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Mars Express: 20 Years of Mission, Science Operations and Data Archiving

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Abstract
Launched on 2 June 2003 and arriving at Mars on 25 December 2003 after a 7-month interplanetary cruise, Mars Express was the European Space Agency's first mission to arrive at another planet. After more than 20 years in orbit, the spacecraft and science payload remain in good health and the mission has become the second oldest operational planetary orbiter after Mars Odyssey.

This contribution summarizes the Mars Express mission operations, science planning and data archiving systems, processes, and teams that are necessary to run the mission, plan the scientific observations, and execute all necessary commands. It also describes the data download, the ground processing and distribution to the scientific community for the study and analysis of Mars sub-surface, surface, atmosphere, magnetosphere, and moons.

This manuscript also describes the main challenges throughout the history of the mission, including several potentially mission-ending anomalies. We summarize the evolution of the ground segment to provide new capabilities not envisaged before launch, whilst simultaneously maintaining or even increasing the quality and quantity of scientific data generated.

Keywords Mars · Mission operations · Flight dynamics · Science operations · Data archiving

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1 Introduction

The Mars Express (MEX) mission was born following the failure of the Russian Mars 96 spacecraft, on a joint international effort to make use of the remaining flight-spare models of European instruments on-board Mars 96, adapting the existing Rosetta spacecraft platform design, to build a low-priced European Mission to Mars (Chicarro et al. 2004; Bibring et al. 2024; Martin et al. 2024). The mission was named after the rapid development time and alluded also to the fact that in 2003 Earth and Mars would be the closest they had been for 60,000 years. To supplement the Mars '96-derived instruments, MEX also included a sub-surface radar and carried the ill-fated Beagle-2 lander (Bridges et al. 2017).

The spacecraft was built by Astrium (now AIRBUS DS) in Toulouse, France, as prime contractor, at a fixed price of 60 M€ for the entire procurement programme, including subcontractors from across Europe. Much of the spacecraft avionics and ground systems were derived from Rosetta and procurement of the Soyuz-FG/Fregat launcher through the Russian/European joint venture Starsem, helped to keep the total cost of the initial mission within the overall budget of 150M€, which is only a small fraction of most other interplanetary missions.

The original mission design requirement was for the spacecraft to remain operational in Mars orbit for a minimum of one Martian year following the 7-month inter-planetary cruise. Fortunately, thanks to the great development and adaptation efforts by all teams involved, the mission remains fully operational after more than 20 years, making it one of the most successful and long-lived science missions ever developed.

A description of the mission elements and orbit is provided in Sect. 1. Section 2 describes all the operational elements of the mission. Data downlink, processing and archiving are briefly described in Sect. 3. Mission challenges are summarized in Sect. 4. Final conclusions and lifetime estimates are given in Sect. 5.

1.1 Spacecraft Platform

The design of the Mars Express spacecraft exploited heritage designs from existing spacecraft. The spacecraft platform and Reaction Control System (RCS) were derived from the Eurostar communication satellite platform with 2 rather than 4 propellant tanks: the solar arrays from the Globalstar platform. The Data Management System (DMS) and Attitude and Orbit Control System (AOCS) hardware and software were largely inherited from systems under development for the Rosetta spacecraft.

The spacecraft is a 3-axis stabilised orbiter with a fixed high-gain antenna, body-mounted instruments and two ∼5 m long solar panel 'wings' extending from the +/−Y-faces. The total launch mass was 1223 kg, including the spacecraft platform, 113 kg of payload instruments, the 60 kg Beagle 2 lander and 473 kg of bi-propellant: 178 kg Mono-Methyl Hydrazine (MMH) fuel and 295 kg Nitrogen Tetroxide (NTO) Oxidiser. The roughly cube-shaped structure was made from aluminium honeycomb with dimensions 1.7 m length, 1.7 m width and 1.4 m height and wrapped in black Multi-Layer Insulation (MLI).

The body-mounted High-Gain Antenna (HGA) is 1.65 m in diameter, connected to X- and S- dual band transponders used for communications, orbit determination and radio science observations. The X-band signal, amplified by a 65 W Traveling Wave Tube Amplifier (TWTA), allows downlink of science (and housekeeping) telemetry at high data rates, whereas the 5 W S-band signal is used in Safe Mode. Two omni-directional Low Gain S-band only antennas on the +/−Z-faces were used during Launch and Early Orbit Phase (LEOP) and could provide a 'back-door' for low bit rate (7.8125 bps) in case that the HGA was not correctly Earth-pointed. Telemetry is transmitted at information data rates varying from 9.3 bps (in Safe Mode) up to 228.5 kbps depending on the Mars-Earth distance. The spacecraft can be configured to receive telecommands at data rates between 9.3 bps (in Safe Mode) and 2 kbps. More information on communications and ground stations is provided in Sect. 2.5 below.

1.2 Scientific Payload

Mars Express has a wide range of scientific objectives covering the whole Martian system (Chicarro et al. 2004) from the geophysics of Mars interior and sub-surface, the geomorphology and geo-chemistry of the surface, the analysis of the atmospheric composition, properties, and dynamics from regional to global scale, reaching up to the ionosphere and plasma interactions of the magnetosphere with the solar wind. Mars Express is also uniquely designed to observe the two Martian moons: Phobos and Deimos (Witasse et al. 2014; Pätzold et al. 2024).

These mission objectives are addressed with a broad suite of science instruments (Wilson et al. 2024), summarized as follows:

- High Resolution Stereo Camera (HRSC), primarily used for geomorphological and surface mapping of Mars and its moons (Gwinner et al. 2016);
- Visible and Infrared Hyperspectral Imaging Spectrometer (OMEGA), used for spectral analysis of the surface and atmosphere (Bibring et al. 2007);
- Ultraviolet and Infrared Atmospheric Spectrometer (SPICAM) (Montmessin et al. 2017) to study atmospheric gases, aerosols, physical and chemical properties;
- Infrared Planetary Fourier Spectrometer (PFS) (Giuranna et al. 2021) which contributes to the chemical and physical study of the atmosphere, and allows temperature retrievals for both atmosphere and surface;
- The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) to characterise physical properties of the surface, subsurface and ionosphere (Orosei et al. 2015);
- The Analyser of Space Plasmas and Energetic Ions instrument (ASPERA) to characterise the ionospheric / thermospheric environment (Barabash et al. 2006);
- The Radio Science Investigation experiment (MaRS), which uses the communication radio link to probe the neutral atmosphere and ionosphere, as well as the surface and solar corona (Pätzold et al. 2016);
- The Visual Monitoring Camera (VMC), a wide-angle context camera that now is being used to study Martian weather and meteorology (Hernandez-Bernal et al. 2024);
- Finally, Mars Express also uses the UHF Radio System, MELACOM, originally designed to communicate with Beagle-2, to perform relay communications with the surface assets, and to perform Mutual Occultation Experiments to retrieve ionospheric profiles (Svedhem et al. 2022; Parrott et al. 2024).

1.3 Beagle 2

In addition to the scientific instruments mounted directly on the spacecraft, Mars Express delivered the Beagle 2 lander to Mars and was intended to act as its orbital relay, forwarding commands from Earth to the lander and returning data. It was conceived by Professor Colin Pillinger of the Open University in collaboration with the University of Leicester to look for evidence of past life on Mars, assess if conditions were ever suitable and test for present-day biological activity. It was named after the Royal Navy ship HMS Beagle, that carried Charles Darwin on his round-the-world voyage.

The lander was disk-shaped with diameter of 0.65 m and depth of 0.25 m. The main body contained the platform systems (battery, heaters, telecoms, processor etc.), environmental sensors and the Gas Analysis Package (GAP) instrument, including ovens and a mass spectrometer. The remaining instruments were in the Payload Adjustable Workbench (PAW) on the end of a 0.75 m robotic arm. These included a pair of stereo cameras, a wide-angle camera, meteorological sensors, a microscope, two types of spectrometer (Mössbauer and X-ray) and a torch to illuminate surfaces. The PAW also housed a corer/grinder and a 'mole' for collecting rock and soil samples for analysis. Candidate rocks for analysis would be identified by the cameras, the grinder would expose material below the weathered surface for analysis by the microscope, or the spectrometers or return samples to the GAP for further analysis. The mole could both crawl up to several metres across the surface or burrow 1 m vertically to collect samples (Wright et al. 2003).

Beagle 2 was released from Mars Express as the spacecraft approached Mars and was due to land at *Isidis Planitia* on 2 June 2003. Repeated attempts were made to contact the lander, but to no avail. In February 2004 it was declared to be lost. An ESA/UK Government board of inquiry was unable to determine what was the actual cause (Bonnefoy et al. 2005). In December 2015 NASA announced that the High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter (MRO) had located the remains of the lander. The pictures showed that the probe had landed in one piece, but one of its solar panels had failed to deploy and had remained obscuring the lander's antenna, thus preventing it from communicating with relay orbiters (Bridges et al. 2017).

The board of inquiry also made 19 recommendations for future lander missions (Bonnefoy et al. 2005). These recommendations were taken into consideration in the design of the ExoMars Schiaparelli Entry, Descent and Landing Demonstrator Module (EDM) and of the joint ESA/Roscosmos Descent Module that would have delivered the Rosalind Franklin rover to the surface of Mars in June 2023, which was unfortunately cancelled and will be replaced with a new mission design, currently under development.

Although the Beagle 2 mission failed, two units on the Mars Express orbiter, associated with the lander mission – the Visual Monitoring Camera (VMC) and the MELACOM Radio – have subsequently found new roles (see Sect. 4.5).

1.4 Launch, Cruise, and Orbit Insertion

Mars Express was launched from the Baikonur Cosmodrome on a Soyuz-FG/Fregat on 2 June 2003 at 17:45 UT and was placed briefly in a parking orbit. The Fregat upper stage was then fired again to put MEX into a Mars transfer orbit and then separated from the spacecraft 3 minutes later. The initial trajectory was slightly off pointed from Mars such that the Fregat booster would coast into inter-planetary space rather than crashing into the planet, to comply with planetary protection requirements. Two days later Mars Express performed a manoeuvre to put the spacecraft on course for Mars marking the end of the Launch and Early Orbit Phase (LEOP) of the mission and the start of the interplanetary cruise phase.

The early phases and interplanetary cruise had been expected to be quiet, dedicated to commissioning, trajectory maintenance and preparations for the Beagle 2 release and Mars Orbit Injection phase, as illustrated in Fig. 1. However, they turned out to be very challenging, due to a series of anomalies and unexpected events which kept the Mission Control Team busy from launch to arrival at Mars, amongst them 51 platform anomalies, 30 payload anomalies, and 12 Safe Modes, which affected many of the platform sub-systems and required significant effort to update the ground and onboard SW systems (Companys et al. 2004; Fischer et al. 2006).

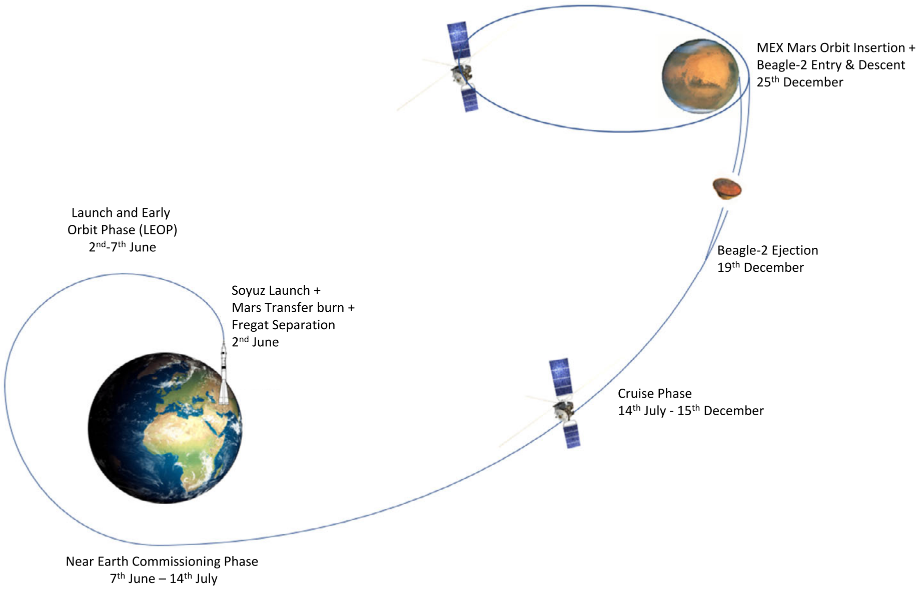

Fig. 1 Illustration of Mars Express Launch and Early Orbit Phase (LEOP), Near Earth Commissioning, Cruise Phase, Beagle-2 separation, and Mars Orbit Insertion (MOI)

Some of the issues experienced during LEOP and cruise were solved within days or weeks, but some others had significant implications for the whole mission (e.g. miswiring of solar arrays caused a reduction in power available to <70%, see Ferretti et al. 2006 and Sect. 4.1.1). Most issues occurred because of the accelerated development schedule of this 'express' mission. However, as they were a re-use of systems under development for Rosetta, that mission and subsequently Venus Express benefitted from the experience of Mars Express by effectively debugging them in flight.

