ICKEPS 2012 Challenge Domain:
Planning Operations on the Mars Express Mission

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Abstract

Over the last decades planning systems research has been deeply influenced by challenges offered by space applications. The ESA Mars-Express mission (MEX) offered interesting multi-objective planning, scheduling and optimization problems requiring the satisfaction of a number of temporal, resource and causal constraints. Most of these problems have been addressed separately without taking into account the fact that they were steps of the same process. This document provides the specification of a planning and scheduling domain for mission planning activities abstracted from the real context of the MEX mission. The abstraction aims at putting together steps of the real planning process that are currently handled separately by the MEX operation team.

1 Introduction

The Mars Express Mission (MEX) is a very successful mission of the European Space Agency launched on June 2003. The space spacecraft is orbiting around Mars since January 2004, producing 2-3 GBit of scientific data on a daily basis (see Figure 1). Mission planning for space operations is traditionally addressed hierarchically by dividing it into Long, Medium and Short Term planning (LTP, MTP and STP), and Mars Express is not an exception.

Currently planning for Mars Express is carried out through a collaborative problem solving process between a Science Team located at ESA-ESAC which manages the PIs requests for operating on-board payloads and the Mission Planning Team located at ESA-ESOC, which is responsible for spacecraft operational constraints (see *Figure 2*).

These two groups of human planners iteratively refine a plan containing all activities of the mission. The process starts at the long term plan (LTP) level – three months of planning horizon – and gradually refines to obtain a Medium Term Plan (MTP) and then a set of fully instantiated activities at short term plan (STP) level – one week of planning horizon. In particular, the STPs are then further refined every two days to produce final executable plans.

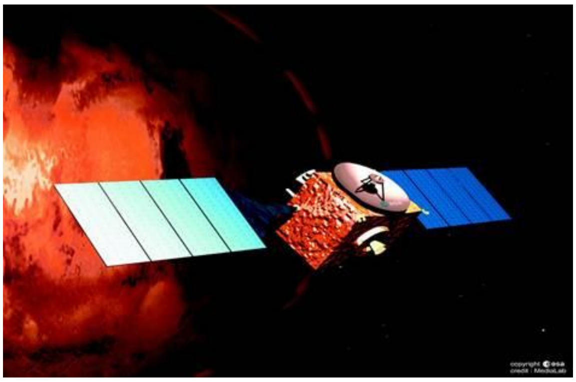


Figure 1 - Mars Express S/C

Broadly speaking the two groups of managers at ESOC and ESAC share information and collaborate at each level of abstraction. At LTP level the plan is abstract and flexible and many decisions can be negotiated. As soon as the planning process moves toward the STP level, plan activities are more in charge of the Mission Planning Team, constraints become mandatory and requests for science observations can hit against the real constraints imposed by the spacecraft (e.g., power availability, illumination constraints, maintenance windows or flight dynamics constraints). When defining a starting LTP the lack of an accurate model of the spacecraft on the Science Team side is one of the main causes for performing many expensive iterations between the two groups. On the other side the Mission Planning Team has only partial information about the requested science operations for Mars Express, thus adding further sources of uncertainty to the decision process.

