Science planning and operations for Mars Express

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I. Introduction

The Mars Express orbiter instruments collected their first scientific data orbiting Mars on the 14 January 2004. Since then the seven orbiter payload experiments have acquired outstanding scientific data. The scientific achievements were based on a science operations scheme characterized by variability, flexibility, and diversity.

Science operations for Mars Express constitute a challenging process. The science goals for all instruments are set ambitiously, and this is combined with changing observation conditions over the course of the mission. Mars Express’ elliptical orbit provides ideal science opportunities for the instruments, varying from monitoring the plasma environment (Aspera) to high-resolution surface imaging (HRSC and Omega). The variation in pericenter latitude throughout the nominal and extended mission ensures the possibility to obtain global coverage by the imaging instruments as well as seasonal and local time coverage by the instruments measuring the atmosphere and Mars environment. The diversity of science goals for various instruments, plus the continuous variability in the combination of the main mission parameters (pericenter latitude and illumination, occultations, eclipses, data rate) adds to the complexity of the Mars Express science operations. Further driving elements for the science operations design are the requirement for high accuracy of the science pointings, limited resources with regard to downlink capability and spacecraft power, and the fixed high-gain antenna, excluding combined science pointings and data relay.

Several methods are applied from mission design to science mission planning in order to foster an optimum science return: One of the key elements for planning is the “frozen orbit” concept, warranting a highly accurate long-term orbit prediction and thus a detailed long- to mid-term planning cycle. Another element is the two-step planning approach consisting of an iterative process on instrument mode level to find an optimal use of resources for the given scientific tasks in a particular period, followed by a checking and fine-tuning process on instrument command level.

II. Mars Express spacecraft, payload and orbit

The Mars Express orbiter instruments have been designed to fulfill a broad variety of science objectives concentrating (1) on the surface: global high-resolution photogeology and global mineralogical mapping, (2) on the subsurface: investigation of the subsurface structure a few kilometers down to permafrost, (3) on the atmosphere: global atmospheric composition and circulation studies, surface-atmosphere interactions, and interaction of the upper atmosphere with the solar wind, (4) on the general goals of making an inventory of water in atmosphere, subsurface throughout history and searching for traces of biological activity, and (5) on general physics: e.g. gravity anomalies, surface roughness. These diverse objectives result in very different requirements for each instrument regarding the observation conditions in terms of spacecraft altitude and pointing, illumination conditions, and frequency and duration of observations. These different requirements are shown in Figure 1.

The Mars Express spacecraft has been designed to perform the following general science pointing modes: nadir pointing, inertial pointing, spot pointing, and specular pointing. In addition, it is possible to modify these basic pointing modes by applying a series of 3 rotations around S/C directions. In this way it is possible e.g. to compensate for mis-alignments of instruments. The nadir pointing is carried out with a yaw correction to compensate the Mars rotation for the “observer” and has two sub-modes: across-track nadir and along-track nadir. For across-track nadir the spacecraft is tilted about the roll axis creating a ground track parallel to the sub-spacecraft ground track. The inertial attitude is used to point a payload towards a fixed direction: the attitude of the spacecraft is kept constant with respect to an inertial reference frame, i.e. one spacecraft axis of the spacecraft is oriented towards a fixed point in space. The direction of the resulting axis can be selected as either power-optimized or pre-defined. The spot pointing mode is aimed at pointing the optical instruments to a Mars surface feature and track it
whereas the specular mode is aimed at pointing the spacecraft’s fixed-mounted high-gain antenna to the surface point that results in specular reflection of the radio wave being directed to the Earth.

Furthermore, the Mars Express orbit (shown in Figure 2) was tailored to the diverse instrument observation requirements: the elliptical orbit provides optimal observing conditions for all scientific experiments, namely instruments measuring the atmosphere and Mars’ environment from high altitude and surface observing instruments that acquire their data primarily around pericenter. The average pericenter altitude during the nominal mission was 287 km. The apocenter altitude was lowered in May 2004 from 11560 km to 10100 km changing the orbital period from 7.566 h to 6.721 h.