The spacecraft arrived at Mars in December 2003, after a 400 million km journey and a series of course corrections. The separation of the lander shortly before Mars Orbit Insertion (MOI) required precise targeting to ensure redirection of the satellite away from a planetary collision course. Rapid determination of a new trajectory was required in case a contingency correction was necessary before the lander was prepared for the MOI on 25 December 2003. To support the navigation effort, Doppler and Delta Differential One-way Range (DDOR) data were regularly acquired on NASA's Deep Space Network (DSN) antennas in addition to the daily passes on New Norcia (Han et al. 2004).

The Beagle-2 lander was released on 19 December 2003 on a ballistic course towards the surface (Morley et al. 2004), as illustrated in Fig. 2. This was the first ever ballistic release of lander from hyperbolic trajectory before orbit Mars insertion. One day later a small manoeuvre was performed to put the spacecraft on course for Mars Orbit Insertion (MOI). In the early hours of the morning on Christmas Day the spacecraft slewed to the MOI attitude before disappearing behind Mars. The Main Engine then fired for 37 minutes putting MEX into a highly elliptical 400 km x 180,000 km initial capture orbit with an inclination of 10°. On the same day, the Beagle-2 lander entered the Martian atmosphere, unfortunately no signals were ever received from the lander, and it was subsequently declared lost.

Over the next few days, starting on 30 December 2003, the main engine and thrusters were used in a series of manoeuvres to bring Mars Express from this capture to its opera-

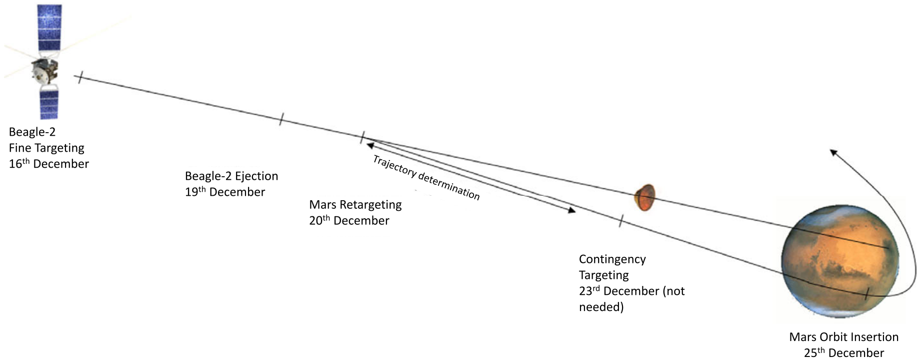

Fig. 2 Illustration of Mars Express trajectory for Beagle-2 release and Mars Orbit Insertion

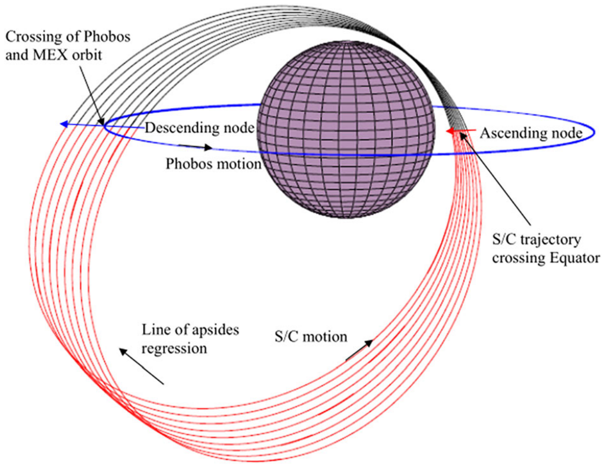

Fig. 3 MEX elliptical orbit around Mars, illustrating the latitudinal drift of the pericentre/apocenter, which allows for seasonal crossings of Phobos and MEX orbits every 4 to 6 months

tional orbit. The apocentre was lowered and inclination increased, putting the spacecraft in a 258 km x 11,560 km near polar (86.3° inclination) orbit with a period of 7.5 hours.

1.5 Orbit Design and Evolution

The initial science orbit design (Hechler et al. 2003) consisted in a nearly resonant eccentric orbit, using the gravity coefficients of Mars to enable global coverage at balanced sun illumination conditions for optical and radar payload, and provide regular communications relay contacts to the lander. The global coverage requirement implied a near-polar orbit and the near resonance with Mars rotation. The available propellant prevented the satellite from reaching a low altitude circular orbit, therefore an eccentric orbit was chosen, with drifting ascending node (for the longitude coverage) and argument of pericentre (for the latitude coverage), as illustrated in Fig. 3.

An update to the strategy was integrated during the cruise to Mars (Hechler et al. 2005) to rebalance the initial pericentre illumination conditions towards the illuminated day side

Table 1 Evolution of main events and relevant orbital parameters of Mars Express at various key dates

Date	Inc. (deg)	Ecc. (deg)	Period (days, h, min)	Periapsis altitude (km)	Apoapsis altitude (km)	Event
2003/06/02						Launch
2003/12/19	13.5	1.5				Beagle Separation
2003/12/20	9.8	1.67				Re-targeting for Mars Insertion
2003/12/25	9.9	0.96	∼10 days	434	183,386	Mars Orbit Insertion
2004/01/04	86.6	0.89	29 h 20 min	247	38,873	Apoapsis lowering manoeuvres
2004/01/07	86.6	0.72	12 h 20 min	274	18,706	Apoapsis lowering manoeuvres
2004/01/11	86.6	0.68	10 h 02 min	275	15,392	Apoapsis lowering manoeuvres
2004/02/01	86.5	0.61	7 h 35 min	270	11,570	13/4 Mars Resonance
2004/05/10	86.6	0.57	6 h 43 min	266	10,182	11/3 Mars Resonance
2007/12/17	86.7	0.58	6 h 50 min	314	10,296	18/5 Mars Resonance
2009/01/19	86.8	0.58	6 h 53 min	305	10,419	27/5 Mars Resonance
2010/03/22	86.8	0.58	6 h 59 min	361	10,521	88/25 Mars Resonance
2018/02/04	87.0	0.57	6 h 59 min	365	10,492	23/21 Phobos Resonance
2024/01/01	87.1	0.58	6 h 59 min	355	10,508	23/21 Phobos Resonance (present)

of the planet, favourable to the optical instruments, delaying the night side ones favourable to the radar. It was implemented from February to May 2004 via a 13/4 resonance, that is 13 orbital revolutions of MEX matched 4 rotations of Mars. In May 2004 the orbit was modified to a 11/3 resonance, improving night observations, even though the radar could be deployed only in mid-2005. Following plans for mission extension beyond 2008, it was realised that a good HSRC coverage had already been achieved, but at a high propellant cost. It was decided to abandon the tight pericentre control (Müller et al. 2006; Carranza et al. 2007). A retargeting to support NASA's Phoenix landing occurred in 2007, then a switch to a 18/5 resonance, better in terms of day light observations and Sun eclipses, was performed. Additionally, the optimisation of Phobos close encounters was initiated. In 2009, Mars Express entered a 27/5 Mars rotation resonance, then 88/25 in March 2010. In 2018, a final correction was implemented to reach a 23/21 resonance to Phobos, that is 23 MEX orbit revolutions currently match 21 revolutions of Phobos around Mars (see Pätzold et al. 2024). As of 2024 it is not planned to make any further changes due to the lack of fuel. Table 1 shows a summary of the main orbital elements at the beginning of the mission and at present.

To date, the main driver of the orbit strategy remains the optimisation of Phobos close encounters. Thanks to the drift of the argument of pericentre of Mars Express of 1 revolution every 609 days, the orbits of the spacecraft and the moon cross each other every 130 or 165 days. Tiny adjustments of the orbital period performed in advance are enough to obtain close encounters, only limited for safety reasons to either 1000 seconds of relative phase or 50 km of orbit distance (see Pätzold et al. 2024).

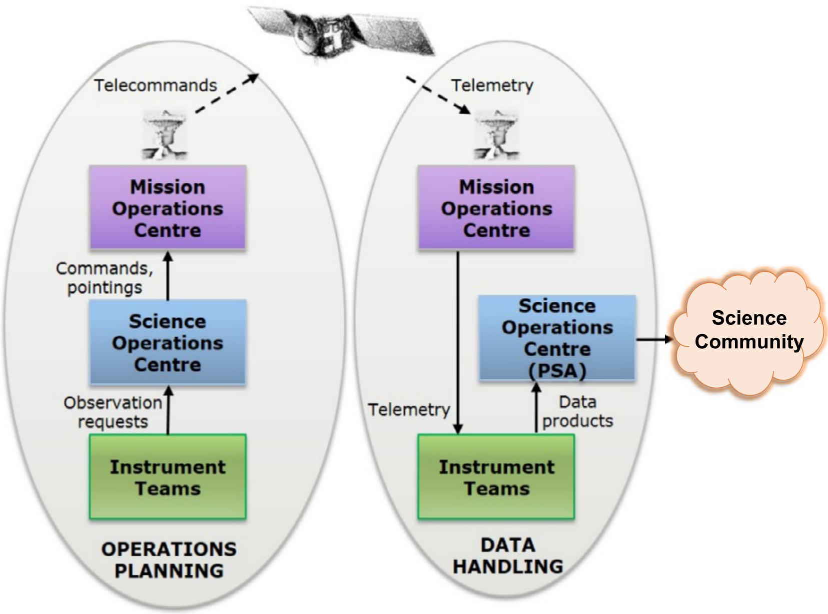

Fig. 4 Simplified illustration of the main actors involved in Mars Express operations: PI Instrument Teams, Science Operations and Mission Operations Centres all work together for the planning of operations and handling of data products before ingestion in the Planetary Science Archive (PSA) and distribution to the science community

2 Operations

Mars Express mission operations are performed by a multi-centre, multi-disciplinary Ground Segment including scientists and engineers involved in the operations planning and data handling. The main actors, shown in Fig. 4, are the following:

- **Instrument Teams:** Located at each Principal Investigator (PI) research institution in Europe, responsible for the operations and data processing of each instrument. They must define the scientific priorities and routinely provide the instrument observation requests and commanding sequences necessary to achieve the scientific goals of the mission, also including calibration and instrument engineering observations. They are also in charge of the instrument data-processing, data calibration and data analysis, and finally delivery of data products to the SOC for archiving.
- **Science Operations Centre (SOC):** Located at the European Space Astronomy Centre (ESAC) in Madrid, Spain. Responsible for the coordination of all science operations activities and the delivery of instrument commands and pointing requests to the MOC for execution. SOC is also responsible for the final archiving of the instrument data processed by the PI teams and public distribution to the science community via the Planetary Science Archive (PSA).
- **Mission Operations Centre (MOC):** Located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. Holds the Flight Control Team (FCT) responsible for the overall mission operations, managing all spacecraft subsystems and coordinating the ground stations to uplink all telecommands to the Spacecraft and download all house-

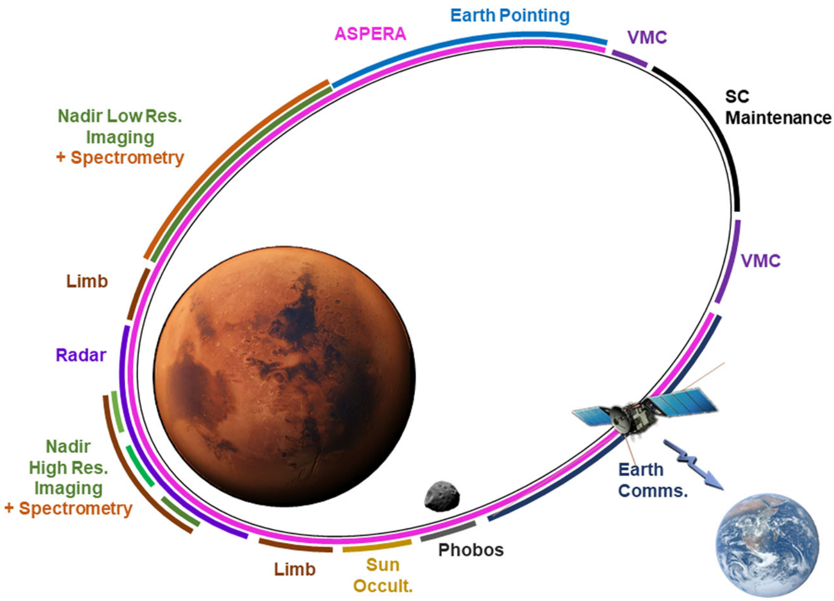

Fig. 5 Simplified timeline illustration of the Mars Express orbit. High resolution science observations are done at pericentre (Nadir imaging, spectroscopy, and radar) with additional limbs, occultations, Phobos, and other observations at various distances. Low resolution imaging and spectroscopy is extended to cover mainly the illuminated side of Mars. ASPERA plasma monitoring is operated continuously, except around SC maintenance periods, which occur every ∼24 h at apocenter. ASPERA gaps around maintenance are also used for VMC global imaging. Earth communications is done whenever the stations are available and the spacecraft is pointing to Earth

keeping and science telemetry packets. The MOC also includes the Flight Dynamics (FD) team, responsible for the spacecraft pointing attitude and orbit control.