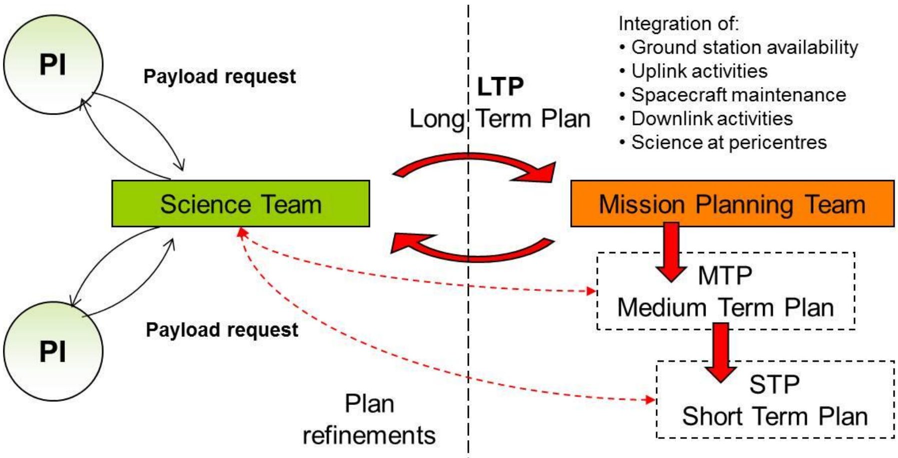


Figure 2- MEX Mission Planning

Currently a waterfall model is adopted to design the plan. The three plans are sequentially generated, with little or no information from following steps or feedback from previous steps taken into account. Capturing all the relevant aspects and constraints of the MEX mission planning at the three level of abstraction in the same domain is extremely challenging but is a fundamental requisite to start considering the process as a whole to entail powerful optimization and more informed planning at each step. Moreover when plans are

executed, multiple sources of exogenous events impact the plan: s/c or ground segment facilities failures, human intervention to modify the workflow to fulfill contingent priorities and so on. Again a model of the whole process would entail more robust execution as well as more flexible and powerful chances of interacting with the plan for the human supervisors.
The next section describes in detail constraints, inputs and expected outputs of the problem.

2 Problem Description

2.1 The Process

The operations of MEX are largely dictated by the geometrical conditions of the orbit, the attitude requirements in support of science and the availability of the ground station to upload command and dump data. The Master Science Plan, a high-level consolidated timeline of payload activities, is the result of the long-term planning. Long-term planning is for the most part performed by the SOC (Science Operation Centre) and the PI (Principal Investigator) teams, as it deals with long-term scientific goals and priorities. The long-term planning period typically covers up to 6 months of operations, during which one of the major activities is to freeze the science and communication windows for each orbit. While fixed windows are defined for orbit maintenance and wheel off-loading, science operations can be scheduled around these within an orbit observing a minimum communications time to allow command uploads and data downloads.

Inputs to this step of the process are:

- Long-term event file (EVTF) as produced by Flight Dynamics
- Bit rate file (BRF) as produced by the Flight Control Team
- Ground Stations Allocation Files
- A set of Payload Operation Requests to be performed

Outputs of this step are:

- A plan for spacecraft pointing indicating parts of the orbits used for science, for communication (uplink and downlink) and for s/c maintenance

- A choice of ground station to be used

The long-term plan is further divided into planning segments of 4-week duration. Medium-term planning is performed by the PIs, PST and POS (Payload Operation Service), in close collaboration with the MOC (Mission Operations Centre), and leads to the production of Payload Operations Requests (POR) for all orbiter instruments. In this phase the plan of S/C pointing is checked by Flight Dynamics, and iterated if necessary, to verify that the required attitudes are feasible within the S/C constraints. In parallel, the Flight Control Team generates operations requests for the S/C subsystems and performs a detailed data analysis to ascertain that the science data generated and stored in the on-board memory can also be transferred to the ground. With this information early resource and constraints checks can be performed in order to flag conflicts and try to resolve them without major impact on science.

Inputs to this step of the process are the outputs of the previous step.

Outputs of this step are:

- PORs. A Payload Operation Requests file contains lists of detailed operations to be carried on by the payloads and the expected amount of data generated as a consequence of operations execution.

The medium-term planning segment is further broken down into weekly slices, with the final delivery of the payload operations requests once per week, specified by instrument on an orbit-by-orbit basis as well as a set of upload and download commands, delivered as a Master timeline Detailed Agenda File (MDAF).

Inputs to this step of the process are the sets of POR files as seen in the previous step.

