key parts of the latter functionality are the uplink database and the management and generation of SIFs by a graphical user interface.

The intelligent environment of RAXEM helps the users analyse the problem and take planning decisions as a result of an interactive process. Different aspects have been considered, like integrating flexible automated algorithms, promoting user active participation during problem solving and guaranteeing continuity of work practice. The tool was developed in JAVA and as such it can run on different platforms (WINDOWS, UNIX, MacOS). The initial RAXEM and RAXEM2 enhanced version do not differ as far as the external interfaces are concerned.

RAXEM requires as input:

a) the MDAFs of the previous planning period in order to be able to determine the status of the MTL buffer
b) the MDAFs of the current planning period
c) a file that lists the useable uplink windows. This file is a product of the medium-term planning process and is automatically generated.

The user can interact with the tool by means of a graphical user interface (GUI), see Fig. 3 through Fig. 7. The complete uplink history is maintained in an uplink database which is presented in a table view after starting the application. The user defines the directory that contains the MDAFs, selects the appropriate uplink windows file, edits the configuration for the planning session (size of the MTL to be used operationally, uplink planning margins, MDAF type definitions) and sets the baseline time (this determines the time from which RAXEM starts to plan). RAXEM imports the MDAFs in the defined directory and displays only new MDAFs in the GUI (see Fig. 3). RAXEM reads MDAFs manually generated on the Mission Control System if they adhere to the file naming convention and includes them in the solution. All MDAFs that are tagged 'to be uplinked' are included in the solution. The algorithm then produces a solution based on the setting of the

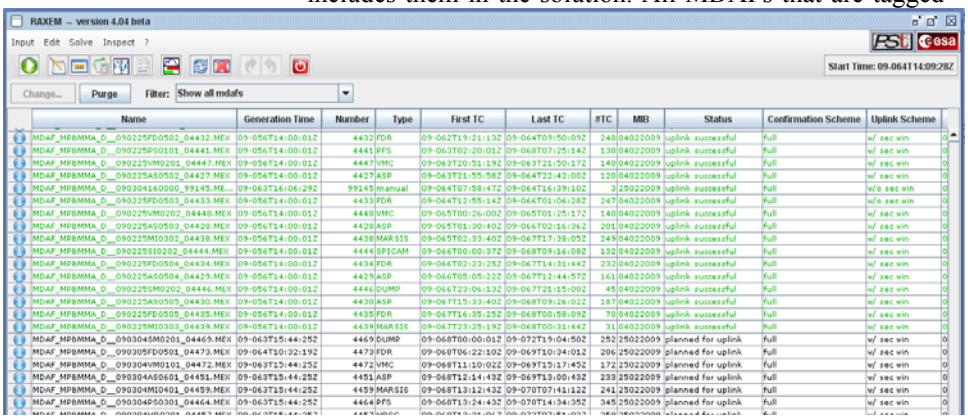

Figure 3. RAXEM Database View. Uplinked MDAFs are shown in green. The confirmation and uplink schemes (control flags) may be set by user or calculated by RAXEM.

constraint flags. These flags are set by default to a) the use of secondary uplink windows, i.e. for each primary uplink window a secondary one exists on another station and b) the employment of full confirmation of the uplinked telecommands. The control flags can be set to actively influence the solution generation, i.e. disabling the use of secondary uplink windows, excluding MDAFs from the uplink plan and, in case of tight planning windows, the disabling of the uplink confirmation option. Should a solution not exist for the default configuration, the application will try to find a solution by changing the control flag settings, i.e. a) try without a secondary uplink window and if still not feasible b) try without full confirmation. If a solution cannot be found to uplink all the MDAFs, the MDAF will be set to 'not to be uplinked' and the user will be alerted. In this case, the user may decide to split the files into smaller segments that may fit into the uplink window and/or MTL, whatever the driving constraint. If absolutely no solution can be found, the MEX Resource Allocation Board (RAB) convenes to decide which MDAFs are to be dropped from the uplink plan (the RAB comprises the Mission Manager, Spacecraft Operations Manager, Science Operations Centre, mission planning team). This is a last-resort activity which has so far never occurred during the 6 years of operations of MEX. A commit and roll-back function is provided to facilitate usability.