Figure 2 also illustrates the “pericenter window” of about 20 min with best observation conditions below 500 km orbit height for the surface and subsurface instruments (HRSC, Omega, Marsis). However, the actual observation time within this window is further narrowed by the amount of data which can be downloaded.

A significant segment of each orbit is used to turn the fixed-mounted spacecraft antenna to Earth for data downlink and command uplink. These “downlink windows” cannot be used for pointed science observations. The location and duration of the downlink windows depend on ground station availability and can be defined by the scientists within certain constraints. The average downlink duration per day is 8-10 hours spread over several link sessions of about 3 hours each. Typically, one out of four pericenter windows is blocked for Earth communications.

The illumination conditions for the pericenter window vary over the mission: during the nominal mission three periods of 136, 179 and 140 days with the pericenter window on the day side were intermitted by 131 and 111 day periods with pericenters on the un-illuminated side for night time observations mostly used by Marsis. This corresponds to a 60:40 share of day- and night-time pericenters for the nominal mission.

The latitude of the sub-spacecraft point at pericenter covered all latitudes twice during the nominal mission and will cover it twice during the extended mission. Thus, targets at the same latitude can be observed during different seasons.

Figure 3 shows the evolution of the main orbit characteristics over the nominal mission, in particular the variation of the solar elevation angle at the sub-spacecraft point at pericenter, the latitude coverage and downlink rate representing the Mars-Earth distance.

The sub-pericenter points for a certain period are grouped in 11 clusters as a result of the 3:11 orbit resonance. For each cluster a new adjacent ground track is added after 11 orbits or 3 days. This resonance has been designed specifically for HRSC to ensure the ability to build mosaics for surface mapping. The longitude shift from one orbit n to its adjacent orbit n+11 is driven by the HRSC requirement for overlapping image strips: for all sub-pericenter points between ±60° the longitude shift is controlled by a about 10% side-overlap of adjacent HRSC image strips. The pericenter time (and thus also ground track) control is realized with small corrective acceleration or deceleration spacecraft manoeuvres using the regular reaction wheel off-loadings. This way the actual orbit is flown to the reference orbit or “to the long-term plan”. This concept of orbit control is called “frozen orbit”. It is a key element of the Mars Express observing strategy because it allows for a long lead time in the planning process.

III. Operational constraints

A number of operational constraints are drawn from the technical design of the spacecraft originating in turn from the available amount of power, the battery size, thermal limitations, details of the operations of spacecraft units (e.g. transmitter) etc. A large part of these constraints changes over the mission time because of their dependence on the Mars-Sun distance or other orbit-related parameters. In order to keep flexibility in the planning process many of these constraints are expressed as available resources rather than as predefined operational scenarios: for example the thermal limitation for Sun illumination on the spacecraft +Y panel is given as 450 Wh/m² instead of a fixed observation duration per pointing mode. Below a few crucial operational constraints are listed:

The maximum duration of an inertial pointing window in one orbit is 90 min. For nadir and nadir-like observations the maximum duration is 68 min per orbit. Not more than 2 science pointings per orbit are allowed.

Eclipses (Mars is between the spacecraft and the Sun) and occultations (Mars is between the spacecraft and the Earth) impose specific operational constraints: during eclipses the spacecraft batteries are the only source of power. Due to a failure in the solar panels circuitry design actually only 70% of the planned solar array power is available on Mars Express. This leads to longer battery recharge cycles and as a consequence to operational limitations for eclipses longer than 40 min. During the nominal and extended mission there are 5 eclipse periods. The eclipse duration reaches up to 90 min. During occultations, communication with the Earth is not possible. This imposes constraints for the selection of the downlink windows within an orbit.
The available downlink volume is another major operational resource. It is defined by the downlink rate, which varies from 28 kbps to 184 kbps depending on the Mars-Earth distance and on the allocated downlink time. Mars Express uses ESA’s groundstation in New Norcia and DSN stations. Thanks to the DSN support Mars Express has a much higher groundstation coverage, which increases the downlinked science data volume and also gives the scientists a better flexibility in planning science pointings and downlinks.