Outputs of this step are:

- MDAFs. A Mission Detailed Agenda File is a file containing operation requests that are made up of a set of telecommands (TC) to be transferred to the spacecraft where they will be executed. Besides detailed TCs for operating payloads, an MDAF contains also both a plan for uploading further MDAFs and a plan for downloading the data stored in the on-board memory (both telemetry and science data).

2.2 Input and Output

Let us suppose here given in input of the whole process we want to model a set of experiments to plan, provided as PORs files. These files contains real examples of data production patterns during experiments. They are made of a set of commands and resource usages specified on time with respect to a temporal base offset (that has to be planned). In the real scenario, POR files specify *exactly* the timing for each command and resource allocation because they are actually the result of a late step of the whole processes. In the abstracted scenario they are taken as examples of the real complexity of the problem in terms of the size of the problem to be managed, but we do not consider the exact timing for the data production reported in the files, only the relative position with respect to an offset that has to be planned. In other words, we take fragments of detailed real plans, we extract realistic patterns of low-level commands and we plan for allocating similar fragments in the future. The rational is to maintain the problem realistic but abstract from all the low level procedures performed to bring a plan on-board to the spacecraft.

Hence the input of the problem can be considered provided as a set of files providing information on the experiments to be performed and some files specifying additional information about the orbit of the spacecraft and the availability of ground stations to communicate. For each type of experiment is provided:

- A set of PORs files specifying the amount of data produced by the experiment and the time that the experiment takes. The base temporal reference offset for each file is a point in time of the orbit when the observations will be scheduled for being performed (see Section 2.4 for details on orbits and experiment allocation, Sections 2.3 and 2.5 for details on memory allocation). Each file is related to a single instrument and it specifies a set of data produced on the on-board memory described as a set of records like the following ones:

```
-00:27:00          00000300
-00:22:00          00000300
-00:20:00          00033450
-00:15:00          00060000
00:15:00           00033450
00:20:00           00000300
00:22:00           00000000
```

  Each record specifies a flexible time tag (positive or negative with respect to the offset) and an amount of data produced. According with the current practice, the offset is the centre of the time interval where the experiment is scheduled.
- A set of files specifying:
  - S/C orbital events (EVTM files)
  - Ground station availability (SAF and ESAF files)

- Antennas transmission rates (BRF files)

Given that, the planning problem will be described in detail in the next sections breaking it down into three sub-problems:

- Planning for S/C pointing and ground station choice
  - Input: PORs, EVTM, SAF/ESAF, BRF
  - Output: Plan for pointing, operations and communication
- Planning for downloading data
  - Input: PORs, plan for operations and communications
  - Output: Plan for dumping data
- Planning for uploading commands
  - Input: Plan for operations, pointing, communication and dumping data
  - Output: Commands to upload and plan for uploading them

First of all, a brief description of the Mars Express spacecraft and its available resources will be provided.

2.3 The Mars Express S/C

The Mars Express spacecraft is equipped with 7 scientific payloads aimed at collecting data to study the Martian atmosphere and the planet's structure and geology:

- ASPERA - Energetic Neutral Atoms Imager (AS)
- HRSC - High-Resolution Stereo Camera (HR)
- MARSIS - Mars Advanced Radar for Subsurface and Ionosphere Sounding (MI)
- OMEGA - IR Mineralogical Mapping Spectrometer (OM)
- PFS - Planetary Fourier Spectrometer (PS)
- SPICAM - UV and IR Atmospheric Spectrometer (SI)

- VMC – Visual Monitoring Camera (VM) – Currently not any more in use

During regular operations, the spacecraft either points to Mars, to performs payload operations, or points to Earth, to download the produced data or to upload commands. As a consequence, on-board data and uploaded commands generally require to be first stored in a Solid State Mass Memory (SSMM) and then transferred to Earth (data) or executed on bard (commands). Each payload produces, when used, a pre-defined amount of data stored on the on-board SSMM. In addition to that, an amount of housekeeping data is produced as a consequence of pre-planned operations and stored on the SSMM as well. The SSMM is subdivided into 7 packet stores of finite capacity:

