SP-1291
June 2009

MARS EXPRESS

The Scientific Investigations

European Space Agency

OPERATIONS AND ARCHIVING

Mars Express Science Planning and Operations

R. Pischel & T. Zegers

ESA/ESTEC, Research and Scientific Support Department, Postbus 299, 2200 AG Noordwijk, the Netherlands

Mars Express is the first ESA planetary science mission to be fully operational in orbit, and has been a remarkable success since science operations started in January 2004. The instruments on Mars Express have diverse science goals and science operations requirements, which vary in terms of pointing requirements, illumination conditions and distances to the Mars surface. The elliptical orbit of Mars Express was chosen in such a way that these diverse requirements would be met during different periods of the nominal and extended missions. As a consequence, the scientific opportunities and mission constraints on science operations (resources available, power considerations and thermal constraints) vary considerably throughout the mission. In order to maximise the science return for Mars Express under these diverse and variable conditions, a science operations concept was developed that is characterised by its flexibility. At the root of this concept is the 'frozen orbit', which is accurately predicted typically six months ahead. Medium-term science planning is carried out on a monthly basis, with iterative planning of the pointing and instrument operations within the modelled resource envelopes. During the short-term weekly planning cycle the science planning and the up- and downlink schedule to ESA and DSN ground stations are finalised and executed.

1. Introduction

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

Planning the science operations for Mars Express is a challenging process. The science goals for all instruments are ambitious, especially in view of the changing observation conditions over the course of the mission. The elliptical orbit of Mars Express provides ideal science opportunities for the instruments, which range from monitoring the plasma environment (ASPERA-3) to high-resolution surface imaging (HRSC and OMEGA). The variation in pericentre latitude throughout the nominal and extended missions 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 the Mars environment. The diversity of the science goals for the various instruments, plus the continual variability in the combinations of the main mission parameters (pericentre latitude and illumination, occultations, eclipses and data rate) add to the complexity of the Mars Express science operations. Further driving elements in the design of the science operations include the need for high accuracy in the science pointings, limited resources with regard to downlink capabilities and spacecraft power, and the fixed high-gain antenna, excluding combined science pointings and data relay.

From mission design to science mission planning, several methods have been applied in order to maximise the science return. One of the key elements in planning is the concept of the ‘frozen orbit’, which warrants highly accurate long-term orbit predictions and thus a detailed long- to mid-term planning cycle. Another element is the two-step planning approach, consisting of an iterative process at the instrument mode level to ensure the optimal use of resources for the given scientific tasks in a particular period, followed by a process of checking and fine-tuning at the instrument command level.

This chapter describes the science planning for the nominal mission and the first extension. While the general concept, requirements and constraints remained unchanged, details of the planning process and the teams responsible for science planning were modified later in the mission during the second extension.

2. Mars Express Spacecraft, Payload and Orbit

The Mars Express orbiter instruments have been designed to meet a broad range of science objectives, concentrating on:

— the surface: global high-resolution photogeology and global mineralogical mapping;
— the subsurface: investigation of the subsurface structure, down to a few kilometres into glacial deposits;
— the atmosphere: global atmospheric composition and circulation studies, surface–atmosphere interactions, and interaction of the upper atmosphere with the solar wind;
— general goals, such as making an inventory of water in the atmosphere, understanding the geological evolution and searching for traces of biological activity; and
— global physics, such as investigations of gravity anomalies.

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 the frequency and duration of observations (see Fig. 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 three rotations around the spacecraft axes. The nadir pointing is carried out with a yaw correction to compensate for the rotation of Mars and has two sub-modes: across-track and along-track nadir. For example, in 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, while the attitude of the spacecraft is kept constant with respect to an inertial reference frame, i.e. one axis of the spacecraft is oriented towards a fixed point in space. The direction of the remaining axis can be selected as either power-optimised or predefined. The spot pointing mode is aimed at pointing the optical instruments to a surface feature on Mars and to 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 Earth.

