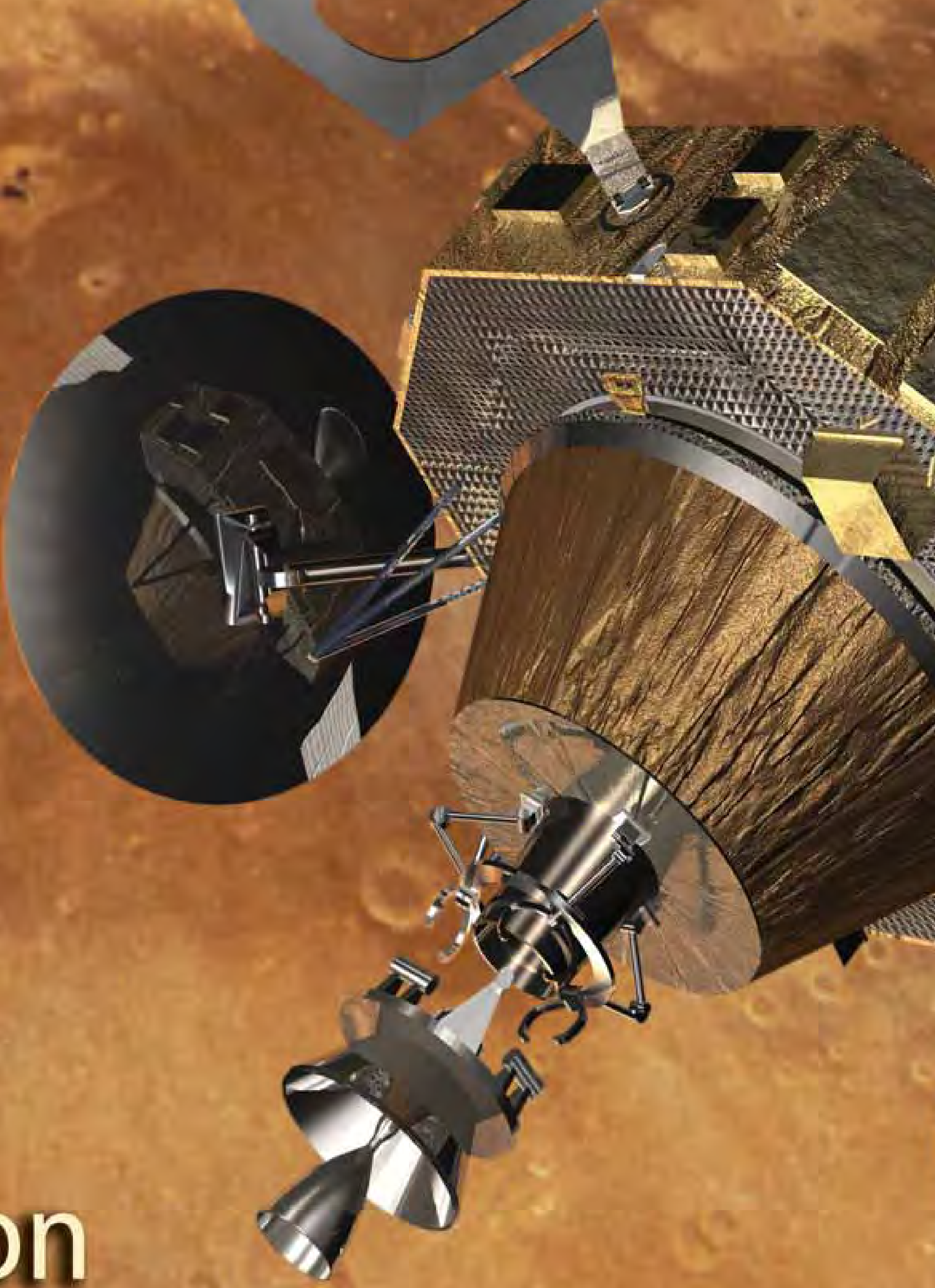

Mission Analysis

Towards a European Harmonisation


Artist's impression of ESA's Mars Sample Return orbiter vehicle. This mission presents many mission analysis challenges

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Mission analysis forms an integral part of every space project, and strongly influences the mission and element design. Once an exclusive activity of ESA experts, mission analysis now relies on a network of competent European industrial, academic and ESA partners, all integrated into the process.

Introduction

'Mission analysis' is the analysis of satellite orbits to determine how best to achieve the objectives of a space mission. This is performed during the entire definition, development and preparation phases of each project.

Mission analysis support has been provided to ESA projects by the European Space Operations Centre (ESOC) mission analysis team since the early 1970s. For many years, this team has been the focal point for mission analysis within ESA, coordinating activities with units at the European Space Research and Technology Research Centre (ESTEC), which concentrate on Earth observation, astrodynamic tools and research, as well as cooperation with national agencies.