IV. Science planning cycles

The science planning is done using 3 levels:

1) long-term planning:
   science priorities are defined by the instruments’ Principal Investigators and the Project Scientist for a period of 6 months based on mission and instrument science objectives, on the mission phase (with implications on resources as power and downlink), and on previous measurements

2) mid-term planning:
   based on the long-term science priorities and the actually available resources a plan is established covering 4 weeks or 100 orbits

3) short-term planning:
   converts the 4-weekly mid term plan to commands covering a week period taking into account most recent orbit predicts and modifications due to changes in resource availability

The mid-term planning (see Figure 4) is the major planning level: the requests from all instruments have to be harmonized amongst each other and with respect to the operational constraints (i.e. spacecraft resources and downlink). This harmonization process is executed at instrument mode level using the MIRA (MEX Instrument Resource Analyser) software developed by Rutherford Appleton Laboratory. This software simulates the orbit, the spacecraft power balance, the data downlink, and checks for violations of constraints and flight rules (e.g. spacecraft illumination).

The input for the mid-term planning is delivered by ESOC and ESTEC (orbit and event files, groundstation availability) and by the instrument teams (instrument requests) which partly use their own software to plan the observations. The harmonization process typically starts 10-11 weeks before execution of the 4-week plan.

The result of this process is a mid term plan (MTP) covering 4 weeks and containing the following files:
- pointing request file: timeline of all spacecraft pointings
- instrument requests timeline on mode level

This output is delivered to ESOC eight weeks before execution of the 4-week plan. ESOC checks this plan with more detailed models. If necessary, changes are implemented. The mid-term plan is finally frozen four weeks before execution.

The updated and finally frozen mode level instrument plans are semi-automatically converted into instrument commands. This task is split up into 4 commanding periods covering one week each. The instrument command file generation is carried out by the Rutherford Appleton Laboratory in a feedback-loop with the instrument teams so that they confirm the final command files. After this confirmation the instrument command files (covering one week) are sent to ESOC 10 days before execution. ESOC integrates payload and spacecraft commands. Up to this moment all instrument requests on mode and on command level were relative to pericenter. During the last processing steps ESOC converts the relative times to absolute times using the most recent orbit predicts—typically 2-3 days “old”. The final combined command files are uploaded to the spacecraft 2-3 days before execution and are then carried out per time-tagged timeline.

The process described above is depicted in Figure 4.

V. Experience and results after more than two years of Mars Express science planning

From its first orbit around Mars on the 4. January 2004 to the 31. December 2006 the Mars Express spacecraft has orbited the Red planet 3832 times with 3 to 4 orbits per day. Out of these nearly 4000 orbits about 60% have been used for science observations, 25% for communications, and 15% for specific spacecraft needs (eclipses, conjunction, commissioning etc.).

During this period 34 mid-term 4-week cycles have been successfully planned. The mid-term planning concept proved to be effective and gave the instrument teams a very high level of control and flexibility in using spacecraft and groundstation resources. The major resources like pericenter window time, available downlink time were used close to 100%. In addition, new science pointing modes have been implemented which were not foreseen at the beginning of the mission: spot pointing, specular pointing, and the combination of more than one across pointing angle in a nadir pointing window. The original flight baseline has been expanded by controlling resources rather
than using predefined scenarios. The 70% power problem has been fully incorporated in the mid-term planning process.

The Mars Express spacecraft showed excellent performance, partly exceeding the numbers originally specified:
- the orbit position of the spacecraft is measured with an average accuracy of better than 200 m
- the average difference between the one week in advance predicted and the real position is 2 km where the main component of the error is along the orbit trajectory and corresponds to about 0.5 to 1 s
- the accuracy of the spacecraft attitude knowledge is 0.01 deg

A number of special observations and activities has been conducted in addition to the “nominal” science plan: Phobos and Deimos observations, Phobos shadow observations, communication tests and joint observations with the NASA Mars Exploration Rovers Opportunity and Spirit, Marsis antenna deployment after one year of routine operations.

During these 3800 orbits about 2300 Gbit of raw (for some instruments: compressed) science data have been acquired. These data are analyzed by the instrument teams and can be used by the general public via the ESA Planetary Science Archive. Since the arrival at Mars in December 2003 the Mars Express instrument teams together with their associated science teams have been publishing more than 200 papers.