Packet Store	Payload	Capacity (bits)
SI	SPICAM	312475468
AS	ASPERA	464388096
MI	MARSIS	800014336
PS	PFS	890109952
OM	OMEGA	2129395712
HR	HRSC	4262772736
AX	HRSC	25378816

MEX orbit takes around 7 hours. For each orbit pericenter (the closest orbital point to the planet) and apocenter (the farthest orbital point from the planet) passages are given. During the pericenter period the spacecraft is preferably requested to point to the planet thus allowing observations of the planet surface with its payloads – this is generically referred to as Science Operation. Between pericenter and apocenter passages, the spacecraft can transmit data to Earth or receive commands from Earth (Communication), if pointing to Earth. Maintenance operations should occur around the apocenter passages. More in detail, the following science pointing modes are interesting for this domain:

- Nadir Pointing (NAD)
- Inertial (FIX)
- Earth Pointing (EARTH)

Slew operations (of the approximate duration of 30 minutes) are required to change pointing direction. The typical science pointing profiles (one or two science pointing) are shown below in Figure 3 with respect to the spacecraft altitude above the Martian surface. Blue indicates planned slew to/from a science pointing direction (~30 minutes duration). Red indicates the margin advised by Flight Dynamics for planning slews. Green indicates the periods of fixed science pointing. Figure produced by the Payload Operations Service.

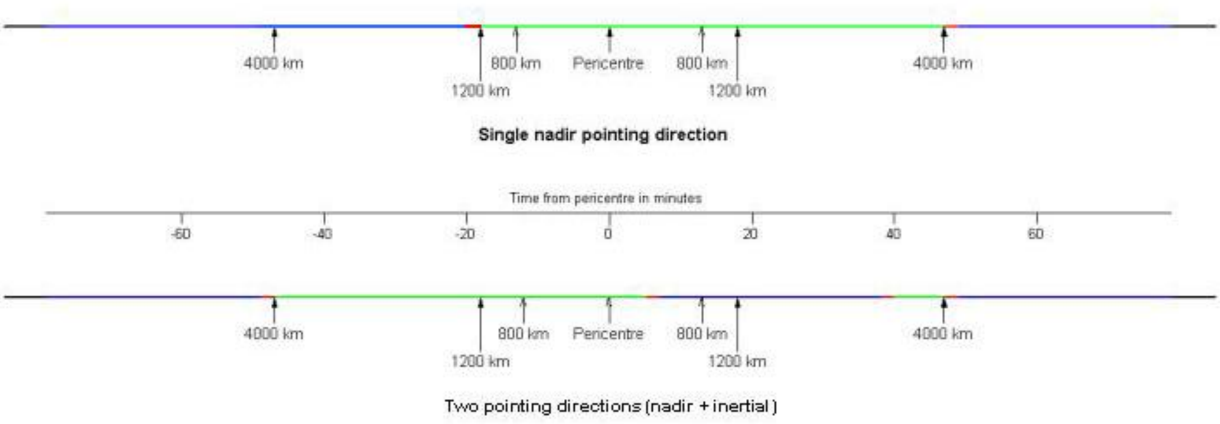


Figure 3 - Science pointing profiles

Payload scientific observations have proven during the Mars Commissioning phase to be able to be conducted in parallel.

2.4 Planning for Pointing and Ground Station De-Overlapping

The problem consists in deciding a set of slewing actions to generate slot assignments for the main activities of the spacecraft (i.e., Science, Communication and Maintenance) such that all the operative constraints are satisfied, to perform as much as science is possible being sure that all the commands can be uploaded and all the data collected can be downloaded. The availability of overlapping visibility windows for ground stations (with different bit rates) affects also the total amount of data that can be uploaded and downloaded during communication activities.