In recent years, the network has been enlarged to include European industrial and academic partners. The European workshops on space mission analysis, the first of which was held at ESOC on 10–12 December 2007, acknowledge this evolution and provide a unique platform for technical exchange between the experts involved. With 87 participants and 40 presentations, the first workshop covered the entire spectrum of mission analysis subjects.

Several joint presentations on major projects such as BepiColombo, LISA Pathfinder and Mars Sample Return showed the high degree of harmonisation. They are used here to illustrate the mission analysis process and the way in which the cooperation with industry and universities is implemented, while at the same time guaranteeing continuity and completeness of the mission analysis support, system optimality and industrial competition.

Mission Analysis Process

At the start of a project, the mission requirements are evaluated in order to provide an overview of the available trajectory options. For each option, the mission analyst computes the information needed by the project to perform a proper trade-off between the different options and to define one or more baseline and back-up solutions for further detailed analysis, definition and optimisation.

This information usually includes: the timeline of major events; launcher injection orbit and mass; delta-V budget; power and thermal aspects, such as eclipses and distance from the Sun; Earth distance; Sun-spacecraft-Earth and Sun-Earth-spacecraft angles and their influence on communications; coverage of science targets; and a qualitative assessment of complexity and operational risk. At this stage the emphasis is on a good overview, rather than on accuracy and optimality.

The information is usually compiled in a Mission Analysis Guidelines (MAG) document. A frequent interaction with the project team allows the mission analysts to adjust their work to evolving mission requirements and design and ensuring that the information provided is properly interpreted.

A generalist, familiar with all mission analysis aspects, is preferable at this stage to ensure that the best solutions are chosen. In this context, a close link to operations or, even better, operational experience is of high value.

Later on in a project, the baseline solution is studied in more detail in order to demonstrate feasibility and further optimise performance, in addition to generating all the information needed for platform, payload, ground segment, launcher service and operations design.

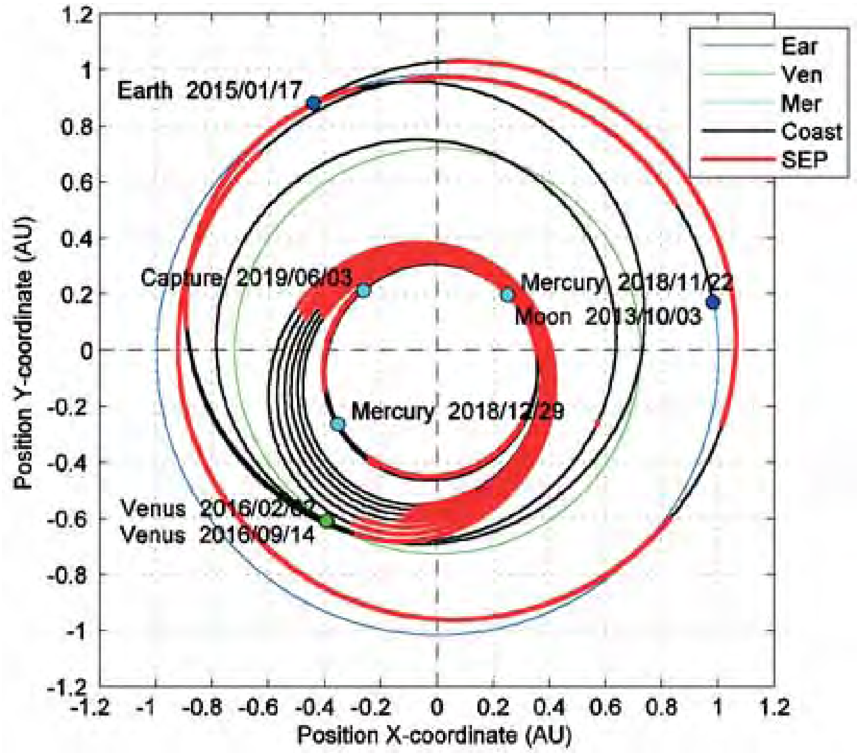
The orbit analysis includes the determination of the frequency of manoeuvres to maintain the operational orbit and the fuel needed for these, bearing in mind payload operations and spacecraft safety. Usually the manoeuvres compensate for known orbital perturbations, such as third-body gravitational effects, and those caused by the asymmetries of the planet's gravitational field.

The navigational analysis has to show that the stochastic disturbances affecting the trajectory can be sufficiently measured and corrected in order to guarantee spacecraft safety and achieve the accuracy needed for payload operations. The fuel needed to correct these errors is also computed. Typical disturbances are launcher injection errors, orbit correction manoeuvre errors, uncertainties in the solar radiation pressure and atmospheric drag, as well as velocity increments associated with attitude control.