Furthermore, the orbit of Mars Express (Fig. 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 the Mars environment from high altitude, and surface observing instruments that acquire their data primarily around pericentre. The average pericentre altitude during the nominal mission was 287 km. The apocentre altitude was reduced in May 2004 from 11 560 km to 10 100 km, changing the orbital period from 7.566 h to 6.721 h.

Fig. 2 illustrates the ‘pericentre window’ of about 20 min with the best observation conditions below 500 km orbit height for the surface and subsurface instruments

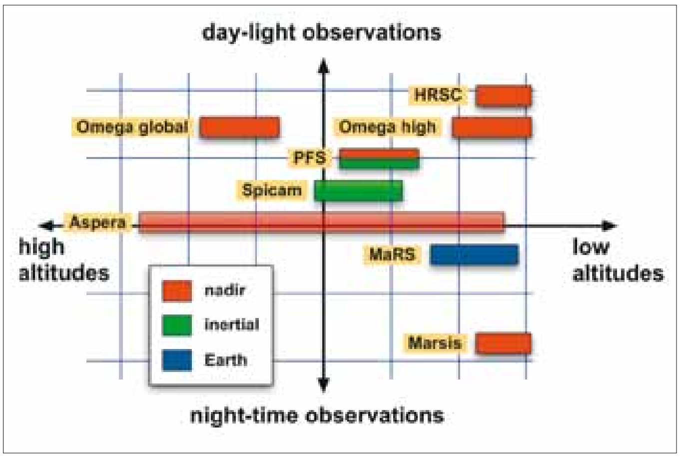


Fig. 1. The various observation requirements of the Mars Express instruments in terms of illumination conditions, altitude and pointing type.

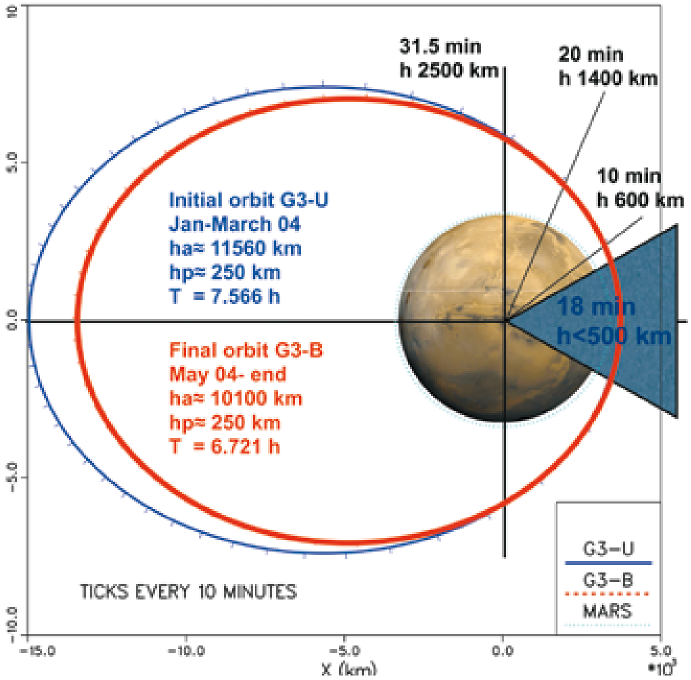


Fig. 2. Mars Express orbit characteristics for the nominal and first extended mission. The initial orbit (blue) was changed to the final orbit (red) in April 2004.

(HRSC, OMEGA and MARSIS). Within this window, however, the actual observation time is further narrowed by the amount of data that 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 the availability of ground stations, and can be selected by the scientists within certain constraints. The average downlink duration per day is 8–10 hours, spread over several sessions of about three hours each. Typically, one out of four pericentre windows is blocked for Earth communications.

The illumination conditions for the pericentre window vary over the mission. During the nominal mission, three periods of 136, 179 and 140 days with the pericentre window on the dayside were interspersed with 131- and 111-day periods with pericentres on the unilluminated side for night-time observations, mostly by MARSIS. This corresponded to a 60:40 share of day- and night-time pericentres for the nominal mission.