There is an amount of hard and soft constraints on feasible solutions. For a simple scenario we can take into account the following ones:

- Science requires Mars pointing (either NAD or FIX) for all the instruments excepted ASPERA, Communication always requires Earth pointing, both for uplink and downlink, Maintenance does not require a specific pointing, but it requires the same pointing during all of its duration. ASPERA can be on all the time and can collect data also during uplink and downlink, other instruments are mutually exclusive with uplink and downlink operations.

- Science slots have to be synchronized around the Pericentres (excepted ASPERA),

- The duration of a nadir-pointed science shall be limited to 68 minutes.
- The maximum duration of an inertial pointing window shall be 90 minutes.
- Maintenance slots has to be synchronized around the Apocentres.
- Maintenance always requires 90 minutes
- Slots for spacecraft maintenance windows must be allocated between 2 and 5 orbits apart

Communication activities are source of several constraints:

- Each communication operation requires the exclusive use of a single ground station. Uplink and downlink operations can be performed in parallel.
- Minimum station booking is typically 2 hours duration of useable D/L.
- There is a minimum 5 min handover between G/Stns.
- It is required a non-preemptable four-hours uplink time each 24 hours (there is also the possibility to split a four-hour uplink window into two-hour uplink windows allocated each 12 hours). This communication constraints has to be considered as a soft-constraint of the problem, so it is acceptable a small degree of violation for the constraint and we can cast its satisfaction as a minimization problem

The EVTM file given in input for this problem contains a lot of information about the S/C orbit. What is relevant here is just the timing and the orbit number for apocentre and pericentre passage. Here is an excerpt from an EVTM file describing two passages:

```
MPER      1949  R  05-203T11:44:48.488Z      0  PERICENTRE_PASSAGE_1949_/_SSP_(135.41,016.20)_/_SZA_081
…….
MAPO      1950  R  05-203T15:06:23.000Z      0  APOCENTRE_PASSAGE_1950
```

These are the pericentre passage for orbit #1949 (day 203 of 2005 at 11h, 44m, 48s and 486ms) and the apocentre passage for orbit #1950 (day 203 of 2005 at 15h, 6m and 23s).

Ground station availability files, coupled with the BRF (bit rate file) give information on communication opportunities. Ground station availability files contains tuples specifying:

- Two interval of times for station availability, one contained into the other. Only the internal one can be used for transmitting data

- A string codifying a dish available at a ground station
- A string specifying the mission to which the dish has been pre-allocated. Only station pre-allocated to the MarsExpress mission can be used ("MEX" code).

Here is an example:

04 065 0937 1022 1300 1300 DSS-75 MEX

This tuple specify that the dish "DSS-75" is available for the mission "MEX" in day 65 of year 2004 in the intervals of time [09:37,13:00] and [10:22,13:00]. Data can be transmitted during the time interval [10:22,13:00]. Any other information possibly reported after the mission code is not relevant for this problem.

A BRF file contains tuples describing intervals of time and bit rates (in Kb/sec) available for three different sizes of the dishes. Here is an example:

```
04-080T11:00:00Z    57.100  57.100  182.800
04-110T08:00:00Z    45.700  45.700  182.800
```

This pair of tuples specifies that from day 80 to day 110 of 2004 there are two bit rates available: 57.1 Kbit/sec and 182.8 Kb/sec. The mapping between dish codes and column to be considered is the following one:

- First Column: "DSS-74" and "NNO"
- Third Column: "DSS-14" and "DSS-63"
- Second Column: any other dish code