The contingency analysis quantifies the consequences of spacecraft failures, such as a missed orbit manoeuvre or a spacecraft safe mode, proposes risk mitigation or recovery strategies, and quantifies the fuel and time penalty to implement them.

The launch window analysis determines the days during which the spacecraft can be launched and the time slots when lift-off can occur, as well as the target injection orbit. It has to be proved that the mission objectives can be achieved in each of these windows. The

The BepiColombo interplanetary cruise to Mercury, ecliptic projection showing swingbys



Artist's impression of BepiColombo in cruise configuration (exploded view). From top to bottom, the Mercury Magnetospheric Orbiter (MMO), the sunshield, the Mercury Planet Orbiter (MPO) and the BepiColombo transfer module

extra fuel required to compensate for the non-optimal injection time and orbit also has to be quantified. This task requires interaction, via the project, with the launcher authorities.

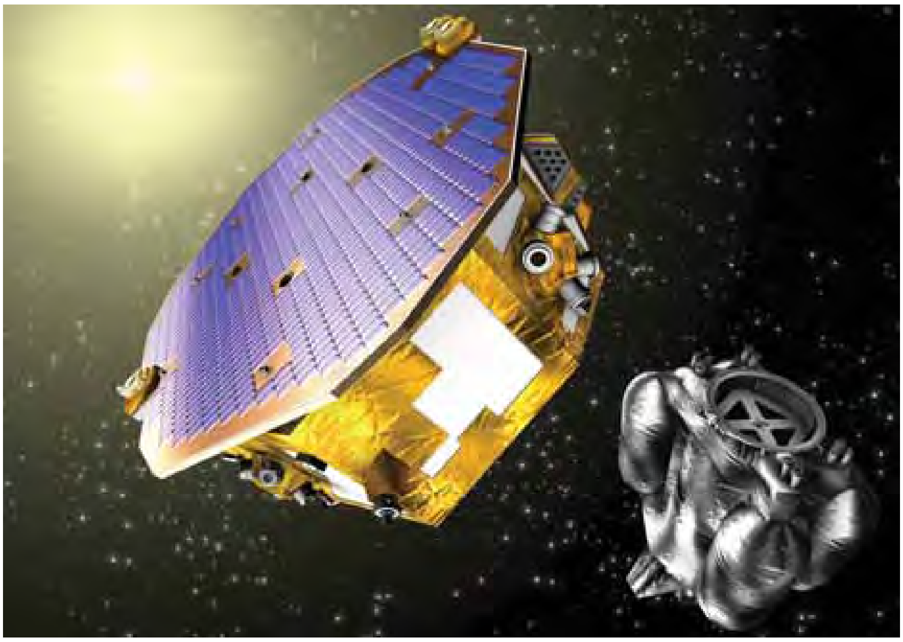
The results of the in-depth analysis for the baseline solution are compiled in the Consolidated Report on Mission Analysis (CREMA).

Launch delays, spacecraft mass overruns, technology development problems or other difficulties often prevent the baseline mission from being flown as planned. During mission operations, contingencies may also require a mission redesign within the constraints of the existing spacecraft, payload and ground segment. Continuity in the mission analysis support throughout the entire lifecycle of the project guarantees a continuing awareness of the possible alternatives that were assessed in the early phase of the project. Typical examples are the redesign of the Cassini-Huygens mission after the identification of a transponder design problem and the redefinition of the Rosetta mission after losing the option to fly to Comet Wirtanen in January 2003.

BepiColombo

The first assessment studies for an ESA mission to Mercury started in November 1993. Since then, the mission design evolved from a single Mercury orbiter that used chemical propulsion and gravity assists to reach the planet, to a system with two orbiters, based on electrical propulsion. Now, as the fifth cornerstone mission of the ESA Horizons 2000 scientific programme, BepiColombo consists of two scientific spacecraft, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO). The latter spacecraft will be built and operated by the Japan Aerospace Exploration Agency (JAXA) and passively attached to the MPO during the cruise to Mercury. The two spacecraft will study the origin and evolution of Mercury, its interior dynamics and the origin of its magnetic field.

Going to Mercury is not simple: if no planetary flybys are used, it would cost even more fuel than a journey to Pluto! So, before starting the competitive definition study with Alenia Spazio and



Artist's impression of LISA Pathfinder, showing the science spacecraft and propulsion module after separation

EADS Astrium, the framework of the mission had to be defined. A complex interplanetary trajectory was designed, working together with mission experts at the Institut d'Astrophysique Spatiale in Orsay, France. Originally, when the powerful Ariane-5 rocket was to be used, just two flybys at Venus and two at Mercury were required, in combination with solar-electric propulsion. The target could then be reached in less than three years. But mission analysis does not end when a good trajectory is found. In the case of BepiColombo, the Ariane rocket became unaffordable and solutions with the smaller Soyuz rocket had to be found.