The Mars Express mission has been extended by ESA for a second Mars year until October 2007. The science objectives are mainly to accomplish remaining global coverage, to achieve the original Marsis science goals, to study periodic time variations of atmospheric parameters and variable surface phenomena, and to revisit areas of Mars Express science discoveries.

The lifetime of the Mars Express spacecraft is mainly defined by its fuel reserves (it was 35 kg at the end of the nominal mission with ca. 2.0-2.5 kg year fuel consumption per year), and by the battery degradation.

Figure 5 gives an overview about the orbit and resources of the extended mission compared to the nominal mission.

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**Figure 1.** Variety in observation requirements of MEX instruments in terms of illumination conditions, altitude, and pointing type
Figure 2. Mars Express orbit characteristics. The initial orbit (blue) was changed to the final orbit (red) in April 2004.

Figure 3. Evolution of Mars Express downlink rate, pericenter latitude, illumination conditions, and local time over the nominal mission.
Figure 4. Overview of Mars Express mid-term planning cycle, covering a 4 week period (=100 orbits).

Figure 5. Mars Express nominal mission and extension 1 timeline. The colored bars show the average expected downlink volume per day with the colors indicating the illumination conditions from red (dayside pericenters with Sun elevation higher than 60 deg) to magenta (night side pericenters with Sun elevation lower than -15 deg).
Figure 6. Mars Express illumination conditions for nominal and extension 1 mission:
- x-axis shows mission days (starting 14-January 2004) and covers the nominal mission plus extension 1
- y-axis shows true anomaly (0 deg is pericenter, 180 deg is apocenter) which describes the s/c position in orbit
- plot show isolines of sun elevation angle of the sub-s/c point at a given orbit (day) for a given position in orbit

Figure 7. Mars Express ground track pattern with the 11:3 resonance over 4 weeks (or 100 orbits). The red triangles depict the pericenter, the green strips show the HRSC image swath below 500 km s/c altitude. The map colors represent Mars topography, based on the Mars Global Surveyor MOLA experiment.
Figure 8. Mars Express long term orbit evolution taking into account the planned orbit maneuver in 2007 increasing the orbital period and changing the resonance from 11:3 to 18:5. The lower panel shows the eclipse seasons with the y-axis showing the duration of eclipses per orbit.
Abstract (205 words)
Mars Express is the first ESA planetary science mission to be fully operational in orbit: science operations started in January 2004 and successfully continue to date.

The science instruments on board of Mars Express have diverse science goals and science operations requirements, varying in pointing requirements, illumination conditions and distance to the Mars surface. The elliptical orbit of Mars Express was chosen in such a way that these diverse requirements are fulfilled during different periods of the nominal and extended mission. As a consequence, science opportunities and mission constraints on science operations (resource envelope, power considerations, thermal constraints) vary considerably throughout the mission. In order to maximize the science return for Mars Express under these diverse and variable conditions, a science operations concept was developed which is characterized by its flexibility. At the basis of this concept is the ‘frozen orbit’, with a period of 6.7 hours, which is accurately predicted for typically 6 months ahead. Medium term science planning is carried out on a monthly basis, interactively planning the science pointings and instrument operations within the modelled resource envelopes. During the short term weekly planning cycle the science planning, as well as up- and downlink on ESA and DSN ground stations, are finalized and executed.

Conclusions
Mars Express has a high degree of complexity, with multiple types of science pointings, a fixed high gain antenna, multiple ground stations, and high variability in both science opportunities and mission constraints. The science operations concept and practice for Mars Express have evolved to a highly flexible system. The flexibility is driven by the diverse science requirements and science opportunities (specific ground targets) of the instruments, and the high variability in the conditions (e.g. illumination) and resource envelope (e.g. energy, data rate).

The current science operations practice is the end result of close collaboration and interaction between various teams (seven principal investigator teams, ESA science operations and operations teams, Rutherford Appleton Laboratories), all aiming to make the best possible scientific use of the Mars Express space craft.