The sub-spacecraft point at pericentre varies during the course of the mission. During the nominal mission all latitudes were covered twice, and twice during the first 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 in the solar elevation angle at the sub-spacecraft point at pericentre, the latitude coverage and downlink rate representing the Mars–Earth distance.

The sub-pericentre points for a certain period are grouped into 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 three 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-pericentre points between ±60° the longitude shift is controlled by a side-overlap of adjacent HRSC image strips of about 10%. The pericentre time (and thus also the ground track) control is achieved by small corrective

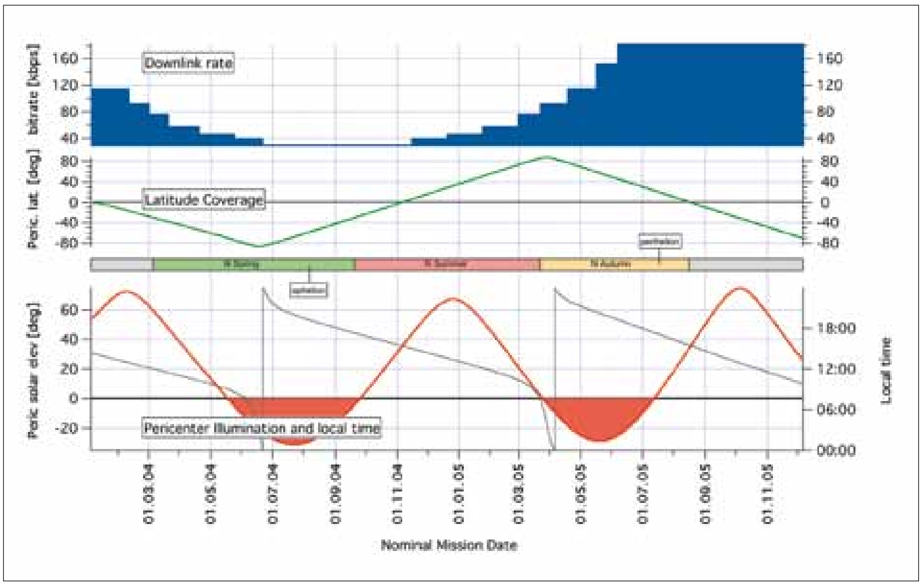


Fig. 3. Evolution of Mars Express downlink rate, pericentre latitude, illumination conditions and local time since the nominal mission.

spacecraft manoeuvres using the regular reaction wheel off-loadings. In this way, the actual orbit is flown to the reference orbit or 'to the long-term plan'. This concept of orbit control, called the 'frozen orbit', is a key element of the Mars Express observing strategy because it allows for a long lead time in the planning process.

3. Operational Constraints

A number of operational constraints are derived from the technical design of the spacecraft, and in turn from the amount of power available, battery size, thermal limitations, details of the operations of spacecraft units (such as the transmitter), etc. Many of these constraints change over the mission time because of their dependence on the distance between Mars and the Sun, or other orbit-related parameters. In order to retain flexibility in the planning process many of these constraints are expressed in terms of available resources rather than as predefined operational scenarios. For example, the thermal limitation for solar illumination on the spacecraft +Y panel is given as 450 W/m^2, rather than a fixed observation duration per pointing mode. Some of these crucial operational constraints are described in the following.

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. No more than two science pointings per orbit are allowed.

Eclipses (when Mars is between the spacecraft and the Sun) and occultations (when Mars is between the spacecraft and Earth) impose specific operational constraints. During eclipses the spacecraft batteries are the only source of power. Due to a failure in the solar panel circuitry design only 70% of the planned solar array power is actually available on Mars Express. This leads to longer battery recharge cycles and, as a consequence, to operational limitations for eclipses lasting longer than 40 min. During the nominal and the first extended missions there were five eclipse periods. The eclipse duration in each of these periods reached up to 90 min. During occultations, communication with Earth is not possible, and this imposes constraints on 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 to 184 kbit/s, depending on the Mars–Earth distance and on the allocated downlink time. Mars Express uses ESA's ground stations New Norcia in Australia and Cebreros in Spain and as well NASA's Deep Space Network (DSN) stations. Thanks to the support of the DSN, Mars Express has

