Saving Fuel on Mars Express using “LowFAT” - A Torque Neutral Attitude

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The ESA spacecraft Mars Express is the first and to-date the only European mission to the red planet and has contributed many scientific discoveries in the search for water and traces of life on Mars ever since its arrival in Mars orbit. Launched in 2003 it exceeded its nominal lifetime already by more than four years and will be supported by ESA at least until 2014. As the spacecraft is aging, the remaining propellant is becoming a potentially life limiting resource and effort is put into developing methods to save fuel. The fuel demand of Mars Express originates mainly from reaction wheel momentum management called “wheel offloading” which is governed by the disturbance torques resulting from two external forces: ‘solar radiation pressure’ and ‘gravity gradient’. These external torques vary with the spacecraft attitude and are automatically counteracted by the on-board attitude control system using the reaction wheel assembly. The wheels accumulate a considerable load of angular momentum over time which needs to be off-loaded regularly by means of thruster actuations. In Mars Express operations an approach has been established to reduce the accumulated angular momentum by assuming an attitude which reverses the perturbation torques whenever the science schedule allows. This method saves approximately 20% fuel in routine operations by gradually cancelling out some of the angular momentum which has been earlier absorbed by the reaction wheels. This paper introduces a new fuel saving approach for Mars Express. It is based on the “Low Fuel Attitude” (LowFAT), a stable inertial attitude which has the special property that the angular momentum accumulated through external forces is nearly zero after every full orbit. The orientation of the spacecraft is chosen such that the gravity gradient component is counterbalanced by the solar radiation pressure component. In contrast to the first approach the new one cannot be used in routine science operations since a fixed attitude needs to be maintained continuously. But the fuel demand can be reduced to almost zero which makes this method useful for extended periods of suspended science such as the five weeks solar conjunction phase or, should this ever be required, a mission hibernation phase.

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Nomenclature

$\mathbf{T}$	=	torque
$\mathbf{H}$	=	angular momentum
$\mathbf{F}$	=	force
$\mathbf{F}^{\mathrm{Abs}}$	=	solar radiation absorption force
$\mathbf{F}^{\mathrm{Spec}}$	=	solar radiation specular reflection force
$\mathbf{F}^{\mathrm{Diff}}$	=	solar radiation diffusive reflection force
$\mathbf{r}_{Sun}, r_{Sun}$	=	vector spacecraft to Sun, distance spacecraft to Sun center of mass
$\mathbf{r}_{Mars}, r_{Mars}$	=	vector spacecraft to Mars, distance spacecraft to Mars center of mass
$\mathbf{r}^{CoM}$	=	vector location of center of mass in spacecraft frame
$\mathbf{r}^{CoP}$	=	vector location of center of pressure for a certain surface in spacecraft frame
$\mathbf{n}$	=	unit vector normal to surface
A	=	surface area
α	=	surface absorption coefficient
ρ^{Spec}	=	surface specular reflection coefficient
ρ^{Diff}	=	surface diffuse reflection coefficient
$p_{SRP}(r_{Sun})$	=	solar radiation pressure (function of the sun distance)
$\mathbf{I}$	=	spacecraft matrix of inertia
μ_{Mars}	=	Mars gravitational constant

I. Introduction

MARS Express (MEX) is the first European mission to our neighbor planet Mars. It was launched on 2nd June 2003 from Baikonur, Kazakhstan, and arrived in Mars orbit on 25th December of the same year. Since then it has been successfully executing its task of collecting scientific data with its seven payload instruments in the search for water and traces of life on the red planet[1]. Originally designed for a lifetime of two Martian years which was achieved in 2007 it is now operating already in its fifth Martian year. One of the life limiting factors of the mission could be the exhaustion of the consumable Monomethylhydrazine (MMH) which is the fuel component of its liquid bi-propellant propulsion system. After more than eight years in orbit the remaining fuel amounts to only 7.5 kg MMH according to mass bookkeeping with an uncertainty of ±8 kg which was introduced during the long burn of the orbit insertion maneuver[6] and an unknown amount of unrecoverable fuel due to the tank design which is in the order of 2 kg[7,8]. With an average consumption of 485 g per year[*] the fuel could be enough for another 15 years of operations or it could be depleted at any time. Thus, to increase the mission lifetime, strategies for fuel economic operations are developed[2,3].

This paper gives a short overview of the operations concepts, constraints and fuel demanding factors which lead to the development of two different approaches to save fuel. The "Warm-up" approach[3,4] which has been established in routine operations already in 2007 will be briefly discussed. A second and new approach called the low fuel attitude (LowFAT) will be introduced and discussed in detail.