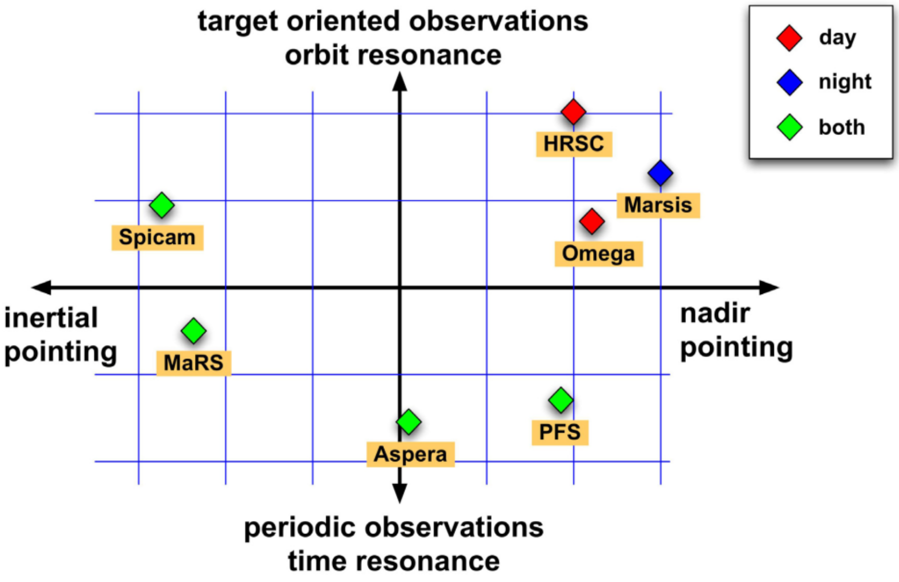
These files define a set of overlapping temporal windows where ground station are available for communication. We do not distinguish in this abstraction between stations available only for downlink and stations available both for uplink and downlink, we suppose all the available station always bookable either for uplink or downlink. Different station has sensible different bit rates (spanning approximately from 28.500 bit/sec to 182.800 bit/sec to give an idea). The choice of the station among those available is also one of the object of the planning process (station de-overlapping).

A more complex scenario involves planning for science slots also taking into account the fact that there are several preferences and constraints related with the fact that the different instruments require different illumination conditions and distance of the s/c from the planet surface. The EVTM file contains information about when the s/c is lighted, semi-lighted or not lighted and the altitude of the s/c:

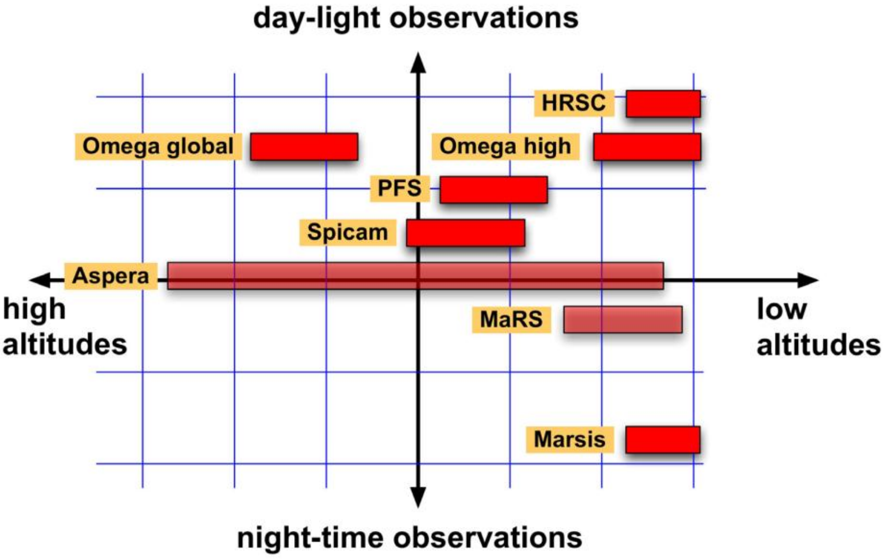
```
KMDS    18173  R  07-200T00:31:22.000Z    5917  4000_KM_DESCEND
UMBE     2210  R  07-200T00:50:53.000Z       0  MAR_UMBRA_END
PENE     2291  R  07-200T00:51:18.000Z       0  MAR_PENUMBRA_END
……..
```