2.1 Summary of Operational Capabilities and Constraints

Mars Express has great scientific capabilities derived from its broad payload suite and unique orbital characteristics. The selection of a medium sized spacecraft, with a fixed HGA and body mounted instruments following a highly eccentric near-polar orbit allows observations at varying scales and conditions. The long-term evolution of the orbit precession ensures stable and slow-changing seasons and long observation campaigns, which allows both global monitoring and mapping of specific targets, plus regular flybys of Phobos.

The main objective of the MEX Science Operations Centre and Mission Planning System (MPS) teams is to meet the science goals of the mission, generating commanding products that control the space and ground segment, respecting all constraints imposed by power, data, ground station availability and spacecraft pointing requirements.

The main driver for the mission is the fixed high-gain antenna (HGA), which needs to be pointed to Earth during all communication passes. This allows for approximately 1.5 to 3 hours of science observations every orbit, as illustrated in Fig. 5, resulting in an approximate science operations duty cycle of 20 to 40%, with high variability depending on the season. Most science observations are focused around pericentre at lower altitudes, although global context observations are also performed at higher altitudes up to the apocentre, depending on solar illumination and season. ASPERA observations are also an exception since they are

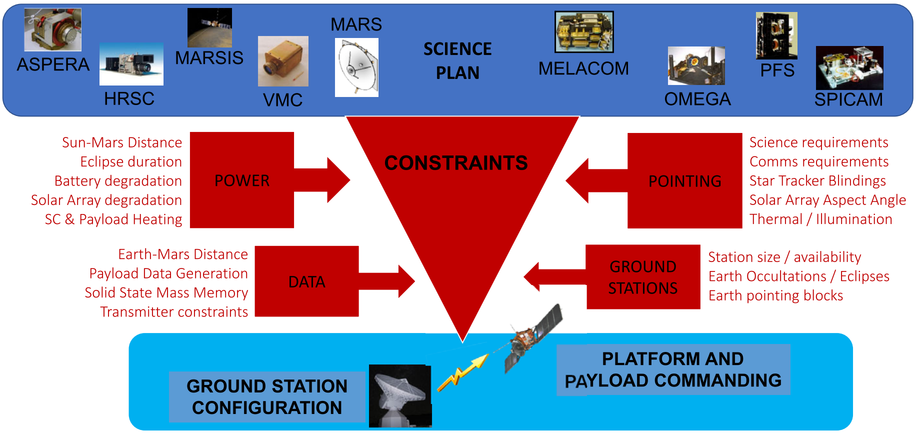

Fig. 6 The Mission Planning Problem

operated almost continuously, while the Radio Science experiment is operated only during Earth communication passes.

The excellent performance of the spacecraft has allowed the payload to be operated at almost any point in the orbit, while adhering to technical rules and constraints to ensure mission safety. These constraints cover all subsystems of the spacecraft, including electrical power, communications, thermal, propulsion, commanding, and more, as shown in Fig. 6 and Fig. 7.

The orbit of the spacecraft around Mars and its evolution around the solar system impose constraints for the planning of science observations, ground station passes and other mission operations. Communications depend heavily on Earth-Mars distance (data rate and latency) and require constant pointing and visibility to Earth, which may be blocked by other science pointings and/or earth occultation periods. Also, the limited availability of ground stations imposes further communication constraints, and the mission makes use of a network of antennas with varying capabilities from ESA and other international partners (see Sect. 2.5).

Pointing attitude is constrained by thermal and illumination constraints with specific flux/illumination limits for the different faces of the spacecraft as well as specific field of view constraints for pointed instruments. Moreover, the power produced by the solar panels is based not only on the distance to the Sun but also on the spacecraft orientation and solar array rotation. Power is also particularly limited by eclipses, when MEX is not illuminated by the sun as it is occulted by Mars, causing a significant discharge of the battery that must be closely monitored. This restricts the science operations near/during eclipse and requires additional warm-up pointings to ensure the thermal conditions of the spacecraft. Additionally, solar conjunction periods for 4 weeks roughly every 2 years limit operations.

2.2 Routine Operations Planning

Mission and science operations planning is a routine iterative process performed at long (>6 months), medium (4 weeks) and short (~ 1 week) term timescales. The instrument teams, science planners at the SOC, and mission planners in the Flight Control Team distil the instrument science plan and platform operations into a coherent set of weekly command products for uplink to the spacecraft, in coordination with Flight Dynamics, and produce a schedule of ground station passes.

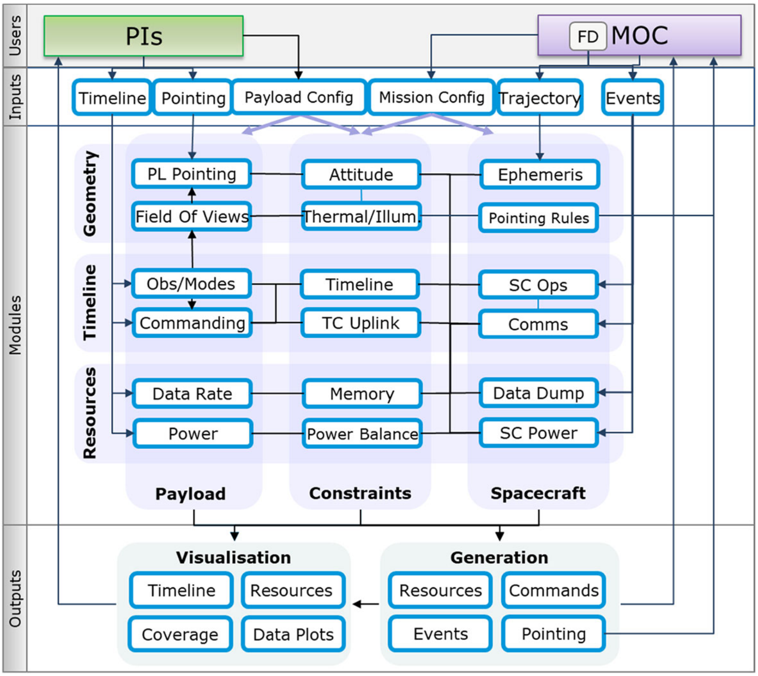

Fig. 7 Science Operations system diagram, showing all the elements modelled and simulated during the planning process. The diagram is shown from the SOC perspective, with the observation requests coming from PI teams, for the generation of commanding and pointing products for the MOC

This process is driven by scientific requirements from the instruments, geometrical events driven by the orbit trajectory and operation requirements of the spacecraft sub-system. Figure 7 shows a summary of the elements modelled and simulated during the planning process for science operations. Planning payload and platform operations require powerful and detailed planning tools, with a high degree of software flexibility that has proven useful when adapting to anomalies and challenges throughout the long mission lifetime (Schulster et al. 2006; Rabenau et al. 2010; Merritt et al. 2018; Muñiz Solaz et al. 2022).

2.2.1 Long Term Planning (LTP)

This is the first phase of the mission planning processes and starts at least 6 months in advance of the execution period, when Flight Dynamics team provides the long-term events and reference trajectory, typically propagated over several years to cover the entire mission extension phase. These predicted ephemerides are processed by the SOC and distributed to the science community in SPICE format (Costa 2018). The predictions have an accuracy of ± 10 seconds, which is enough as a baseline for the planning processes.

The aim of this initial phase of the mission planning is to define an operational baseline, including the ground station passes and other parameters, constraints, and events to be used as a framework for the science planning process.

In particular, the station passes for routine telemetry downlink, daily tracking and weekly telecommand uplink are confirmed using various ground stations, explained in Sect. 2.5. In summary, the communications baseline is built using ESTRACK (ESA's Tracking Station

Network), with the exceptional support of Goonhilly antenna in the UK, and additional station time requests from the NASA Deep Space Network (DSN), providing mask files to be considered for the scheduling at a later stage.

This process also defines many other operational long-term events, as shown in Fig. 8, in particular wheel off-loading maintenance periods (at least once a day around apocenter), and other operational parameters (bit rates, solar panel power predictions, etc), together with the boundaries and delivery dates for the upcoming medium- and short-term planning cycles.

The SOC then performs a long-term science opportunity analysis based on the predicted trajectory ephemeris and the operational constraints and events. As previously mentioned, the spacecraft's orbit drifts with a slow precession which causes latitude and illumination seasonal variations at pericentre, as shown in Fig. 9.

These long-term variations define the top-level science observation priorities for different regions of the planet based on the instrument observing requirements and mission objectives. Similarly, these orbital variations also define the long-term operational events and constraining periods (eclipses, conjunction, earth occultations, etc), which are considered for the mission planning and station allocation. This process includes an analysis of all geometrical and operational parameters, and discussion within the science teams to define the long-term strategy and observation campaigns for the next months or years, as shown in Fig. 10.

2.2.2 Medium Term Planning (MTP)

The Medium Term Planning (MTP) cycle, which encompasses a 28-day period of observations, is planned approximately 3 months in advance of the execution. The main objective of this cycle is to achieve a fully detailed pointing and instrument timeline schedule, fulfilling the scientific requirements while respecting the operational constraints of the mission.

The LTP science opportunities and operational events are now used as a starting point to define the specific constraints of each MTP, confirmed by the MOC via the Mission Planning Configuration List (MPCL) to adapt to the specific conditions of power, downlink capacity and eclipse/occultation events.

The instrument teams then provide their scientific priorities and select their science observation requests, which are then discussed, iterated, and harmonized by the SOC to construct a merged science operations plan with all geometry, instrument commanding, power, and data resources. The full plan is simulated and validated using the Mission Analysis and Payload Planning System (MAPPS) (Muñiz Solaz et al. 2022; van der Plas et al. 2016), which models all payload and spacecraft sub-systems and checks for any conflicts or constraint violations within the plan. Once the plan is scientifically and operationally validated, a fully detailed timeline is produced, as shown in Fig. 11, including the detailed pointing requests, payload commands and resources, which are sent to the MOC for analysis and confirmation.