To compensate for the missing thrust from the powerful Ariane-5 rocket, one lunar flyby and an Earth flyby were introduced. The solar arrays had to be reduced in size, cutting the available ion engine thrust in half. As a consequence, the transfer duration increased to five years.

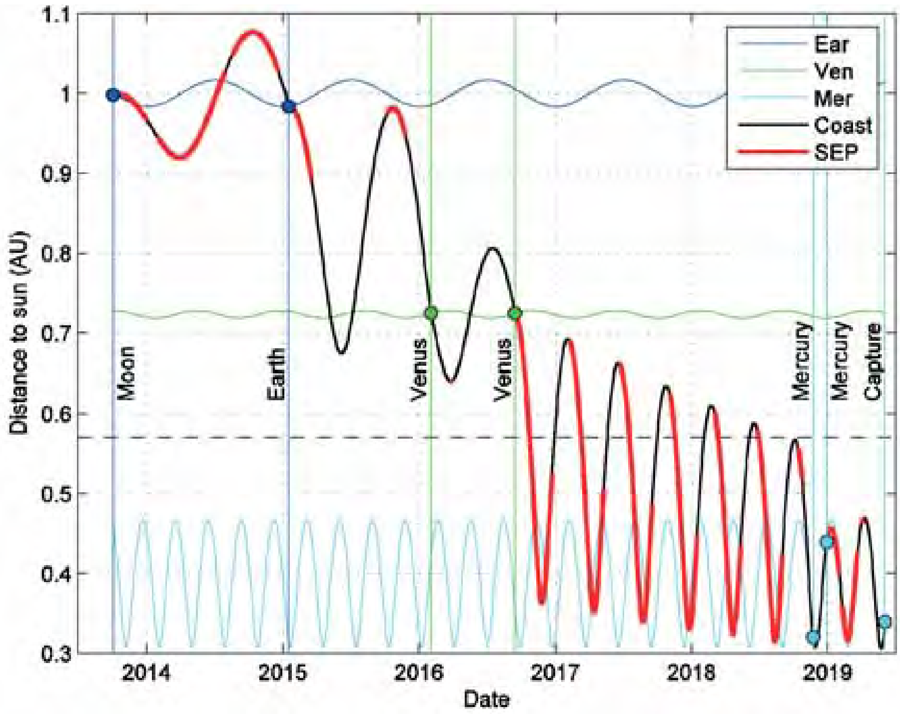
The current interplanetary trajectory is shown on the previous page. It includes single flybys at the Moon, Earth, two at Venus and two at Mercury, as well as several long thrust arcs provided by solar-electric propulsion. However, the mission analysts already have back-up options available, with up to six Mercury flybys giving even more fuel savings.

One way to compensate for a potential mass crisis in the mission is a 'gravity capture' on arrival at Mercury. In collaboration with EADS Astrium, a sophisticated arrival strategy was designed in which the Sun's gravity is used in such a way that the spacecraft is decelerated enough to be temporarily captured in a high orbit around Mercury. If the orbit insertion fails, there are multiple opportunities to attempt another capture burn before the spacecraft eventually drifts away and the mission is lost.

For such a demanding ESA cornerstone mission, the ESOC mission analysis team relies on industrial support to analyse all aspects of the mission in the required detail. One example is navigation, a key issue for the safety of the mission. When six flybys may need to be performed with high precision, a detailed simulation of the orbit determination and trajectory correction is required. This resulted in dedicated software being written by Deimos Space, building on ESA's long-standing expertise and prototype software.

As a consequence, we now know which trajectory correction manoeuvres can be made with solar electric

BepiColombo cruise from lunar swingby to capture at Mercury



propulsion or have to be done using chemical propulsion. Mission analysts from the University of Glasgow and Politecnico di Milano have been called upon to write software for trajectory optimisation and graphical user interfaces to make the very complex trajectories easier to present and to understand. Finally, the Spanish technological business group GMV has delivered the 'ASTRO' toolbox to visualise the complex navigational aspects and simplify many day-to-day astrodynamic calculations.