KMDS	18174	R	07-200T00:53:15.000Z	3295	2000_KM_DESCEND
KMDS	18175	R	07-200T01:02:15.000Z	2217	1200_KM_DESCEND
…….					
KMDS	18176	R	07-200T01:07:29.000Z	1591	800_KM_DESCEND
……..					
KMAS	18173	R	07-200T01:34:00.000Z	0	800_KM_ASCEND
………					
KMAS	18174	R	07-200T01:39:12.000Z	0	1200_KM_ASCEND
KMAS	18175	R	07-200T01:48:10.000Z	0	2000_KM_ASCEND
……..					
KMAS	18176	R	07-200T02:09:59.000Z	0	4000_KM_ASCEND
…….					
PENS	2292	R	07-200T06:36:26.000Z	3495	MAR_PENUMBRA_START
UMBS	2211	R	07-200T06:37:08.000Z	3428	MAR_UMBRA_START

The following tables give information about what detailed pointing, lightening conditions and altitude are required by the different instruments:



Pointing requirements plotted versus the resonance and periodicity of the payload observations. Illumination requirements of each instrument are also indicated.



Payload altitude requirements plotted versus illumination requirements.

A more detailed planning for s/c pointing would require to take into account also these constraints, removing the simplifying assumption that science slots have to be synchronized with the pericentre and allocating science slots on the basis of the experiments to perform:

- MARSIS and HRSC close or around the pericentre (resp. <2000Km and <1000Km alt.)
- PFS preferably as closest as possible to the pericentre
- SPICAM and OMEGA can be at any point in orbit, i.e. altitude
- ASPERA performs experiments during the entire orbit

Input for this step: PORs, EVTM, SAF/ESAF, BRF files

Output for this step:

- Plan for pointing: time intervals with associated s/c operational status: Slewing, NAD (Nadir Pointing, FIX (Inertial Pointing), EARTH (Earth Pointing), COM (Communicate)
- Plan for operations: time intervals with associated payload to operate
- Plan for communication: an association of ground stations to COM time intervals

2.5 Planning for Downloading Data

This part of the planning problem can be described in a nutshell as follows: the spacecraft instruments produce data stored in the on-board memory subdivided into slots called packet stores. The goal is then to create a set of commands for downlinking such data to Earth. In general, synthesizing the plan involves managing the constraints due to the bounded on-board memory, limited number of downlink sessions, and the different data transmission rates of the communication windows.

In the specific case of Mars Express, there are pairs of commands that can be used to start and stop the download of each single packet store. The amount of data downloaded depends obviously on the bit rate of the dump station chosen. Packet store downloads cannot be overlapped.

Two major quality metrics have to be taken into account to evaluate the quality of the plan:

- The percentage of data lost. Packet stores are cyclically used by the S/C. New data are stored after the previous and data are overwritten when the end of the buffer is reached. If data are not downloaded in time, there is a loss of information if new data are generated when experiments are performed.
- The size of a dump plan, measured as the number of dump commands in a solution. This is an important quality for the plan because commands require both a certain time to be uplinked to the spacecraft and a memory space on-board before being executed (See Section 2.6). For these reasons mission planners strongly prefer short plans.

A more complex scenario would involve also taking into account:

- One possibility of unexpected memory overwriting can occur when a greater than expected volume of data has to be stored and not enough space in the packet store is available. For this reason a specified amount of space for each packet store should be preserved in order to safeguard against overwriting.
- Planning for downlinking housekeeping data. The Mars Express S/C produces daily an amount of h/k data over 6 packet stores. The amount of data produced is fix and occurs a specified, known in advance instants, does not depend on performed operations and has to be always downloaded with an higher priority with respect to scientific data. H/k data does not add complexity at modeling level, but the amount of data generated is not trivial and it makes harder to accommodate scientific operations. This table specify the packet store that has to be dumped once a day and their capacity:

Packet Store	Capacity (bits)
AC	900000
EV	1050000
DM	30000000

DI	25000000
AO	60000000
PH	20000000

The dumping of these packet stores cannot be fragmented, once started has to be finished.