The first step of the MOC (Initial Analysis) during MTP is to verify the pointing, instrument timeline and resource usage with respect to all the constraints and which are free of operational conflicts. A standard mission operations timeline is shown in Fig. 12. In particular, great effort is devoted to optimizing the communication timeline to avoid data overflow of onboard packet stores, and trimming station passes to reduce unused dump capacity and avoid power violations due to long transmitter times. Science observations may also conflict with ground station passes that are required for 2-way tracking, time correlation or uplink of commanding products. The detailed dump plan is created at this stage, establishing the optimal downlink priority with an Artificial Intelligence system (Cesta et al. 2007). Special attention is also given in this process to uneven power balance during eclipse seasons, which

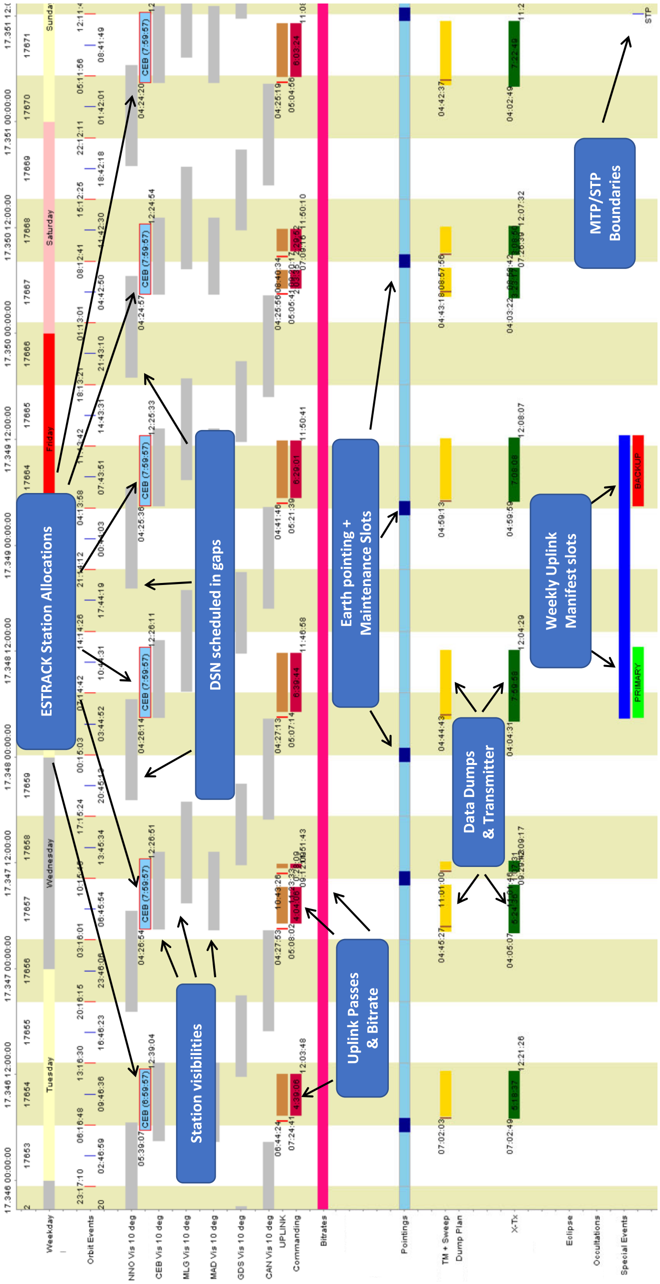

Fig. 8 Example overview of a basic Long Term Mission Plan showing station allocations and other operational events over a six-day period

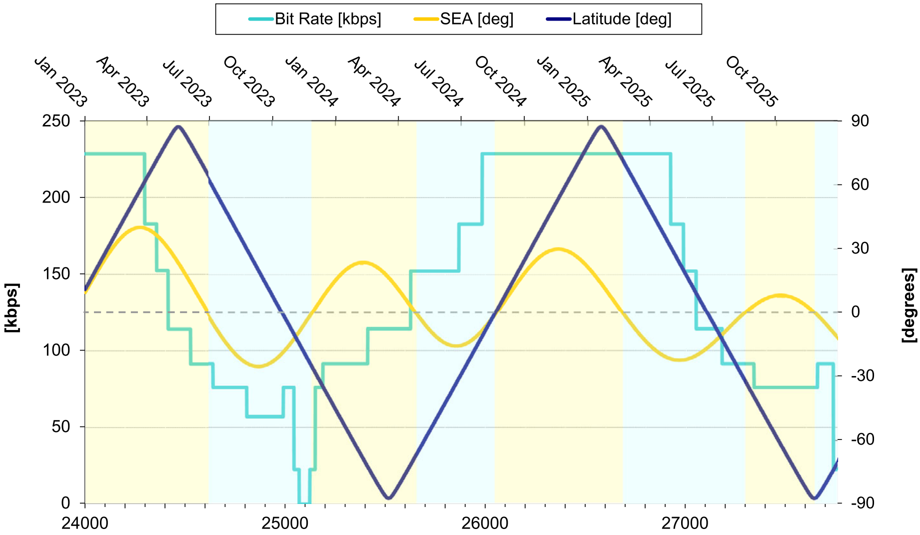

Fig. 9 Basic operational and geometrical parameters for 2023-2025: Bit Rate (light blue), Solar Elevation Angle (yellow) and spacecraft latitude (dark blue) at pericentre. X axis shows orbit number and date. Background colour shows illumination of the pericentre, either dayside (yellow) or nightside (blue) season

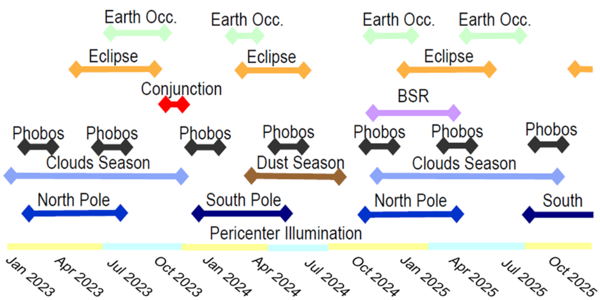

Fig. 10 Long Term Planning seasons and observation campaigns for 2023-2025

may lead to excessive battery discharge if batteries are not able to recharge sufficiently between eclipses.

Once the Initial Analysis is confirmed, the pointing requests are submitted to the FD team for detailed geometrical analysis and confirmation of the spacecraft attitude. Once this is complete, the plan is considered feasible and frozen (Final Analysis). This is then ready to start the generation of final planning products (Transition Analysis).

2.2.3 Short Term Planning (STP)

Finally, the Short Term Planning (STP) cycle is used to confirm the detailed commanding of all payloads on-board. This last planning iteration is done on a weekly basis just before the generation of spacecraft commanding products by the MOC for uplink to the spacecraft. It considers all operational events, parameters and constraints during a full commanding week as illustrated in Fig. 12.

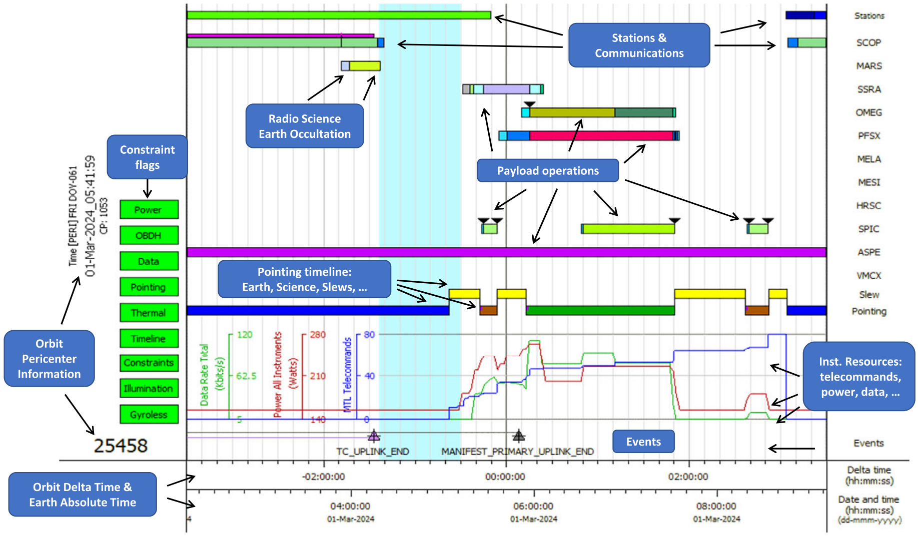

Fig. 11 Science operations timeline for a single orbit as simulated with MAPPS software. Time is shown in the horizontal axis as orbit delta time, relative to the pericentre (delta time 00:00:00 at the centre of the image), and the corresponding absolute time on Earth (UTC, Coordinated Universal Time). Timeline includes station passes and communications, all instrument operational modes, pointing and slew blocks, instrument resource plots and other operational parameter information

In this cycle the satellite pointing remains unchanged: only the instrument command sequences and parameter settings are optimized. The SOC uses the pre-approved MTP timeline to generate the baseline Payload Operation Request (POR) files, containing the default commanding sequences, parameters and resources for each instrument. PI teams can then iterate to optimize their observing parameters (e.g. integration times, depending on the scientific objectives and the latest geometrical information) or introduce larger modifications for dedicated instrument testing. Final POR files must be sent to the MOC at least 10 days before the uplink to the SC.

During this process, shown in Fig. 13, the final commanding files are prepared for the weekly uplink to the spacecraft (manifest) and all the operational constraints are validated again for consistency. In particular, due to the nature of the FAST commanding concept (File Activity on Short Timeline, see 4.3 and Lakey et al. 2014), great attention is dedicated to the use of the on-board short Mission TimeLine (MTL) and the execution of On-Board Control Procedures (OBCPs).

2.3 Platform Control

Overall responsibility for operation of the platform and its sub-systems is with the Flight Control Team (FCT), in collaboration with other teams. The FCT monitors the health of all sub-systems, responds to anomalies, and performs routine maintenance tasks. The FCT tracks the evolution and performance of all hardware units, monitoring the long-term performance of the solar arrays and batteries, predicting power available to platform & payload and setting budgets for operations during eclipse seasons, as input to the science planning process.

The FCT also monitors the temperature of critical platform and payload elements, define strategies particularly in thermally challenging seasons such as eclipse seasons, around

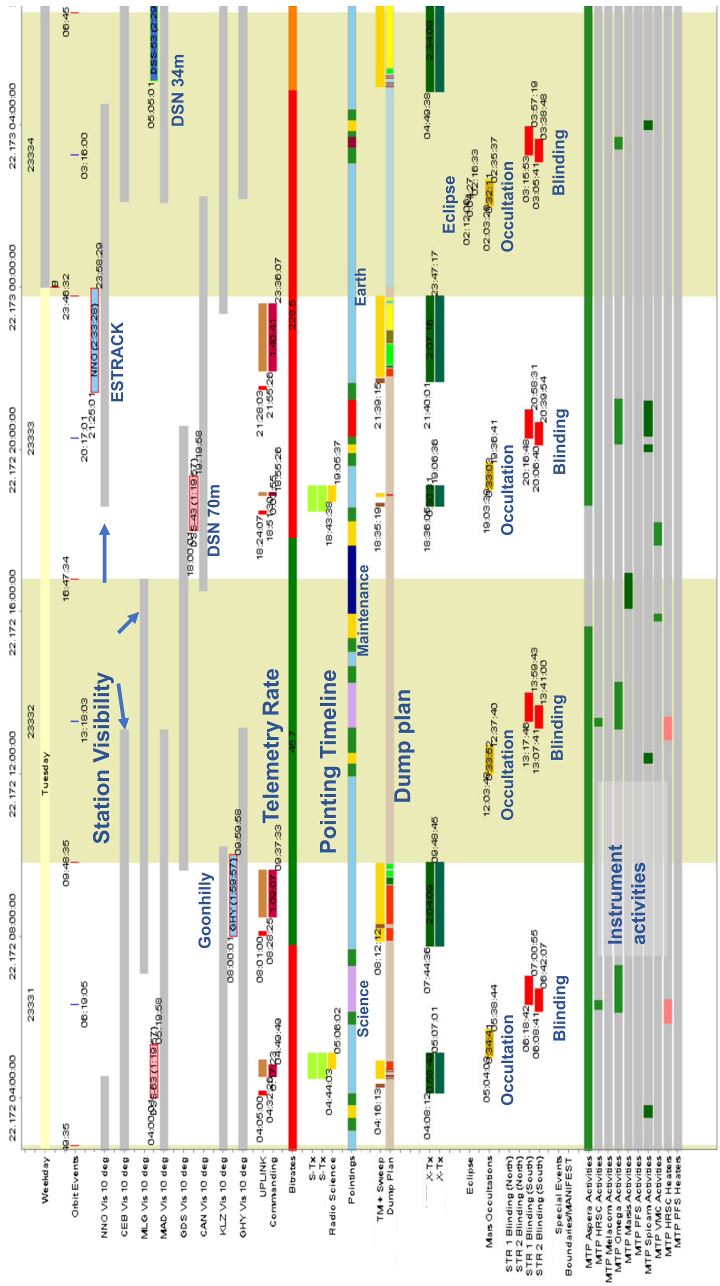

Fig. 12 Full mission operations timeline over 4 orbits (~1 Earth day), including all payload observation requests, ground station passes, pointing allocation and basic operational events