II. Mission Background

The following subsections provide an overview of basic notions and concepts specific to the Mars Express mission which are required to understand the details about its fuel demand and the fuel saving approaches.

A. Spacecraft

MEX is a three-axis-stabilized spacecraft which consists basically of a box shaped body of 1.4 m side length with 3.5 m x 1.8 m solar arrays (SA) attached to its +Y and –Y faces. They can be individually rotated around an axis in Y direction of the spacecraft body frame. The SA rotation axis has an offset towards +Z from the center of mass such that the spacecraft has the tendency for passive attitude stabilization during an aerobraking maneuver.

[*] According to mass bookkeeping, starting from September 2006.

This maneuver was envisaged for the contingency case where chemical propulsion would not have achieved the desired orbit, however, it has never been and will never be performed. Most of the payload instruments are integrated in the +Z face and also pointed in +Z direction in spacecraft frame. The high gain antenna (HGA) is fixed on the +X face and pointed in +X direction. It is used for communication with Earth in X- and S-Band. While the main engine is mounted in the center of the –Z face just below the center of mass, maneuvering thrusters are located at each of the four corners of the –Z face, all pointed in –Z direction. The –X face is equipped with star trackers and radiators.

B. Orbit and Operations Concept

MEX orbits Mars in a highly eccentric polar orbit with its apocenter at an altitude of 10,000 km and its pericenter 350 km above the planets' surface. It has an inclination of 86 degrees and an orbital period of 7 hours. Due to the fixed arrangement of instruments and HGA it is not possible to do science observations during Earth communication passes or vice versa. Therefore the mission timeline is a sequence of Earth pointings and science pointings with slew phases in between to rotate the spacecraft into the next target attitude. Maintenance slots are regularly inserted at every 3-5 apocenters to accommodate wheel off-loading maneuvers.

C. Attitude Control

The attitude and orbit control system (AOCS) of MEX is able to maintain a commanded attitude using a closed control loop. Star trackers and ring laser gyros provide measurement of attitude and rotation rates which are corrected by the control computer using reaction wheels and maneuvering thrusters as means of actuation.

In Earth pointing the spacecraft attitude is maintained by an auto guidance mode of the AOCS software. The auto guidance mode is designed to point the HGA towards Earth and align the SA rotation axis normal to the ecliptic plane such that maximum power output from the arrays is guaranteed. There are two possible configurations which satisfy the above mentioned constraints: the +Y solar wing may be pointed either towards ecliptic North or South. The preferred option is commanded by ground and for thermal reasons. By geometry, it is always selected North from solar opposition to solar conjunction and South from solar conjunction to solar opposition. Thus ensuring some solar illumination on the propellant pipework on the –Z face and thereby reducing the thermal power demand during the power-greedy communication sessions with the Earth.

III. Fuel Demand

The propulsion system of MEX is based on a liquid bi-propellant with MMH as the fuel component and Dinitrogen Tetroxide (NTO) as the oxidizer component. The 10N-thrusters operate most efficiently with a mixture of approximately 2:3 MMH:NTO. At present, the remaining amount of NTO (about 20 kg) is more than 1.5 times the amount required to burn all of the remaining MMH and is therefore not a critical issue for the mission lifetime. On average MEX requires about 350 g of propellant (= 140 g MMH + 210 g NTO) per year in routine operations which can be fully attributed to reaction wheel angular momentum management (wheel off-loading). Additional requirements arise from 1-2 orbit control maneuvers per year (approx. 50-165 g propellant) and occasionally from a safe mode (approx. 150 g propellant). These are not further discussed here as they are in general unavoidable and do not exhibit any potential to save fuel.

As major contributing factor to the fuel demand of MEX, we will briefly discuss here the angular momentum management and the external perturbation forces which are driving it.

D. Angular Momentum Management

The reaction wheel assembly (RWA) of MEX consists of four reaction wheels (RW) in a tetrahedral configuration. The default wheel levels (±5 Nms) are chosen such that every wheel is running at roughly half of its maximum speed (±12 Nms) and the total spacecraft angular momentum is zero. The wheels are required individually to always operate at speeds that correspond to an angular momentum between 1 and 10 Nms. As time passes the perturbation torques act on the spacecraft and disturb its attitude. The attitude control loop reacts by commanding the RWs to produce a counter torque to the disturbances. This way the wheels absorb any external torques and accumulate angular momentum according to Euler's moment equation,