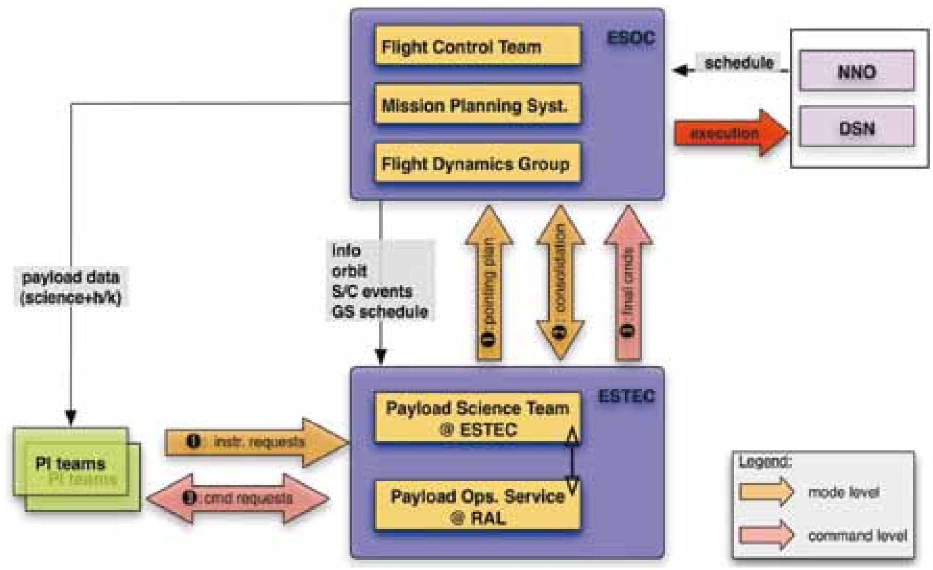


Fig. 4. Overview of the Mars Express mid-term planning cycle, covering a four-week period (=100 orbits).

a much higher ground station coverage, which increases the downlinked science data volume and also gives the scientists greater flexibility in planning science pointings and downlinks.

4. Science Planning Cycles

The science planning comprises three levels:

— Long-term planning: science priorities are defined by the Principal Investigators and the Project Scientists for each instrument, for a period of six months, based on the mission and instrument science objectives, on the mission phase (with implications for resources such as power and downlinks), and on previous measurements.
— Mid-term planning: based on the long-term science priorities and the resources actually available, a plan is drawn up covering four weeks or 100 orbits.
— Short-term planning: the four-week mid-term plan is subsequently converted to commands covering four periods of one week each, taking into account the most recent orbit predict and modifications due to changes in the availability of resources.

The mid-term planning (see Fig. 4) is the major planning level. The requests from all instruments have to be harmonised with respect to each other and to the operational constraints (i.e. spacecraft resources and downlink availability). This harmonisation process is executed at instrument mode level using the MEX Instrument Resource Analyser (MIRA) software developed by the Rutherford Appleton Laboratory in the UK. 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).

Inputs for the mid-term planning are provided by the European Space Operations Centre (ESOC) in Darmstadt and the European Space Research and Technology Centre (ESTEC) in Noordwijk (orbit and event files, ground station availability) and by the instrument teams (instrument requests), some of which use their own software to plan the observations. The harmonisation process typically starts 10–11 weeks before the execution of the four-week plan.

The result of this process is a mid-term plan (MTP) covering four weeks and containing the following files: a pointing request file, a timeline of all spacecraft pointings, and a timeline of instrument requests at the mode level. This output is delivered to ESOC eight weeks before the execution of the four-week plan. ESOC checks the plan with more detailed models and implements changes if necessary. 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 four command periods of one week each. The instrument command file is generated by the Rutherford Appleton Laboratory in a feedback loop with the instrument teams so that they can confirm the final command files. Once confirmed, the instrument command files (covering one week) are sent to ESOC ten days before execution. ESOC integrates the payload and spacecraft commands. Up to this moment all instrument requests at mode and command levels were relative to pericentre. During the last processing steps ESOC converts these relative times to absolute times using the most recent orbit predict, which is 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 in accordance with the time-tagged timeline. The process is depicted in Fig. 4.