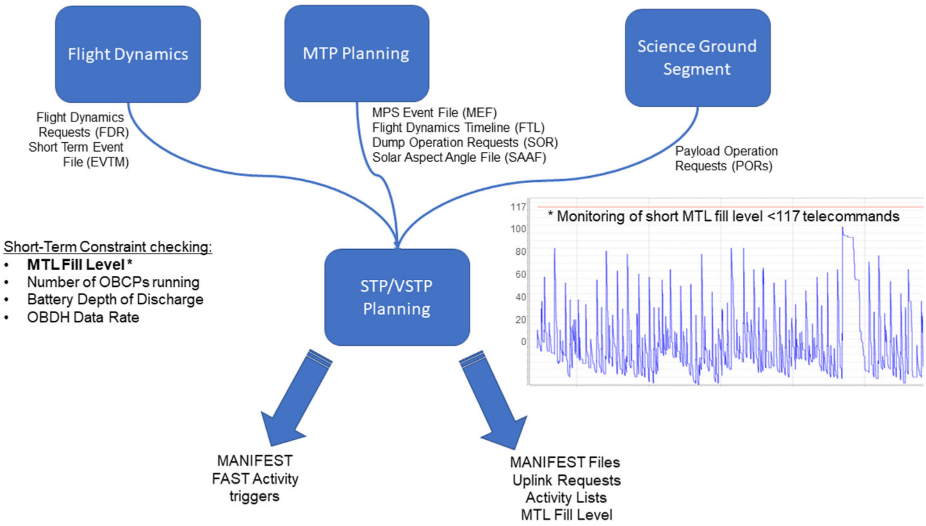

Fig. 13 Illustration of the Short Term Planning (STP) and very-STP process

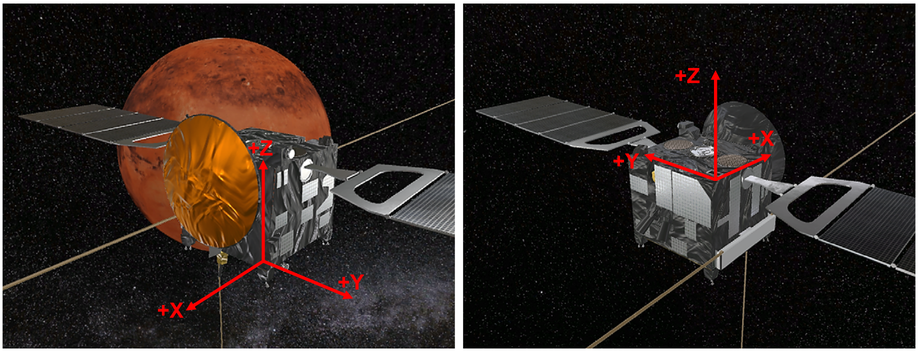

Fig. 14 MEX spacecraft frame: +Z Remote Sensing Payloads (and Beagle-2); +X High Gain Antenna, +/−Y Solar Arrays. Right figure shows the mounting of the MARSIS antenna on −Y panel, with dipole extending along +/−X axis, and monopole towards −Z axis

perihelion and solar conjunction, and define requirements for special pointing attitudes for thermal or power reduction purposes (e.g. warm-up blocks to heat the bottom of the SC to increase internal temperature and reduce heater power). In the worst case several of these conditions can occur simultaneously, e.g. the 2021 eclipse season which coincided with Solar conjunction, shortly following the aphelion of Mars.

The Flight Control Team also has full responsibility (since 2009) for the On-Board Software (OBSW) and Data Management System (DMS). When required, patches can be generated for the platform OBSW and can also be coordinated for the payload SW with input from the PI teams, if requested. The FCT monitors the health of the DMS and Solid-State Mass Memory (SSMM) and responds to anomalies.

The FCT also monitors the performance of the Telemetry, Tracking and Command System, calculates the link budget and sets the telemetry data rate for each pass and depending on the gain of the ground station and the Earth-Mars distance.

2.4 Attitude & Orbit Control

Mars Express is a three-axis stabilised spacecraft. Nominally, the attitude is estimated on board through hybridisation of gyroscope and star tracker measurements and controlled via 4 reaction wheels. The two solar wings, mounted symmetrically as shown in Fig. 14, can be rotated around the Y axis. The High Gain Antenna points towards +X and must be oriented towards Earth during ground contacts. The on-board software contains enough autonomy to maintain the Earth pointed attitude with solar panels Sun steering using knowledge of Earth and Sun ephemerides.

The wheel off-loading (desaturation of angular momentum) and the regular orbit control manoeuvres are performed using four redundant 10 N thrusters located on the $-Z$ face, opposite to the instruments. A main engine of 400 N nominal force, located on the same $-Z$ face, was used during the cruise and for Mars orbit insertion. During the main orbit control manoeuvres, accelerometers have been used to estimate the achieved change in velocity. In the early phases of a Safe Mode, two Sun sensors are used to point the $+X$ face of the spacecraft and the solar arrays towards the Sun.

The Attitude and Orbit Control System (AOCS) presented several challenges, in part due to anomalies, immediately after launch up to insertion around Mars (Companys et al. 2004). It required calibrations of the star tracker performance, of the full attitude estimation process during a major solar flare during cruise, and assessment of the delta-V efficiency and measurement accuracy (Lauer et al. 2004).

Once in orbit around Mars, observations of the planet are typically performed closer to pericentre and mostly focusing on the illuminated side of the planet, although some global monitoring observations may also be performed further away and over the dark side of the planet. For remote sensing science observations, the payload deck on the $+Z$ face is typically pointed towards nadir to observe the Mars surface, or the limb of the planet for atmospheric observations. The communication passes, pointing $+X$ towards Earth, provide tracking data, which enable the reconstruction of the orbital geometry, and is normally acquired farther away from the planet. One hour of two-way Doppler signal per day on average is enough to reach a reconstructed accuracy of a few tens of meters in position and a few millimetres per second in velocity. Maintenance wheel off-loadings are planned around apocenter once per day on average, or about every 4 orbits. Dedicated orbit control manoeuvres were initially regularly inserted at pericentre (Pulido-Cubo et al. 2004), but their frequency significantly dropped after the tight orbit control was deemed no longer necessary (Carranza et al. 2007), as the induced force of the wheel desaturation manoeuvres was further optimised to save propellant (Müller et al. 2006). To cope with the reduced generated power during eclipses, while maintaining nominal temperature, dedicated attitude pointings were designed to pre-warm the satellite by illuminating specific parts such as the launch vehicle adapter ring. Improvement of the solar radiation pressure model and carefully chosen attitudes made it possible to reduce the accumulated angular momentum, and consequently the amount of propellant consumed during reaction wheel desaturation. Finally, an improvement was made to the management of the AOCS, which consisted of updating the on-board software to implement an attitude estimation function relying exclusively on star trackers. This greatly extended the gyroscope lifetime (see Sect. 4.4 for details).

During most of the mission lifetime, orbit control commands were generated by Flight Dynamics on a weekly basis and were delivered to the Flight Control Team one week in

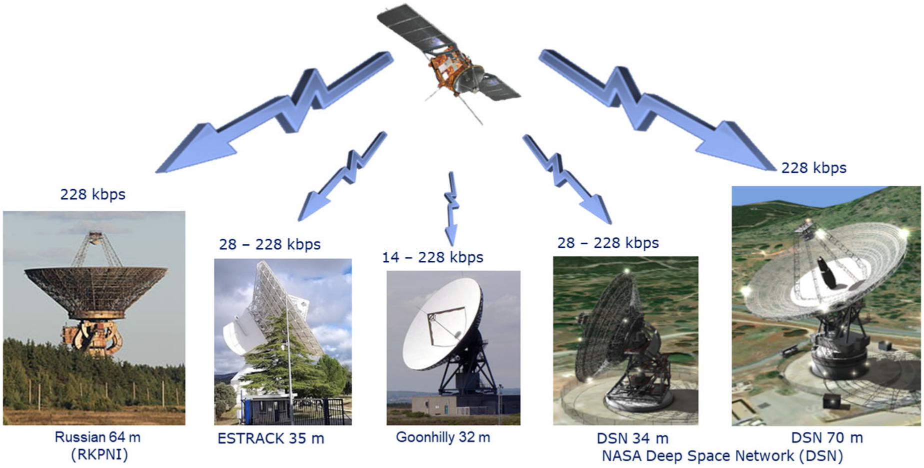

Fig. 15 Ground Station Networks and Capabilities. For the smaller antennas, the variable bitrate (in kilobits per second) depends on the Earth-Mars distance

advance of the start of their on-board execution time. Since the early 2020s, the orbit determination/optimisation is performed only every 2∼3 weeks, adding an additional delay with respect to the execution time. This optimization reduced the workload significantly, although it made it more challenging to maintain the orbital phase difference around Mars between the reference and the reconstructed orbits within a 10 second band considering the uncertainty in the prediction of delta V induced by the wheel offloading. During solar conjunction periods, a single commanding session covering more than 4 weeks is performed, relaxing the requirement on the orbit determination, which can be corrected by an additional orbit control manoeuvre after the conjunction period.

2.5 Ground Stations

For routine science operations MEX uses a wide range of antennas shown in Fig. 15. ESA-ESTRACK 35 m antennas are in New Norcia (NNO) in Australia, Cebreros (CEB) in Spain, and Malargüe (MLG) in Argentina. These are supplemented by the NASA Deep Space Network (DSN) 34 m and 70 m antennas in Goldstone (California), Canberra (Australia) and Robledo (Spain) and the 32 m antenna at Goonhilly (UK). In the past the Russian Complex for Scientific Information (RKPNI) 64 m station at Kalyazin has also been used. (Doat 2018).

Ground station scheduling is a challenging process, performed in negotiation with other ESA and NASA deep space missions. ESTRACK stations are allocated during the Long Term Plan for a 6-month period, 6 months in advance, whereas DSN stations are allocated later at Medium Term Plan, 3∼4 months in advance, and other stations such as Goonhilly are allocated separately on request.

The ground station operations and communications plan is constrained by various elements, including spacecraft pointing timeline, station visibility, availability, and other operational constraints and events. Not only the antenna must be pointing towards Earth, but also it cannot be occulted by Mars, and the solar panels must be properly illuminated by the Sun to provide enough power for the transmitter, therefore preventing communications during eclipses.

MEX has nominally 8 hours/day of ground station time split across between 2 and 4 passes. However, this can vary widely depending on Mars and Earth positions along their orbits, since telemetry and telecommand data rates vary with distance. The communication requirements depend also on the volume of science data being generated, the availability of ground stations, visibility and antenna size and gain. The nominal requirements are a daily downlink of 1.7 Gbit (average) for science and ∼100 Mbit for housekeeping telemetry data. The telecommand uplink is routinely performed with weekly manifest uplinks, although some special operations require real-time commanding (e.g. anomaly recovery, additional data dumps and platform maintenance activities). Orbit determination also requires at least 1 hour every day of 2-way Doppler measurements. Moreover, radio science is performed in seasons where orbital geometry permits occultation, solar corona and Bi-Static Radar (BSR) observations (Pätzold et al. 2016).

These challenging requirements on communications are nowadays compensated by the possibility of sharing antennas between the different Mars missions. As the angle subtended by 2 Mars orbiters is always smaller than the beam width of an antenna, passes can be shared between Mars orbiters, using Multiple Spacecraft Per Aperture (MSPA) where the downlink signal from 2 or more spacecraft are received in parallel on one antenna. This is normally the case for ExoMars Trace Gas Orbiter (TGO) and MEX sharing passes on ESTRACK ground stations, and DSN passes might be receiving signals from as many as 6 Martian orbiters.

Multiple Uplink per Aperture for various Spacecraft (MUPA) is also possible, over the New Norcia antenna, to uplink commands simultaneously to both MEX and TGO. Uplinking to 2 spacecraft in the same frequency is not possible as it would cause passive intermodulation interference in the antenna. However, uplinking to MEX in S-band while uplinking to TGO in X-band avoids this problem, as these frequencies are widely separated. Unfortunately, this is not possible on the other ESTRACK antennas as they do not have S-band uplink chains and is also not possible on DSN and Goonhilly antennas. MEX & TGO are the first and so far only interplanetary spacecraft to ever use this technique.

With increasing numbers of missions competing for time on a small number of ground stations, MSPA and MUPA have helped MEX, TGO and other Mars missions to make the best use of this limited resource.

3 Data Downlink, Processing and Archiving

3.1 Downlink and Distribution

Most of the science data volume is generated by the MEX instruments during science pointings, outside of a communications pass, and are routinely recorded on the Solid-State Mass Memory (SSMM) onboard, together with all other spacecraft housekeeping data. This memory is dumped later during the communication passes, following a pre-planned downlink priority scheme (Cesta et al. 2007) and including any "live" telemetry packets generated in real-time during the communications pass itself.

Once the communications bit stream arrives at the ground stations, all the science and housekeeping telemetry are transferred to the Data Distribution System (DDS) at ESOC, which stores all information retrieved from the spacecraft, including telecommand history, telemetry, events, and other Mission Control System data files.