LISA Pathfinder

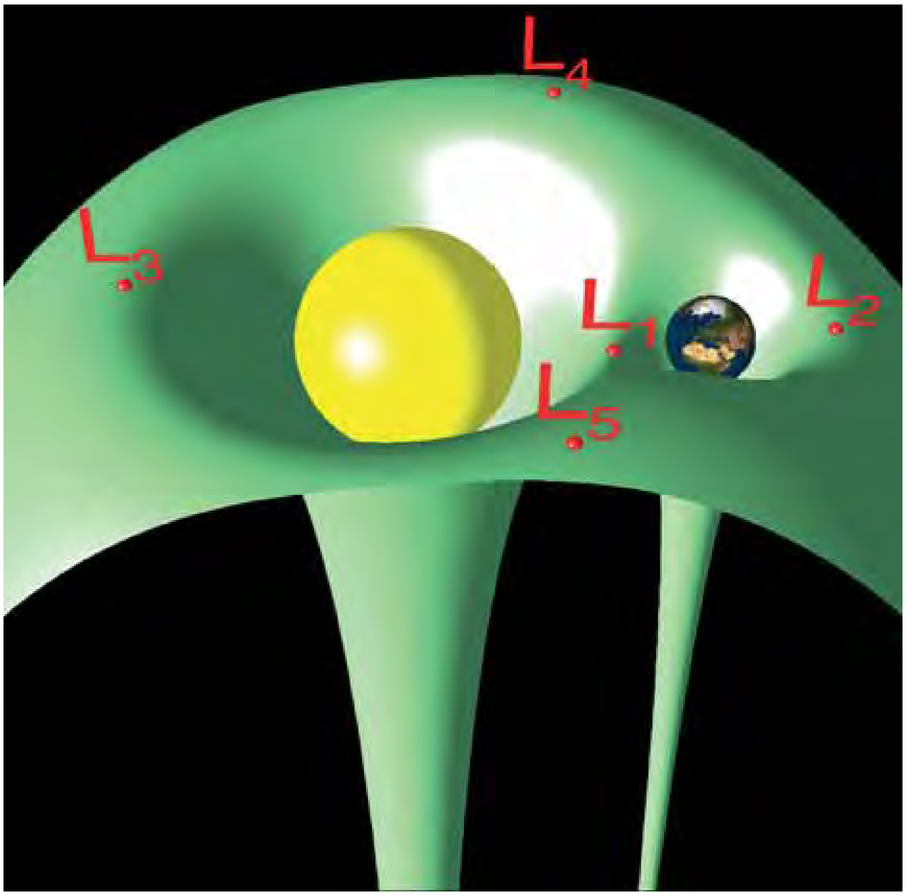
As a precursor for the Laser Interferometer Space Antenna (LISA) gravity wave hunter, the LISA Pathfinder mission is required to perform its experiments in an extremely low-force, low-disturbance environment. For example, any force differences of more than one billionth of a g (1g = 9.81 ms^{-2}, the gravity acceleration on Earth's surface) between the proof masses of the payload is to be avoided, ruling out Earth's vicinity up to distances of 120000 km.

Given these requirements, the dayside L1 Lagrange point of the Sun-Earth system was chosen as the target location for LISA Pathfinder. There, at 1.5 million kilometres from Earth, the forces of Earth's gravity, Sun's gravity, and the centrifugal force of Earth's motion around the Sun cancel each other, so that the spacecraft moves about like a three-dimensional pendulum with a period of roughly 180 days. The pendulum motion in the plane of Earth's orbit has a slightly different period than the motion perpendicular to it, causing non-repeating orbits about the Lagrange point. The size of the free pendulum, or libration, motion is of the same order as the distance of the Lagrange point from Earth, so that the spacecraft appears to be circling the Sun on an annulus between 10° and 45° when viewed from Earth.

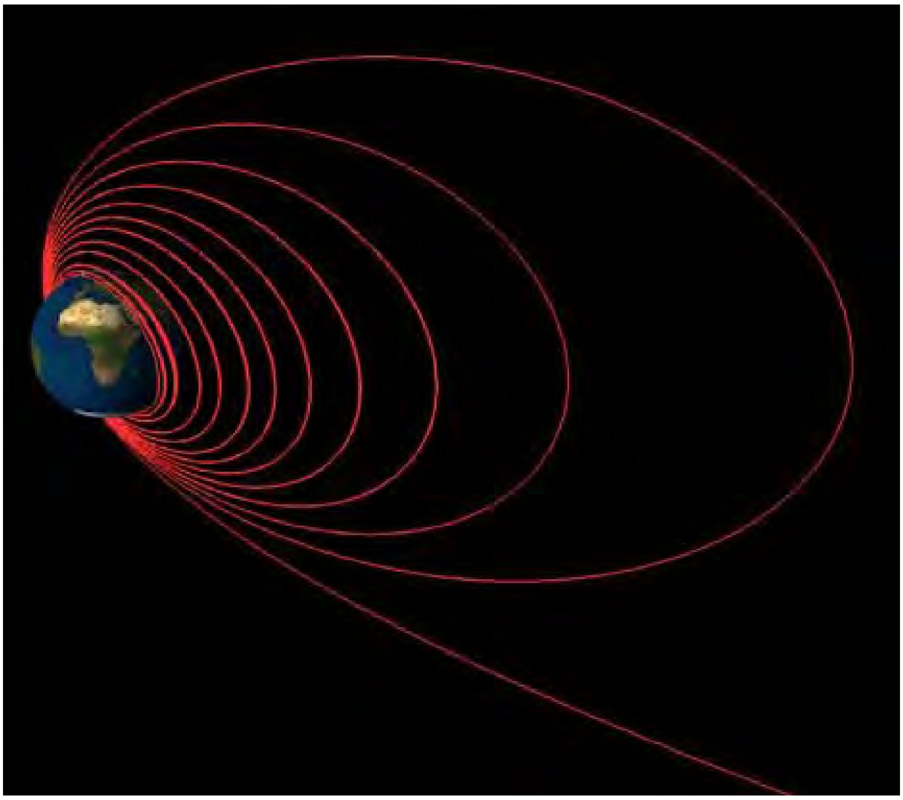
LISA Pathfinder is not an unusual case when it comes to the coordination of mission analysis activities in Europe. There are industrial and academic players who work with ESA's experts, sometimes in parallel, sometimes by providing tools, and sometimes by reviewing each other's results.