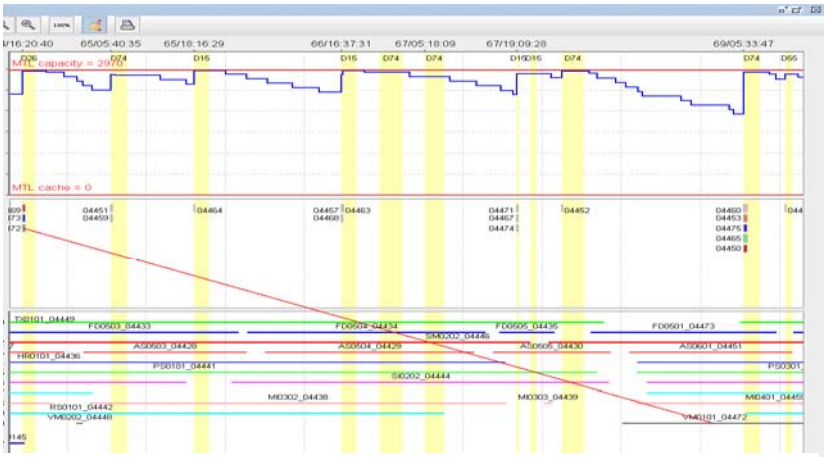

Figure 4. Graphical representation of a solution. The combined graphics view contains in the top part the MTL buffer history, the middle part shows the MDAF uplink time, the uplink window and the ground station, the lower part displays the execution period of the MDAFs on-board. Lines are drawn to connect the uplink time with the execution time, thus facilitating a quick visual check of the uplink plan. Tool tips provide a complete overview of the MDAF and its uplink planning.

tart time (secondary)	End time (secondary)	Start time (actual)	End time (actual)	Mul	Checked	SIF no
-060T15:47:50Z	09-060T15:56:06Z	09-060T00:36:37Z	09-060T00:44:53Z	1/1	✔	3197
-062T07:27:16Z	09-062T07:40:32Z	09-060T15:47:50Z	09-060T16:01:06Z	1/3	✔	3198
-062T07:27:16Z	09-062T07:40:32Z	09-060T15:47:50Z	09-060T16:01:06Z	2/3	✔	3198
-062T07:27:16Z	09-062T07:40:32Z	09-060T15:47:50Z	09-060T16:01:06Z	3/3	✔	3198
		09-064T01:28:39Z	09-064T01:36:59Z	1/2	✔	3199
		09-064T01:28:39Z	09-064T01:36:59Z	2/2	✔	3199
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	1/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	2/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	3/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	4/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	5/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	6/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	7/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	8/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	9/10	✔	3200
-064T16:20:40Z	09-064T17:08:56Z	09-064T01:36:59Z	09-064T02:25:15Z	10/10	✔	3200
-065T05:40:35Z	09-065T06:01:35Z			1/3	✔	3201
-065T05:40:35Z	09-065T06:01:35Z			2/3	✔	3201
-065T05:40:35Z	09-065T06:01:35Z			3/3	✔	3201
-065T18:16:29Z	09-065T18:32:17Z			1/2	✔	3202
-065T18:16:29Z	09-065T18:32:17Z			2/2	✔	3202
-066T22:24:31Z	09-066T22:36:01Z			1/1	✔	3203
-066T22:24:31Z	09-066T22:40:29Z			1/2	✔	3204
-066T22:24:31Z	09-066T22:40:29Z			2/2	✔	3204

Figure 5. RAXEM Database View. The database also includes the SIF numbers. Merged MDAFs are contained in the same SIF. Before the user can allocate the SIF numbers (automatically performed by the application), the check box has to be set.

Based on the solution, the resulting uplink plan contains for each MDAF the start of the uplink window, the duration of uplink and start of the secondary uplink window. More than one MDAF will be merged into a single uplink if uplink window duration and MTL margin permit. In this case, all MDAFs uplinked together will have the same uplink time.

The user can view the solution graphically (see Fig. 4). In the combined chart view, the MTL buffer size is displayed, the MDAFs are shown in their respective uplink windows (MDAFs grouped together are arranged vertically) and the execution time of the MDAF is depicted as a timeline chart. By clicking on a timeline, the most important information of the MDAF is displayed as a tool-tip and a line is drawn that connects the MDAF in the uplink window with the execution time thus giving the user an immediate account of the uplink margin.

A function has been implemented in the most recent version of RAXEM that transforms the uplink plan into a human-readable format for the on-duty spacecraft controllers to execute. These so-called Spacon Instruction Forms (SIF) are maintained in a SIF database within the RAXEM application. A SIF may contain one or several MDAFs as generated by the RAXEM solution. To generate SIFs the user selects the MDAFs from a solution. The application automatically allocates the next higher SIF number from the SIF database (see Fig. 5). A separate SIF tabular and form view are available to the user by means of which the SIFs can be managed. The SIF tabular view provides an overview of the status of all SIFs (see Fig. 6). In the SIF form view, the actual SIF format is displayed (see Fig. 7). The user can change the SIF number and the uplink times if required. The tool provides syntax and consistency checks on any entries made. Comments and instructions for the SPACON may be added to a SIF.

After the successful uplink of the MDAFs contained in a SIF, the uplink time has to be manually entered in the SIF database, thus locking the MDAFs belonging to this SIF in the database for further editing/planning.