5. Experiences and Results

In the period between its first full orbit around Mars on 4 January 2004 and 31 December 2006, the Mars Express spacecraft orbited the Red Planet 3832 times, with 3–4 orbits per day. Of these orbits, about 60% were used for science observations, 25% for communications, and 15% for specific spacecraft needs (commissioning, eclipses, conjunction, etc.).

During this period, 34 mid-term and four-week cycles were 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 ground station resources. The major resources such as the pericentre window time and the available downlink time were used close to 100%. In addition, new science pointing modes have been implemented that were not foreseen at the beginning of the mission, such as spot pointing, specular pointing, and the combination of more than one cross-pointing angle in a nadir pointing window. The original flight baseline has been expanded by controlling resources rather than using predefined scenarios. The problem of the 70% power has been fully incorporated into the mid-term planning process.

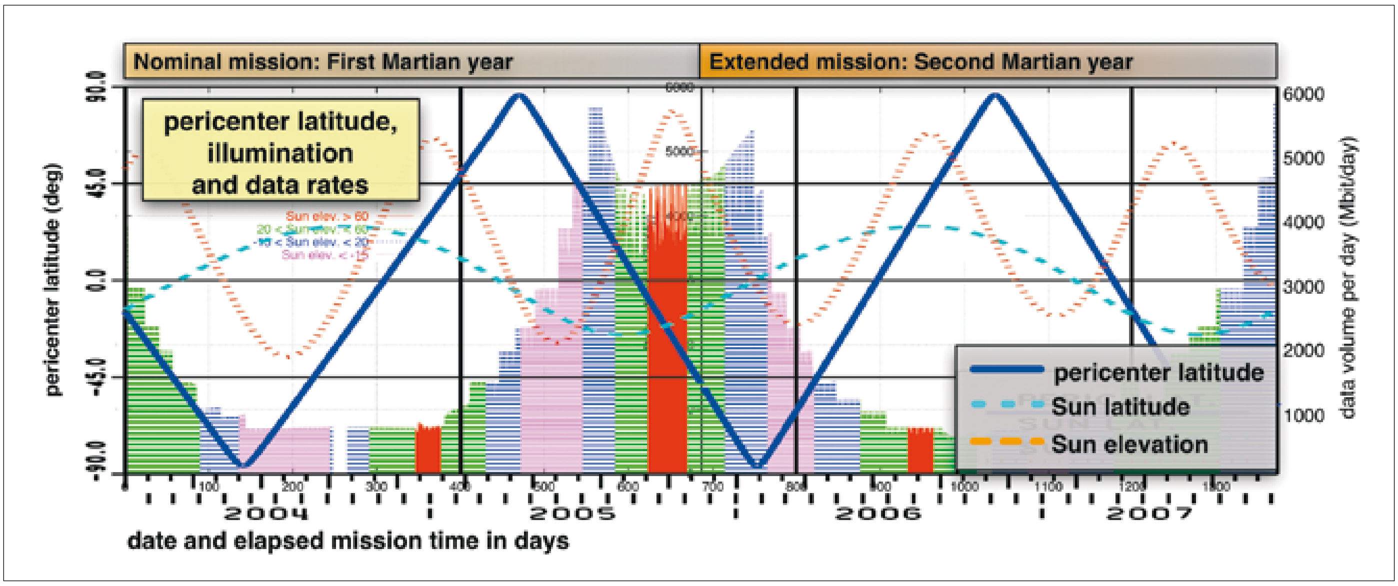
The Mars Express spacecraft has shown excellent performance that has partly exceeded the numbers originally specified:

— the orbit position of the spacecraft can be measured with an average accuracy of better than 200 m;
— the average difference between the position predicted one week in advance and the real position is 2 km, where the main component of the error is along the orbit trajectory and corresponds to about 0.5–1 s; and
— the attitude of the spacecraft is known to an accuracy of 0.01°.