The possibility of putting LISA Pathfinder as a co-passenger on a commercial Ariane-5 launch was excluded in phase A. This means that, instead of being injected into a geostationary transfer orbit, a dedicated small Russian Rockot launcher will place the spacecraft in a slightly elliptical low Earth orbit below an altitude of 1000 km. The most efficient way to transfer the vehicle from this initial low-energy orbit and send it towards the Lagrange point was sought. The strategic approach to use a number of perigee burns was regarded as the only possible solution. Since this transfer strategy could only be optimised under the constraints given by the spacecraft capabilities, it was a logical decision to assign this task to the prime contractor and have it reviewed by ESA experts.

One important trade-off in this optimisation was the total number of manoeuvres, with an increase in manoeuvres reducing the propellant expenditure, but at the same time increasing the LEOP duration and complexity. Mission designs with up to 25 manoeuvres were considered by the prime contractor in order to achieve the minimum change in velocity (delta-V, or ΔV). Concerns about the operability of this approach were evaluated, eventually resulting in a reduction to 15 manoeuvres. This number allowed a credible approach for the nominal operations in the Earth-orbiting phase, while also catering for simple contingency situations during that phase. In addition, the radiation exposure could be kept within the constraints given by the spacecraft and payload requirements.



Lagrange (libration) points L1 to L5 on the 'Jacobi surface' (green) in the Sun-Earth system (not to scale)



LISA Pathfinder orbits before departure from Earth

This example shows nicely that the system overview provided by ESA experts, including spacecraft, mission, operations, and ground segment, is invaluable when it comes to the realisation of solutions that are often driven by a desire to improve the propellant budget situation.

For the everyday work on Lagrange point missions, ESA specialists use the LODATO software package that has its roots in the rapid prototype development undertaken by them in the past. LODATO was improved by Deimos Space under contract with ESA, using software design guidelines.

The results from educational partnerships with academia have been included in LODATO, so that the rendezvous problem at the Lagrange points can be treated, as well as lunar flybys and navigation aspects. From an insider's point of view, it pays to have the competence for new developments in mission design software within ESA, while also using industrial and academic capabilities to expand and maintain the software to the latest standards.