The DDS extracts all packets from the data stream, and all housekeeping telemetry (payload and platform) and instrument science data are immediately made available to the instrument teams, identified by an Application Process Identifier (APID) by the mission control

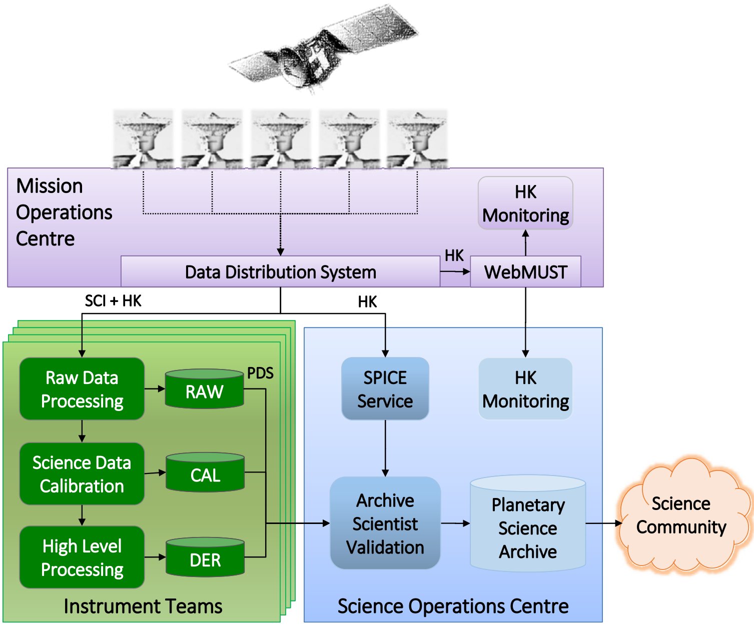

Fig. 16 Illustration of the data distribution for Mars Express: All telemetry data (both science and housekeeping) is downloaded via the antennas and made available via the Data Distribution System (DDS). Instrument teams process their science data, including the instrument housekeeping information, to different levels (raw, calibrated, and derived). All data sets in PDS (Planetary Data System) format are sent to the Archive scientist for validation and ingestion into the PSA for public distribution to the science community. Auxiliary geometry and timing information is also processed by SPICE and archived separately. All SC and Instrument Housekeeping data is also available internally via WebMUST for quick performance monitoring and visualization

system. All telemetry data are sorted and wrapped in a DDS data packet header containing the onboard clock generation time of the packet, converted from the SC Ephemeris Time (SCET) to Sun MJT (standard UNIX time) using time correlation information from the mission control system.

3.2 Science, Housekeeping and Auxiliary Data Processing

Science and housekeeping telemetry data files are retrieved directly by the instrument teams via the DDS interface, typically after each dump. The science data are then processed together with the payload housekeeping and timing information, to generate scientific data products at different levels, from raw binary files to scientifically calibrated and then higher-level derived data for analysis. Instrument science datasets, including the most relevant instrument housekeeping information, are submitted to the SOC in PDS (Planetary Data System) format for validation by the Archive scientist and final ingestion into the Planetary Science Archive for public distribution (see next section). A summary of the overall data processing and archiving is shown in Fig. 16.

Housekeeping (HK) data contain critical operational information of all spacecraft subsystems and instrument sensors, necessary both to process the scientific data and to monitor the performance and health of all hardware components and software processes onboard. All HK data is available to the instrument teams and also available internally to ESA via a web

Table 2 MEX raw datasets available in the Planetary Science Archive (PSA), as of 2024. Level number 2 (CODMAC standard). Datasets are usually split by mission phase (<ext> indicates extension number, 1 to 9 so far). ASPERA NPI and Radio Science raw data are included in the calibrated datasets, listed in Table 3

Level	Instrument	Type	Dataset IDs
2- Raw	ASPERA-3	Electron counts	MEX-M-ASPERA3-2-EDR-ELS-V1.0 MEX-M-ASPERA3-2-EDR-ELS-EXT<ext>-V1.0
2- Raw	ASPERA-3	Ion mass counts	MEX-M-ASPERA3-2-EDR-IMA-V1.0 MEX-M-ASPERA3-2-EDR-IMA-EXT<ext>-V1.0
2- Raw	MARSIS	Radar telemetry and auxiliary data	MEX-M-MARSIS-2-EDR-V3.0 MEX-M-MARSIS-2-EDR-EXT1-V3.0 MEX-M-MARSIS-2-EDR-EXT<ext>-V2.0
2- Raw	OMEGA	Spectral images and geometry in data cubes	MEX-M-OMEGA-2-EDR-FLIGHT-V1.0 MEX-M-OMEGA-2-EDR-FLIGHT-EXT<ext>-V1.0
2- Raw	PFS	Infrared Spectra	MEX-M-PFS-2-EDR-NOMINAL-V1.0 MEX-M-PFS-2-EDR-EXT<ext>-V1.0
2- Raw	SPICAM	Infrared spectra	MEX-Y-M-SPI-2-IREDR-RAWXCRU-MARS-V2.0 MEX-M-SPI-2-IREDR-RAWXMARS-EXT<ext 1-3>-V2.0 MEX-M-SPI-2-IREDR-RAWXMARS-EXT<ext 4+>-V1.0
2- Raw	SPICAM	Infrared spectra cleaned, in analog-to-digital units (ADU)	MEX-M-SPI-2-IRRDR-CLEANED-V1.0 MEX-M-SPI-2-IRRDR-CLEANED-EXT<ext>-V1.0
2- Raw	SPICAM	Ultraviolet spectra	MEX-Y-M-SPI-2-UVEDR-RAWXCRU-MARS-V2.0 MEX-M-SPI-2-UVEDR-RAWXMARS-EXT<ext 1-3>-V2.0 MEX-M-SPI-2-UVEDR-RAWXMARS-EXT<ext 4+>-V1.0
2- Raw	SPICAM	Ultraviolet spectra cleaned, in ADU units	MEX-M-SPI-2-UVRDR-CLEANED-V1.0 MEX-M-SPI-2-UVRDR-CLEANED-EXT<ext>-V1.0
2- Raw	VMC	Low resolution images	MEX-M-VMC-2-EDR-NOMINAL-V1.0 MEX-M-VMC-2-EDR-EXT<ext>-V1.0
2- Raw	Auxiliary	Mission Auxiliary data (beginning of mission only)	MEX-M-ESOC-6-AUXILIARY-DATA-V1.0
2- Raw	Auxiliary	SPICE kernels (archive version)	MEX-E-M-SPICE-6-V2.0

interface called WebMUST (Silva et al. 2016) which allows to handle, visualize, extract and search telemetry, commands, and operational event information for quick-look and system health monitoring. Note that only the payload HK data is being archived regularly, as it is included in the dataset deliveries from the instrument teams to the PSA. The complete set of SC HK parameters is only available internally for operational purposes, although they will be archived at the end of the mission for legacy purposes.

All auxiliary data are processed using the SPICE system (Acton 1996) to compute planetary observation information including timing, spacecraft geometry, pointing, instrument field of view, and other relevant parameters. The ESA SPICE Service (Costa 2018) makes use of the spacecraft ephemeris and attitude orientation data provided by FD team, time correlation and other relevant information retrieved from the DDS to distribute a series of data files, known as *kernels*, and produce a consistent SPICE Kernel Dataset (ESA SPICE PDS), which is then maintained over the lifespan of the mission, peer-reviewed with NASA's NAIF (Navigation and Ancillary Information Facility), archived in PDS format, and distributed to be used by the scientific community via the Planetary Science Archive (PSA), and the We-

Table 3 MEX calibrated datasets available in the PSA, as of 2024. Level number 3 (CODMAC). Datasets are usually split by mission phase (<ext> indicates extension number, 1 to 9 so far). Radio Science separates datasets by observation, identified with a 4 digit number (####). ASPERA NPI and Radio Science raw data are included in the calibrated datasets

Level	Instrument	Type	Dataset IDs
2 - Raw & 3 - Calibrated	ASPERA-3	Neutral particle images, as counts/accumulation & counts/sec	MEX-M-ASPERA3-2-EDR-NPI-V1.0 MEX-M-ASPERA3-2-3-EDR-RDR-NPI-V1.0 MEX-M-ASPERA3-2-3-EDR-RDR-NPI-EXT<ext>-V1.0
2 - Raw & 3 - Calibrated	MRS	Mars Radio Science data, including raw, partially processed, and ancillary data	MEX-M-MRS-1-2-3-CR1-####-V1.0 MEX-M-MRS-1-2-3-EXT<ext>-####-V1.0 MEX-M-MRS-1-2-3-MCO-####-V1.0 MEX-M-MRS-1-2-3-NEV-####-V1.0 MEX-M-MRS-1-2-3-PRM-####-V1.0 MEX-X-MRS-1-2-3-EXT<ext>-####-V1.0 MEX-X-MRS-1-2-3-PRM-####-V1.0
3 - Calibrated	ASPERA-3	Electron differential number flux	MEX-M-ASPERA3-3-RDR-ELS-V1.0 MEX-M-ASPERA3-3-RDR-ELS-EXT<ext>-V1.0
3 - Calibrated	HRSC	Radiometrically calibrated images	MEX-M-HRSC-3-RDR-V4.0 MEX-M-HRSC-3-RDR-EXT<ext>-V4.0
3 - Calibrated	MARSIS	Active ionospheric sounding portion of radar data	MEX-M-MARSIS-3-RDR-AIS-V1.0 MEX-M-MARSIS-3-RDR-AIS-EXT<ext>-V1.0
3 - Calibrated	MARSIS	Radargrams corrected for ionosphere dispersion	MEX-M-MARSIS-3-RDR-SS-V3.0 MEX-M-MARSIS-3-RDR-SS-EXT<ext>-V2.0
3 - Calibrated	VMC	Calibrated low resolution images	MEX-M-VMC-3-RDR-V1.0 MEX-M-VMC-3-RDR-EXT<ext>-V1.0

bGeoCalc (WGC) web site and other software tools to automatically produce, validate and exploit the geometric data for the correct scientific interpretation of instrument observations.

3.3 Planetary Science Archive (PSA)

The European Space Agency's planetary mission data is available to the public for free via the Planetary Science Archive (PSA; Besse et al. 2018). This includes the raw, calibrated, and higher-level data returned by the various missions, including data provided by the MEX instrument teams. The PSA can be accessed at: https://archives.esac.esa.int/psa/.

The instrument teams are required to deliver archival products in the PDS3 format, to ensure the longevity of the datasets as well as making the datasets searchable via the PSA interface. The latest versions of the datasets that are currently available in the PSA for Mars Express are provided in Table 2 (raw), Table 3 (calibrated) and Table 4 (high-level). The level numbers are defined based on the CODMAC (Committee On Data Management And Computation) standard used in PDS3. Note ASPERA Neutral Particle Imager (NPI) and Radio Science (MRS) provide combined datasets with raw/calibrated level data, so they are listed only in Table 3.

Thanks to the efforts put forth by the instrument teams and the MEX Interdisciplinary Scientists (IDS), several high-level datasets have been added to the MEX data holdings in the PSA (Table 4). In particular, the datasets of the type "Legacy set" in Table 4 form the first release of the “Mars Express Legacy Archive”, built thanks to the IDS, and are based on peer-reviewed papers whose analysis utilized MEX observational data.

Occasionally third parties wish to deliver data derived from MEX or other ESA missions, and these can be stored in the Guest Storage Facility (GSF), so long as they are associated with a published peer-reviewed article and contain a user guide. Table 5 provides the list of datasets in the GSF related to Mars Express. In order to facilitate the browsing and searching of the different datasets in the MEX archive, all the information given in Tables 2, 3, 4, 5 is also provided separately in the Supplementary Information.

The ESA’s PSA uses the Planetary Data System (PDS) format developed by NASA to store the data from its various planetary missions. In the case of MEX, the data is stored in the PDS3 format, which primarily uses ASCII files to store and describe the data. Newer missions, from ExoMars onward use the PDS4 data standard, which uses XML files as labels, in addition to several other changes in formatting.

There are three primary interfaces in which to find the data in the PSA. The first direct interface is the SFTP (Secure File Transfer Protocol) area, which houses all the public data in the PSA. Here, there are no advanced search capabilities, but it does provide access to all the supporting files and documentation for the various datasets.

Then, the Table View search interface allows to search using various parameters, such as mission name, target, instrument name, processing level, observation times, etc. The Table View is also linked to the Image View, where users can view the browse images provided by the PI teams, though it should be noted that not all teams deliver such browse images. The Table View interface also has a section for “Free Search”, allowing one to use Contextual Query Language (CQL) to search over additional parameters. These various search methods rely in part on the metadata provided by the instrument teams in the labels associated with each of the data products.

Finally, there is also a Map View for viewing the footprints of data from those instruments where such calculations can be of some utility. This Map View is built using GIS tools, and the geometry data is generated using the same Geogen tool for all missions, although for some missions the adaptation of this tool is still a work in progress. Thus, the Map View benefits from a homogenized approach to calculating geometrical parameters for all data across various missions.