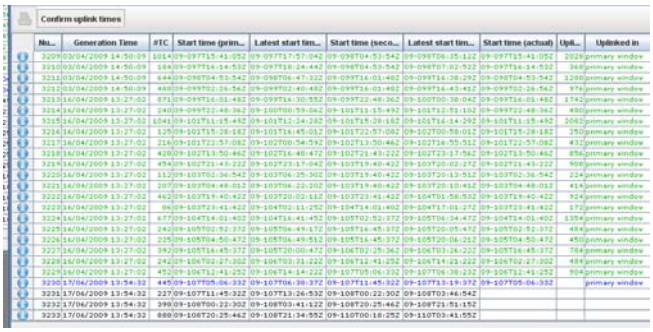

Figure 6. RAXEM SIF Tabular View. The SIF database lists all SIFs generated and their status. Clicking on the 'i' field opens the SIF Form View for editing the SIF. Once an uplink time has been entered in a SIF, the entry is displayed in blue. It is indicated if the SIF was uplinked in the primary, secondary or outside a defined window. Upon confirming the uplink time, the SIF is frozen for further editing and the MDAF status is displayed as 'uplink successful'.

Up to this time, however, the user may regenerate the uplink plan as required, usually if station passes are cancelled at short notice.

Comparing the manual uplink planning using the 'Olligram' with the AI-assisted approach using the enhanced database GUI support and SIF generation functionality, the generation of an uplink plan has been reduced to a matter of minutes from what used to be hours. The time-consuming generation of SIF forms is fully automated and has been reduced to a by-product rather than a full task. Re-planning can be performed within a very short time. What-if analyses may be performed to find the most optimal solution by tweaking the input parameters.

Development Approach and Fast Prototyping

Both MEXAR and RAXEM have been developed based on a set of comprehensive and concise requirements derived from operational experience. Input file and output file formats partly existed from previous implementations and were maintained. Software deliveries were not made, as is traditionally the case, according to a milestone delivery plan but successively whenever a major element was finished.

In this way, the users could test the software in the operational environment and provide feedback that immediately found its way back into the next version. Thus, a faster development cycle could be accomplished as well as introducing the tool to operations earlier. As these tools are usually superior to the manual approach, they can be introduced in the operational process from an early stage in the development process providing all parties are aware of the limitations and constraints. We have found this approach to work very well for these kinds of applications. For any large-scale development efforts, further studies would be needed to address how to apply AI techniques to large-scale space problems. Experience has highlighted a number of constraints that "intelligent" tools shall respect to be successful and accepted. The new tools shall keep as close as possible to known formats and proven processes to maintain the quality of the products. Changes required from the operators to adapt to the new tools and improve the overall efficiency need to be introduced progressively and as publicly as possible. The full control of the options, strategy and decision for even sub-optimal solutions are left to the operator as long as no hard constraint is violated. When generating schedules intended for implementation by a human operator, margins compatible with the reaction time of human beings have to be enforced.

It has to be stressed that the tools used by the mission planning and flight control teams of MEX support, simplify and shorten the operations processes, without changing any of the products that are transferred to and from the spacecraft and without compromising quality – rather the opposite is the case, as the processes produce repeatable results.

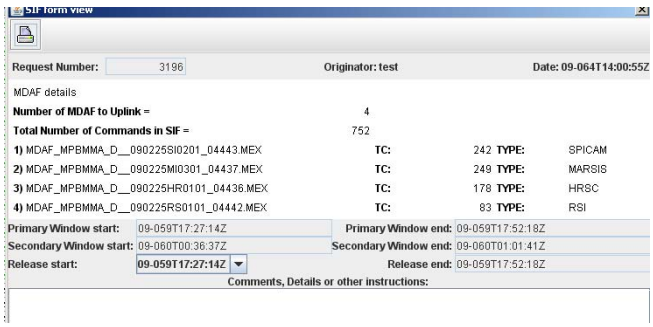

Figure 7. Overview of the SIF Form View. The view shows the MDAFs allocated to a SIF. The request number, primary and secondary window start times can be edited by the user. The release time is the actual time of the uplink to the spacecraft and is entered by the operator after the successful uplink. With the setting of this time, the status will be set to 'uplink successful' in the uplink database.

Conclusion

An uplink planning tool based on AI technology has been introduced into the operations domain of Mars Express that helps the users find solutions to problems as a result of an interactive process performed in an intelligent environment. It has reduced the overall time for generating an uplink plan to a matter of minutes compared to many hours using a manual approach. Re-planning based on resource changes can be easily and quickly performed. Operations engineers can therefore focus on the operational aspects, rather than having to laboriously generate a plan on paper. RAXEM is the second tool employing AI technology in successful operational use by the MEX Flight Control Team at ESOC. It is envisaged that eventually these tools will find their way as building blocks into mission planning systems of the future. They

may play a significant role towards more automated operations: a “lights-out” control room can only be envisaged if the operation engineers are assisted by similar “software slaves” that take over the repetitive, number-crunching tasks at which properly programmed computers are in the long run better suited than properly trained humans.

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