Mars Sample Return

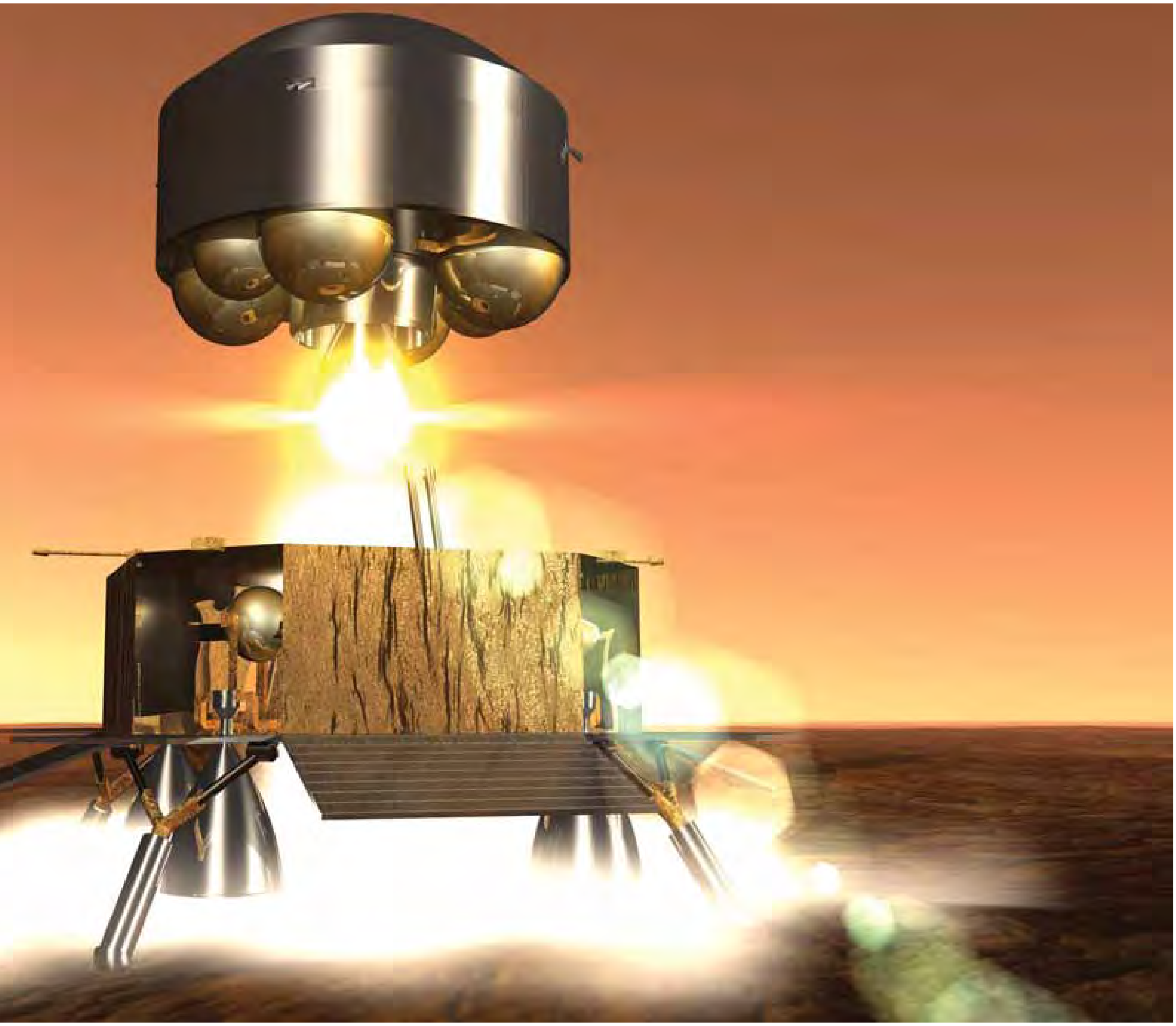
Following ExoMars, the first Mars mission of ESA's Aurora Programme, which is due for launch in 2013, and a technology demonstration mission due in the 2016 timeframe, the Mars Sample Return (MSR) mission is planned to take place towards the end of the coming decade.

The most complex unmanned ESA mission ever, MSR will require two Ariane-5 launches. One will launch a Mars orbiter and an Earth Return Vehicle, the second will launch the Surface Element and Mars Ascent Vehicle (MAV). The Surface Element will probably involve a rover and possibly a drill for sample extraction. After collecting about 500 grams of soil, rock and atmosphere samples, the MAV will launch into a low Mars orbit where the orbiter will gather the sample container, seal it hermetically, carry it back to Earth and place it on an atmospheric entry trajectory.

Artist's impression of the Mars Sample Return Mission, showing lift-off of the Mars Ascent Vehicle (MAV) from the descent module

Among the numerous technical challenges inherent to MSR are:

- targeted soft-landing of a large module on the Mars surface;
- automatic, accurate launch from the Martian surface into low Mars orbit;



- aerobraking to the target orbit around Mars;
- rendezvous and capture of the launched sample container;
- safe Earth return and precise insertion into a narrow re-entry corridor;
- compliance with stringent planetary protection requirements to avoid forward and backward contamination – MSR is by definition a Class V mission involving return of samples to Earth;
- long duration: 5–7 years between first launch and sample return.

Since the sheer magnitude and complexity will result in a mission cost that is too high for a single agency to shoulder, MSR is likely to be a multiagency endeavour. Current studies focus on a NASA/ESA cooperation.

More than most missions, MSR features a series of bottlenecks for which there is no workaround. Mars entry and landing, sample collection, sample launch, rendezvous and capture, sample container sealing, and Earth return and targeting all involve single points of failure with no chance for a second try. Failure to execute any of these steps exactly as planned will result in a total loss of the mission.

The challenges also extend to mission

Artist's impression of the latest concept for the ExoMars rover, now ready for the next phase of development, Phase-B2

analysis. The design of the interplanetary transfers and the Mars operational phase is driven by compliance with the numerous technical requirements. These include arrival at Mars at least six months before the start of the dust storm season, a minimum stay time of six months and no superior conjunctions at Mars approach or during surface operations.

A typical mission analysis product is the timeline shown on the next page, which presents the possible transfers in correlation with these mission requirements and allows the project to make a proper selection. The individual mission analysis tasks comprise launch window optimisation, interplanetary navigation, Entry, Descent and Landing (EDL) optimisation, aerobraking, maximisation of the data relay capabilities, analysis of the effect of natural orbit perturbations and identification of possible mission risks and problems. For each of these tasks, considerable know-how is present within ESA and industry. The key to success, especially in view of the fairly tight schedule, is to make the best possible use of the available expertise.