4 Mission Evolution and Challenges over 20 Years

4.1 Power:

4.1.1 Solar Array Mis-Wiring

Shortly after launch it was discovered that the solar arrays were delivering well below their expected power output and housekeeping telemetry revealed that the array power regulators (APRs) were not behaving normally. On investigation, it was discovered that the solar arrays had not been correctly wired to the APRs. This prevented the power generated by the panels to be equally shared across the APRs, thus only about 60% of the maximum output of the arrays was available to the spacecraft (Ferretti et al. 2006).

The manufacturer of the Power Conditioning Unit subsequently found that fine tuning the clamp voltage settings of the different APRs could reach approximately 72% of the maximum array power originally expected. The clamp voltage settings of the APRs are regularly changed in-flight according to analyses performed by the spacecraft manufacturer,

Table 4 Mars Express high-level datasets available in the Planetary Science Archive (PSA), as of 2024. Level numbers 4-5 (CODMAC standard used in PDS3). Datasets are usually split by mission phase (<ext> indicates extension phase 1 to 9 so far). Radio Science separates datasets by observation, identified with a 4 digit number (####)

Level	Instrument	Type	Dataset IDs
4 - Resampled	ASPERA-3	Solar wind moments: density, velocity, temperature	MEX-SUN-ASPERA3-4-SWM-V1.0
4 - Resampled	HRSC	Legacy set based on published mesospheric cloud positions and wind speed	MEX-M-HRSC-4-DDR-CLOUDS-V1.0
4 - Resampled	HRSC	Map-projected images	MEX-M-HRSC-5-REFDR-MAPPROJECTED-V4.0 MEX-M-HRSC-4-REFDR-MAPPROJECT-EXT<ext>-V4.0
4 - Resampled	OMEGA	Legacy set based on peer-reviewed CO2 non-Local Thermodynamic Equilibrium emissions radiance	MEX-M-OMEGA-4-DDR-PROF-V1.0
4 - Resampled	SPICAM	Legacy set based on peer-reviewed water vapor concentrations and volume mixing ratio	MEX-M-SPI-4-IRDDR-PROF-V1.0
4 - Resampled	SPICAM	Legacy set based on published CO2 concentration and temperature	MEX-M-SPI-4-UVDDR-PROF-V1.0
5 - Derived	HRSC	Digital Terrain Models (DTMs)	MEX-M-HRSC-5-REFDR-DTM-V1.0
5 - Derived	HRSC	Images, DTMs, and mosaics of Phobos	MEX-MSA-HRSC-5-REFDR-PHOBOS-MAPS-V1.0
5 - Derived	MARSIS	Total electron content derived from radar signals in early mission	MEX-M-MARSIS-5-DDR-SS-TEC-V1.0 MEX-M-MARSIS-5-DDR-SS-TEC-EXT1-V1.0
5 - Derived	MRS	Radio occultation season data on ionosphere electron density profiles and neutral atmosphere profiles	MEX-M-MRS-5-OCC-####-V1.0
5 - Derived	OMEGA	Global maps of surface albedo and minerals	MEX-M-OMEGA-5-DDR-GLOBAL-MAPS-V1.0
5 - Derived	PFS	Legacy set based on peer-reviewed maps of water vapor total column retrievals	MEX-M-PFS-5-DDR-MAPS-V1.0

Table 5 MEX related datasets in Guest Storage Facility (GSF)

Dataset	Type
ESA_Mars_Valleys_HRSC_CTX_v1.0	Shape files focusing on fluvial valley networks, based on HRSC & other data
Mars_HRSC_High-Altitude-Mosaic_V1.0	Global mosaics, based on HRSC data
UCL-MSSL_iMars_CTX_V1.0	Mars Digital Terrain Models and OrthoRectified Images, based on HRSC & other data
UCL-MSSL_iMars_HRSC_V1.0	Martian South pole Digital Terrain Models, OrthoRectified Images, and mosaic based on HRSC data
UCL-MSSL_Mars-CERBERUS_CTX-HiRISE-HRSC_V1.0	Cerberus Fossae Digital Terrain Models and OrthoRectified Images, based on HRSC & other data
UCL-MSSL_Oxia-Planum_HRSC_CTX_HiRISE_MADNet_V1.0	Oxia Planum Digital Terrain Models and OrthoRectified Images, based on HRSC & other data
UCL-MSSL_Valles-Marineris_HRSC_V1.0	Valles Marineris Digital Terrain Models and OrthoRectified mosaic Images, based on HRSC

optimizing the overall solar array output power, as the expected temperature of the arrays varies with the distance from the Sun and the effect of planetary heating. After the problem was detected, during cruise the spacecraft manufacturer developed a new version of the on-board software to cope with APR failures and to be able to reduce power consumption in eclipses. The new software was activated on 6 February 2004, just 2 weeks before the start of the first eclipse season on 20 February 2004.

As a result of there being less power available, the spacecraft operates about 10 °C colder than it was designed to. Although this lower operating temperature complicates operations, particularly during eclipse seasons, it has had the benefit that it has slowed the aging of the Li-ion batteries and of the ring-laser gyros, with positive implications for the overall mission lifetime.

4.1.2 Survival Mode (SUMO): 2006 Power-Limited Eclipse Season

Two and a half years after arriving at Mars, from August to October 2006, Mars Express faced an unusually demanding solar eclipse season, where long eclipses coincided with aphelion and conjunction, causing very little illumination of the spacecraft $-Z$ face, where many temperature-critical elements are located, leading to much higher power consumption by the Thermal Control System (TCS). There was concern that the larger power demand combined with reduced generation by the solar array might result in the batteries not fully recharging between eclipses leading to a possible runaway situation and sudden mission termination (Porta et al. 2008).

The Mission Control team and Industry developed a low-power configuration of the spacecraft called SUMO (Survival Mode) in which the power consumption was reduced from 400 W to around 300 W, switching off all science instruments and many avionics modules. A new onboard SW version was also uploaded to include detailed battery house-keeping telemetry at the beginning of each communication pass and allow power health monitoring and quick reaction time in case of any anomalous situation (e.g. runaway).

The Flight Control Team also developed a Long-Term Eclipse Power Situation Simulator (LTEPSS) to predict the power performance of the spacecraft in eclipse seasons, modeling solar arrays, battery degradation, heater power and eclipse timings to predict and monitor the power balance, especially useful to assess the SUMO configurations. The new warmup pointing was also defined in this period to reduce the heater power illuminating the SC $-Z$ face.

Mars Express switched to the SUMO mode on the 23 August 2006, six days before the start of the eclipse season, and was recovered back to nominal on 17 September 2006 as the length of the eclipses shortened. The spacecraft emerged with adverse effects from this challenging period but was able to return to normal operations (Porta et al. 2008).

4.1.3 Battery Degradation

Mars Express experiences eclipse seasons approximately every 10 months, with each season lasting around 6 months. In these seasons the spacecraft passes through the shadow of Mars for a period of a few minutes up to more than 1 hour in each orbit. During eclipses the solar arrays do not receive sufficient illumination, and power is supplied to the spacecraft by three lithium-ion batteries.

The batteries were sized for a 2 Martian Year mission with an original capacity of 1620 Wh. It was assumed that the battery capacity would decline at a rate of about 3.5% per year. However, it wasn't possible to confirm this, as the batteries were never discharged sufficiently deeply to be able to determine their remaining capacity. Mars Express is the oldest scientific spacecraft using lithium-ion batteries, so there was no equivalent history which could be used to create a model of degradation and battery lifetime.

By 2016 it was estimated that the remaining capacity was only around 43% of the original and the deeper discharges caused a major concern that the degradation could be accelerated. The thermal subsystem caused the main power consumption during eclipses, so for the 2017 season a dedicated strategy was defined. The SC was pre-heated before eclipse using warm-up attitudes (developed for SUMO), and increasing the heater parameters to reach a temperature higher than nominal just before the start of the eclipse. This reduced the usage of the heaters during the eclipse itself, minimizing power consumption and battery discharge when no solar power is available. This new strategy lowered the maximum Depth of Discharge of the batteries by 10% (Dressler et al. 2018). Moreover, the power constraints were redefined to further reduce stress on the batteries, monitoring the impact of the payload operations, solar array rotations and possible shadowing during slews, to ensure a minimal discharge before and during the eclipse, and enable fast recharge right at the end of the eclipse (Merritt et al. 2018).

By 2019 the estimated degradation exceeded 60%, making it increasingly difficult to plan eclipse operations with acceptable settings and operational safety margins. Two studies were performed (by AIRBUS and Dudley et al. 2017), to better determine the true capacity of the batteries comparing in-flight data with ground calibration tests. The AIRBUS study concluded that the battery capacity degradation in Jan 2020 was between 18% and 30% (+/− 10%), whereas the Dudley et al. determined the degradation to be in the range of 31%-36%. The most conservative figure of 36%, with a degradation rate of 1.84%/year is now assumed for operational planning (Dudley et al. 2017).

As mentioned, the solar array mis-wiring may have helped to slow the temperature degradation of the batteries reducing the operating temperature by $\sim$10 °C along the mission.

4.2 MARSIS Boom Deployment

The MARSIS radar has a dipole antenna supported on two 20 m long, fibre-glass Kevlar composite tubular booms (Orosei et al. 2015). For launch and interplanetary cruise, the boom tubes were stored flat, folded into 1.5 m segments (see Fig. 14). Deployment of the booms was planned for January 2004, after achieving the operational orbit, but was delayed due to an unexpected risk of a boom hitting the spacecraft during deployment (Mobrem and Adams 2009).

Following further analysis and preparation Boom #1 was eventually released on 4th May 2005. Although initial indications were that the deployment had been successful, subsequent analysis of flexible modes and moments of inertia suggested that hinge #10 remained unlocked and bent at ∼40° from straight. The release of Boom #2 was paused pending further investigation and possible remedy of the incomplete deployment of the first boom. Analysis showed that changing the spacecraft attitude to illuminate and heat the stuck hinge could allow it to straighten and lock. The boom straightened in the first of several planned warming-up stages, confirmed by a re-characterisation of the spacecraft inertia and flexible modes (Denis et al. 2006).

The deployment of Boom #2 performed on the 14th of June was modified to include a slew during the deployment to illuminate the hinges and reduce the probability of an incomplete deployment and was successful on the first attempt (Adams and Mobrem 2009).

4.3 SSMM Anomalies & File-Based Operations

Operating MEX requires about 1000 telecommands per day. Originally these commands were stored in the Mission Time Line (MTL), a cyclic store on the Solid State Mass Memory (SSMM) with a capacity of 3000 commands. In 2011 a series of anomalies with the integrity of execution of commands from the MTL necessitated a switch to using the 117-command short time line (sMTL), normally only used for special operations, when the SSMM isn't available.

The FAST (File based Activities using the Short Timeline) concept, enabled operations to continue at the previous tempo using this much smaller command buffer. In this new concept, operations are grouped together as discrete activities, which start and end in a safe state (e.g., instrument off, spacecraft Earth pointed etc). Each activity is stored in the SSMM as a command file whose component commands are expanded into the short MTL a few seconds before the execution of the first command.

As this mechanism has a smaller overall commanding capacity than the long MTL, around 40 routinely used command sequences have been replaced with On-board Control Procedures (OBCP) which can be executed by a single command from the sMTL, reducing the command load from around 7000 to 2500 per week, while increasing the overall number of science observations.

Around 100 activity files are now uplinked per week, according to a "Manifest file" which instructs the MCS which files to uplink, in which order and with which name. Another procedure called MISO (Mission Scheduling by OBCP) handles the timely expansion of the files to the sMTL according to a schedule also uplinked once per week (Lakey et al. 2014).

In case of an interrupted transfer to the sMTL, a transactional mechanism ensures that all the commands of an activity remain disabled, but the spacecraft, sub-system and/or instrument will remain in a safe state. As spacecraft safety no longer depends on the correct execution of commands from the long MTL, it was possible to disable the risk triggers so no unexpected Safe Modes have occurred since then.

Multiple changes were required to the Mission Planning System, Mission Control Systems and Science Operations software tools to generate and manage the new commanding products (Activity files, Manifest and MISO Schedule), to prevent over filling of the sMTL and to handle other constraints. The Flight Dynamics System was also updated to ensure wheel-desaturation convergence for all possible combinations of unexecuted files. FAST is now an integral part of MEX mission planning and operations. It enabled the rapid recovery of mission operations following a serious anomaly but has also brought about major improvements to the mission. The planning process is more integrated, robust, and automated, and takes about half as long, with reduced uplink requirements that have enabled the sharing of stations using MSPA (Rabenau et al. 2014).