- The time elapsing between when a scientific observation is performed and related data are downloaded should be reduced as much as possible, to preserve the validity of acquired data.

Input for this step: PORs files, plan for operations and communications from the previous step

Output for this step: Plan for dumping data, i.e. timed commands to dump the on board memory

2.6 Planning for Uploading Commands

The problem consists in the generation of a sequence of commands for uploading the MDAF-like files of the chosen experiment to perform first from Earth to the on-board memory of the S/C, in time for being executed when planned, and then from the on-board memory to the mission timeline to start the execution.

Commands are sent to the spacecraft during a ground station pass (during the uplink windows previously allocated), where they reside in a time-ordered buffer and are released for execution driven by the commands time-tags. Commands need to be uplinked with sufficient time margin before execution to provide safe and coherent operations.

What is important in an MDAF file is the number of TeleCommands TC and when they have to be executed. The following table specifies the number of TCs and their timing for pointing, maintenance, operation and dumping:

Operation	#TC	Timing
Pointing	16	In the pointing switch window
Maintenance	30	In the maintenance window
Science - HRSC	23	In the operation window
Science - OMEGA	20	In the operation window
Science - MARSIS	11	In the operation window
Science - PFS	7	In the operation window
Science - SPICAM	3	In the operation window

Science - ASPERA	2	In the operation window
Download - Science	2	Start/End Dumping
Download – H/K	1	Start Dumping
Data Production	As in the POR file	As in the POR file
Trigger to the MTL	1	At the planned time

The process can be hence synthesized in the following steps:

1 Uploading the MDAFs in the dedicated on-board memory;

2 Transferring the MDAFs (via a specific TC) from the on-board memory into the mission timeline (MTL). The MTL is a buffer in which all uplinked TCs are stored and ordered by execution time

The first point requires planning a set of timed uploading commands in which each of the MDAFs can be uploaded to the S/C. The second instead requires the plan of a set triggering commands to start the transfer of the MDAFs to the MTL. Of course the first plan has to consider the availability of the ground passes while the second the size of the mission timeline.

The total capacity of the MTL is 130 TCs, which has to take into account both the triggering commands to transfer the MDAF from the SSMM to the MTL and the TCs itself. The MTL is "consumed" when the MDAF is transferred (to transfer an MDAF requires approximately 1s for each TC in the MDAF) and it is freed when the TCs are executed.

To summarize, given a set of TCs to upload, the plan consists in:

- A set of timed commands to upload the files into the S/C on-board memory
- A set of timed commands to trigger the transfer of the MDAFs to the MTL
- A set of timed commands to upload the triggers for transferring the files into the S/C MTL

Objectives of the planning are:

- Load the MDAF into the mission timeline safely in advance
- Don't overload the mission timeline and maintain it as much full as possible

On a simple scenario, we are not taking into account the fact that also downlink commands generated as a result of the planning process described in Section 2.5 have to be uploaded. We consider only a fix set of commands depending on the chosen operation to be performed.

A more complex scenario will have to take into account:

- Backup uplink window: both for the MDAF and the triggering commands a backup uplink window is required in order to compensate possible communication failures.

- Uplink of downlink command planned to dump data generated by previously executed commands. This creates a loop between uplink and downlink planning that has to be balanced (the downlink plan can generate hundreds of commands to be uploaded and executed)

Input for this step: Plan for operations, pointing and communication from the first step and plan for dumping data from the second step

Output for this step:

- TCs to be uploaded, i.e. timed commands to perform experiments, achieve pointing, perform maintenance, dump data and manage the MTL
- plan for uploading TCs, i.e. an association between planned COM time intervals and groups of TCs files

3 Modeling Language Requirements

There is no restriction on the modeling language to be used while modeling the problem. However, we encourage competitor to use declarative languages widely used in the AI Planning community.

Acknowledgment

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