In addition to the 'nominal' science plan, a number of special observations and activities have been conducted. These included observations of Phobos and Deimos and of the shadow of Phobos on the surface of Mars, communication tests and joint observations with NASA's Mars Exploration Rovers *Opportunity* and *Spirit*, and the deployment of the MARSIS antenna after a year of routine operations.

During these 3800 orbits about 2300 Gbit of raw (for some instruments compressed) science data were acquired. These data were analysed by the instrument teams and can be accessed by the public via the ESA Planetary Science Archive. Since the arrival of Mars Express at Mars in December 2003, the instrument teams and their associated science teams have published more than 200 papers.

ESA approved the first Mars Express mission extension for a second Mars year until October 2007. The main science objectives were to accomplish the remaining global coverage, to achieve the original MARSIS science goals, to study periodic time



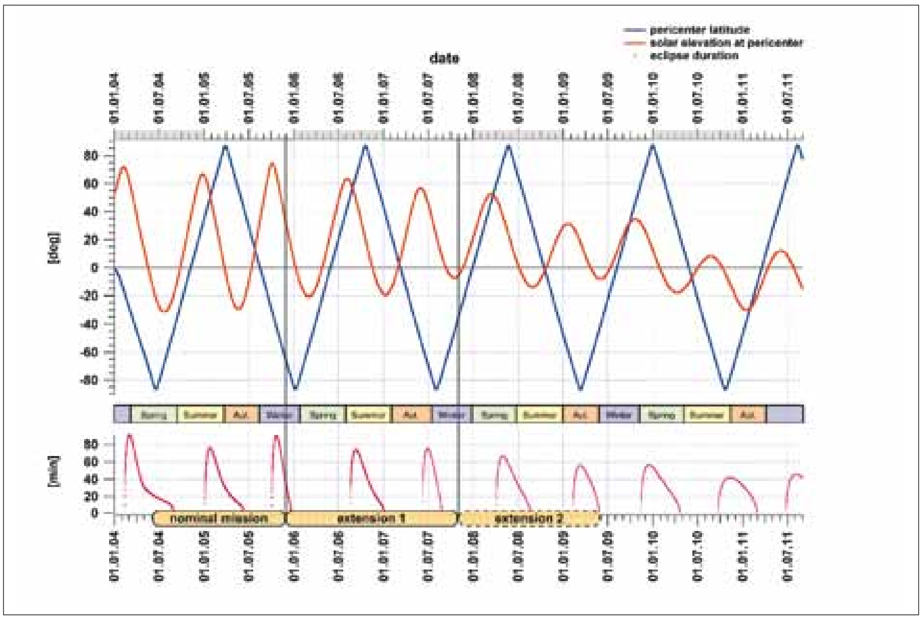


Fig. 5. Timeline for the Mars Express nominal mission and the first extension. The coloured bars show the average expected downlink volume per day; the colours indicate the illumination conditions from red (dayside pericentres with the Sun's elevation higher than 60°) to magenta (nightside pericentres with the Sun's elevation less than –15°).

Fig. 6. Mars Express long-term orbit evolution taking into account the orbit manoeuvre in November 2007 increasing the orbital period and changing the resonance from 11:3 to 18:5. The lower panel shows the eclipse season: the *y*-axis indicates the eclipse duration per orbit.

variations of atmospheric parameters and variable surface phenomena, and to revisit areas of Mars Express science discoveries.

The lifetime of Mars Express will depend on its fuel reserves – 35 kg of fuel remained at the end of the nominal mission (the spacecraft consumes about 2.0–2.5 kg of fuel per year) – and by the rate of battery degradation.

Figure 5 gives an overview of the orbit and resources of the first mission extension compared with those of the nominal mission. Figure 6 shows the long-term evolution of the Mars Express orbit.

6. 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 into 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 the resource envelope (e.g. energy, data rate).

The excellent science return of Mars Express is the end result of close collaboration and interaction between the various teams (seven Principal Investigator teams, ESA science operations and operations teams, Rutherford Appleton Laboratories), all of whom aim to make the best possible scientific use of the Mars Express spacecraft.