These changes have also increased the robustness and flexibility of operations, and subsequently facilitated the introduction of gyroless operations. File based commanding systems, based on the MEX system, are now also used by other missions such as Solar Orbiter and GAIA.

4.4 IMU Aging & Gyroless Operations

The MEX AOCS has a Kalman-filter-based estimator to calculate and control the spacecraft attitude based on gyros and Star Tracker (STR) measurements. At start of mission the estimator required input from a minimum of 3 of the 6 ring laser gyros. In 2017, signs of aging from four of the gyros showed that, if their usage was not reduced, the MEX mission could end by late 2018.

It was proposed to modify the AOCS SW to incorporate a gyroless estimator from the Rosetta AOCS into MEX. This estimator used a dynamics model to replace information from the gyros, using just the Star Tracker input and allowed the IMUs to be switched off. On Rosetta it was only intended to be used in Earth pointing attitude with low external torques during interplanetary cruise, reverting to Safe Mode if the star tracker lost lock.

Analysis showed the Rosetta estimator could support typical MEX science pointings. However, for it to be useful for MEX it had to be available in nearly all orbit phases and attitude modes and in case of loss of STR lock, revert smoothly to the gyrostellar estimator with the gyros switched on. To achieve a significant lifetime extension, the gyroless estimator had to be implemented quickly, while lifetime remained in the gyros and to produce large reductions in the duty cycles of the IMUs.

The new SW was developed by ESOC with support from the spacecraft manufacturer AIRBUS, in 1 year from initial concept to deployment in April 2018. This included modelling of the spacecraft dynamics, integration of the gyroless estimator into the AOCS SW and recompilation, uplink of the new SW image and triggering of a Safe Mode to activate it, and on-board validation. It was also necessary to review and revalidate all AOCS Flight Operations Procedures and extensively overhaul the planning process, in particular to avoid attitudes in which Mars would be in the field of view of a star tracker, causing blinding (Garcia et al. 2019).

The gyroless mode employed by Mars Express since April 2018 makes the spacecraft far more dependent on its star trackers and as a result long star tracker blinding must be avoided. This is achieved by changing the setting of the onboard North/South guidance flag from the default value but with the side effect that illumination of the $+Z$ face of the spacecraft increases. This then needs to be carefully modelled and monitored.

After 5 years of operations the operation of the gyroless SW has been faultless. The initial aim was to reduce the duty cycle of the gyros to 10%, to extend the mission lifetime until 2025. A duty cycle of less than 5% is now being achieved, extending the lifetime of the gyros to the end of this decade. Monitoring of the remaining lifetime of the gyros using their Laser Intensity Monitor (LIM) currents accurately predicted failure of gyro #4 in 2019 and gyro #6 in 2020, giving high confidence in the lifetime of the 4 remaining gyros.

4.5 Beagle 2 Heritage

Although the Beagle 2 mission failed, two units on the Mars Express orbiter, associated with the lander mission have subsequently been repurposed to perform scientific roles: the Visual Monitoring Camera (VMC) and the MELACOM Radio.

4.5.1 Visual Monitoring Camera (VMC)

The Visual Monitoring Camera (VMC) is a small 640x480 pixel CMOS camera with a wide (30°×40°) Field of View (FOV), installed to monitor the release of Beagle 2. On 19th December 2003 the camera took pictures to confirm the correct release and separation of the Beagle 2 lander and then was switched off, having fulfilled its purpose.

In 2007 the camera was recommissioned for education and public outreach purposes, under the banner ‘Mars Webcam’, with the proviso that its operation causes no disruption to standard science operations (Ormston et al. 2011).

From 2016 it became apparent that the images obtained by VMC could have significant scientific value (Sánchez-Lavega et al. 2018) and an agreement was made between the European Space Agency (ESA) and the University of the Basque Country (Spain; UPV/EHU) to put operations of the camera on a fully scientific footing. Over the next two years, operation of the camera was integrated with the science planning process, the image processing pipeline was upgraded, the data were added to the Planetary Science Archive and the scientific production was boosted thanks to the calibration of the instrument in flight (Hernandez-Bernal et al. 2024). VMC now plays a full role in MEX science operations, generating hundreds or even thousands of images per month.

4.5.2 Relay

After Beagle-2 was declared lost in February 2004, the MELACOM UHF radio, included on MEX to act as the lander relay for Beagle-2, has performed relay operations with more landed assets than any other Martian relay orbiter. This includes 6 NASA landers: Spirit, Opportunity, Phoenix, Curiosity, InSight and Perseverance; and the Chinese Zhurong rover, as well as tracking the ExoMars Schiaparelli lander during its descent through the Martian atmosphere.

The first relay demonstration with the Mars Exploration Rover (MER) Spirit, performed in February 2004, shortly after arrival at Mars, was the first-ever demonstration of an inter-agency communications network around another planet. Subsequent overflights with this and the other NASA surface assets have helped to cement the ESA-NASA relay communication at Mars, paving the way for the TGO. Mars Express continues to perform relay overflights with NASA’s Perseverance rover typically 4 times per year and is available to provide emergency relay support to any of the NASA landed assets if requested to do so.

The MELACOM radio was originally designed to forward commands to and receive data from landed assets, and to be able to make open-loop recordings of the radio signals transmitted by landers mostly during their entry, descent and landing (EDL) phases. The instrument´s software was modified twice in flight: firstly, to add a simplex receive only mode (used with Zhurong) and secondly, a carrier-only mode in which it transmits an unmodulated signal used for the MEX-TGO occultation radio science observations (see next section).

4.5.3 MEX-TGO Radio Science

Since November 2020 Mars Express has been performing mutual radio occultation observations with ExoMars Trace Gas Orbiter (TGO) (Svedhem et al. 2022; Parrott et al. 2024). An unmodulated UHF signal is transmitted by the MELACOM radio and recorded in open loop by the Electra relay radio on TGO just before or after the line-of-sight between the two spacecraft is occulted by the limb of Mars. Passage through the ionosphere and atmosphere imprints small frequency fluctuations (< 1 Hz) on the radio signal, which after processing can be used to deduce characteristics such as electron density, neutral density and temperature.

These observations contrast with the 'conventional' radio science occultations performed between MEX's communications transponder and ground-stations on Earth (Pätzold et al. 2016) in that there are many more opportunities, covering a much wider range of latitudes and local times (Cardesín-Moinelo et al. 2021). Although mutual occultation observations are performed routinely by Earth orbiting spacecraft, it has only been previously attempted on a few occasions by Mars Reconnaissance Orbiter and Mars Odyssey, as the near circular orbits of these spacecraft were less conducive to these observations than the highly elliptical orbit of Mars Express.

Neither the MELACOM radio on Mars Express nor the Electra on TGO were designed with radio science observations in mind, so several measures have been required to improve results. The firmware of both radios was updated to allow MELACOM to transmit an unmodulated carrier signal and to allow the Electra radio to receive in the forward link band. Neither radio has a USO: the long-term stability of the Melacom OCXO was confirmed when the Melacom signal was received by the Arecibo radio telescope during tests in 2013 and work is continuing to compensate for instabilities of the Electra TCXO.

Around 100 observations have been performed and vertical electron density profiles have been derived for about half of them. One observation is scheduled per week by the routine planning processes of both missions. (Cardesín-Moinelo et al. 2022; Parrott et al. 2024)

4.6 Special Payload Operations

The main interface for the MEX instrument scientists is via the Science Operation Centre for routine science planning. In principle, the only direct operational contacts between the Mission Operations Centre in Darmstadt and the instrument teams are to report when instrument telemetry values are out of agreed limits, anomalous payload events, command failures and any gaps in the returned science data. In principle, the recovery mechanism for instrument anomalies (or when requested by the instrument team) is to switch off and/or disable operations of the instrument until commands encompassing a recovery action are generated via the science planning mechanism. In most cases, payload anomalies have been transient and have recovered after power cycling the instrument.

Occasionally the MOC, together with the SOC, have been more actively involved with the instrument team in investigating and where possible mediating anomalies. Examples are ASPERA watchdog reset/Safe Mode, ASPERA scanner anomaly, OMEGA cryocooler failure, a MARSIS timing anomaly, SPICAM UV channel failure, OMEGA NIR data corruption, HRSC Total Packet Length anomaly and PFS laser diode anomaly. The MOC and SOC have worked with the instrument teams to recover from anomalies through patching the instrument software, changing the operational command sequences of the instrument to work around the anomaly (including writing OBCPs) and using alternative channels of the instrument.

Instrument software has also been patched to improve performance: e.g. ASPERA IMA high time resolution patch and energy table updates. The most notable instrument patching activity has been to introduce two brand new instrument modes on MARSIS for observation of the Martian surface and of Phobos (Cicchetti et al. 2017, 2023, Pätzold et al. 2024). The new modes will produce a five-fold increase in the volume of useful data, improve the quality of the data and allow it to be operated in parallel to the other instruments. The Phobos mode allows observations to be made from as close as 40 km compared to the previous limit of 250 km. As the instrument and its software is more than 20 years old, the equipment needed to fully test the changes on ground was no longer available. Therefore, the instrument team took the decision to test and debug the new software of the instrument on board the spacecraft. The risk of this unusual approach was very small, as the software changes are mostly concerned with data processing. However, the turn-around time to write a patch, request that the FCT uplink it to the spacecraft and then observe its effects during the next observation could take up to a week rather than the few minutes that it would take on the bench. At time of writing, approximately 100 patches have been applied, and the MARSIS team report that the process is close to completion and that the results are very positive.

4.7 Lifetime Estimates

The most important life-limiting items are thought to be the quantity of fuel remaining, remaining battery capacity and the remaining lifetime of the ring laser gyros.

Of the 473 kg of propellant on board the SC at launch over 90% was consumed during Cruise and Mars Orbit Insertion. Since then, the propellant has been used to perform periodic orbit control manoeuvres, to perform momentum dumps of the reaction wheels and during Safe Modes. Despite the large error bars in the fuel estimations, the latest estimations based on similar calculations for Venus Express (when it ran out of fuel), would indicate that about 2.8 kg of fuel remained available for use on MEX. Currently only a few grammes per year are required for small manoeuvres to maintain the 23/21 orbital resonance with Phobos, which is compensated by maintenance reaction wheel off-loadings, consuming an average of 208 grams of fuel per year. Each Safe Mode consumes 75 g of fuel on average, but there have been no unexpected Safe Modes since 2011. This would give a fuel depletion date in 2036 if no further Safe Modes occur.

Analysis of battery and solar array degradation, long-term predictions of power consumption and propagation of the orbital parameters to assess duration of eclipses, suggest that MEX will have sufficient power to keep operating for approximately two more decades. At present the most significant life-limiting item would appear to be the ring laser gyros. Two of the six ring laser gyros have now failed. The latest calculations indicate that with current usage levels ($\sim$5% duty cycle), the minimum requirement of three functioning gyros can be met for a further 7 years, giving an end of life of this capability and of the mission in 2030 or later if a lower duty cycle can be achieved.

Other hardware elements have exceeded their qualification lifetime, like the reaction wheels, but all of them are monitored closely and are not considered a concern for the mission lifetime.

5 Status and Conclusions

The Mars Express spacecraft has exceeded its intended lifetime of one Martian year by more than a factor of ten. It has completed 25,000 orbits of Mars, performed 100,000 observations and collected more than 10 Tbit of scientific data. The mission is currently funded until end-2026 and provisionally until end-2028. After more than 20 years in space the spacecraft remains in good health and full redundancy is available in almost all platform systems.

Throughout the mission, the MOC, SOC and payload teams have surmounted many challengues to keep the spacecraft operating, and in several cases enhancing mission operations in doing so. Power saving strategies introduced to cope with the solar array mis-wiring have extended battery lifetime by both reducing the strain on the batteries and operating them at a lower temperature. File-based commanding introduced to recover from a major anomaly have allowed the mission planning processes to become more automated. It also facilitated the introduction of gyroless operations and reduced the uplink requirements permitting the sharing of ground station passes with ExoMars TGO for uplink and other NASA Mars missions for downlink. While addressing these issues, the operations teams have progressively increased the scientific output of the mission in terms of volume of data generated and the number, range and quality of observations.

Finally, Mars Express has become a cornerstone for the European scientific community, providing invaluable experience in space technology development, planetary mission operations, data processing and scientific analysis, and has proven to be one of the most productive planetary missions of ESA after 20 years of operations, paving the way for the future exploration of Mars (further described in Titov et al. 2024).

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