MSR stands out from 'usual' missions in several ways. Firstly, to a deeper extent than with other projects, MSR mission analysis is linked with programmatic and systems aspects. Furthermore, it requires profound knowledge of the Martian environment, the scientific goals and the political situation. The extraordinary list of technical challenges has already been mentioned. In combination with the unprecedented mission cost, the mission also faces significant political risks. Both need to be addressed at a fundamental level. Early identification and proactive mitigation of any mission risk are the keys to meeting the challenging schedule. Conversely, failure to address a technical issue in a timely fashion is likely to raise the likelihood of delays or cost overruns and expose the project to political risk.

MSR is not a standalone mission; it will enable Europe to act as an equal partner in even more challenging future projects, such as manned planetary missions. As stated, mission analysis should be seen and conducted as an integral part of global mission design. In view of the complexity, optimising the involvement of all available mission analysis capabilities is essential. The long preparation phase and mission duration and the need for a global, long-term view mandate that ultimately ESA retains full control of the key aspects, of which mission analysis is one.

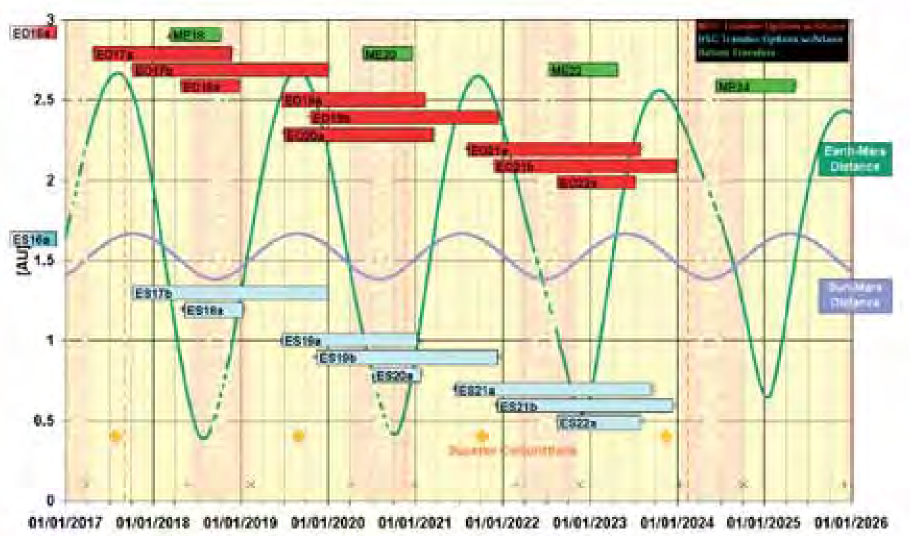
Summary

While remaining responsible for the mission analysis of ESA's projects, the ESOC mission analysis team shares the work with industrial partners, academic researchers, other groups in ESA and, occasionally, other agencies. The industrial contribution is either indirect, in the frame of a system design study or spacecraft procurement contracts, or direct, in the form of a study contract.

Usually a Mission Analysis Guidelines document is produced as input to industrial system design studies, to avoid a complete mission analysis being performed by the contractor. This is cost efficient, in particular for parallel studies. As only a limited number of companies can afford to maintain a sufficiently broad mission analysis expertise, this allows a much larger number of companies to make an offer, thus improving competition. Benefit is taken from the contractor's available expertise by inviting the company to review and enhance the mission analysis guidelines.

Often, the prime contractor of a spacecraft procurement or one of its major subcontractors has significant mission analysis expertise and uses it extensively to optimise spacecraft design. This valuable contribution is coordinated with ESA's work and integrated in the Consolidated Report on Mission Analysis (CREMA). The responsibility for the CREMA remains with the ESOC mission analysis group in order to maintain coverage and optimality of the entire system, including platform, payload, ground segment, launcher service and operations.

Direct industrial support is used for well-defined, specialised, offline study tasks which do not need frequent interaction with the projects. Study contracts are also used to develop new methods and tools, when universities focus on the conceptual work and industry focuses on the implementation.



Timeline chart showing possible outbound and return transfers and environmental conditions

Working groups are a useful platform to harmonise the work of several ESA and non-ESA experts in the case of complex, urgent or critical problems, such as the Rosetta lander mission analysis, the Rosetta mission redesign after losing the Comet Wirtanen opportunity and, recently, the mission definition for the Cosmic Vision missions to Jupiter and Saturn.

Recurring workshops dedicated to mission analysis enable the partners to present their work for feedback, to get an overview on the ongoing activities, to create awareness of the available expertise and, last but not least, establish good personal contacts, which are crucial for our cooperation to function.