$$d\mathbf{H} / dt = \mathbf{T} \tag{1}$$

To avoid any of the four wheels reaching their operational limits regular wheel off-loading maneuvers (WOL) need to be performed in order to neutralize the accumulated momentum. During such a WOL maneuver the wheels are reset to levels specifically calculated in anticipation of the disturbance torques to be absorbed until the next WOL maneuver. The attitude control computer is switched to a dedicated WOL phase which allows to counteract disturbance torques by means of thruster firings. In this mode the torques caused by setting the wheel speeds to pre-calculated levels act as a disturbance to the attitude and are therefore compensated by thruster actuations. On MEX, WOL maneuvers are performed every 3 to 5 orbits which is about once per day. The average fuel consumption attributed to WOL amounts to approximately 1g of propellant (=0.4 g fuel) per day which neutralizes about 1.43 Nms of angular momentum[4].

E. Disturbance Torques

The angular momentum build-up on the reaction wheels is governed by two external perturbation forces:

1. Solar Radiation Pressure

Solar radiation pressure (SRP) is a force experienced by all surfaces exposed to sunlight. It is exerted by photons which transfer momentum to a surface upon absorption or reflection. In space it can be a significant cause of orbit and attitude perturbation. The structural design of MEX with its center of pressure located at an offset from the center of mass provides aerodynamic stability for the aerobraking attitude. But the same design causes solar radiation pressure to generate a torque around the spacecraft –Y-axis unless the –Z face or any Y face points to the sun which is restricted to short periods of time for thermal reasons. The maximum SRP torque is generated when the +X face points to the sun which happens in Earth pointing at small Sun-Mars-Earth angles (SME) e.g. solar conjunction or opposition.

Knowledge of spacecraft technical specifications such as surface geometry and surface optical properties as well as spacecraft attitude and position with respect to the sun allows to model the SRP torque using Eqs. (2-6)[5], where the index *i* denotes a quantity or property attributed to the *i*-th contributing partial surface.

$$\mathbf{F}_i^{Abs} = -\frac{\mathbf{r}_{Sun}}{r_{Sun}} \alpha_i \left(\frac{\mathbf{r}_{Sun}}{r_{Sun}} \cdot \mathbf{n}_i \right) A_i \, p_{SRP}(r_{Sun}) \tag{2}$$

$$\mathbf{F}_i^{Spec} = -\mathbf{n}_i \, 2\rho_i^{Spec} \left(\frac{\mathbf{r}_{Sun}}{r_{Sun}} \cdot \mathbf{n}_i \right)^2 A_i \, p_{SRP}(r_{Sun}) \tag{3}$$

$$\mathbf{F}_i^{Diff} = \left(\frac{\mathbf{r}_{Sun}}{r_{Sun}} - \frac{2}{3} \mathbf{n}_i \right) \rho_i^{Diff} \left(\frac{\mathbf{r}_{Sun}}{r_{Sun}} \cdot \mathbf{n}_i \right) A_i \, p_{SRP}(r_{Sun}) \tag{4}$$

$$\mathbf{F}_i = \mathbf{F}_i^{Abs} + \mathbf{F}_i^{Spec} + \mathbf{F}_i^{Diff} \tag{5}$$

$$\mathbf{T}_{SRP} = \sum \mathbf{T}_i = \sum \left[\left(\mathbf{r}_i^{CoP} - \mathbf{r}^{CoM} \right) \times \mathbf{F}_i \right] \tag{6}$$

2. Gravity Gradient

Gravity gradient (GG) torque is a phenomenon experienced by bodies with a non-spherically-symmetric mass distributions in a gravitational field which is usually the case for any spacecraft orbiting a planet in a low orbit. Parts of the spacecraft which are closer to the planet experience a stronger gravitational force than the parts more distant. This force gradient leads to a torque which will eventually result in the alignment of the principal axis of inertia which has the smallest inertia coefficients with the nadir direction. Knowing MEX' matrix of inertia, its attitude and orbital position we can model the GG torque using Eq. (7).[5]

$$\mathbf{T}_{GG} = \frac{3\mu_{Mars}}{r_{Mars}^5} \left(\mathbf{r}_{Mars} \times [\mathbf{I} \cdot \mathbf{r}_{Mars}] \right) \tag{7}$$

IV. Fuel Saving Methods

A. Warm-up Attitude

Since 2006 an activity called "Warm-up" is routinely performed between science observations whenever the spacecraft is idle and also not communicating with Earth. It was originally introduced to further increase the heating up of the spacecraft –Z face with sunlight in order to reduce the demand for heater power. A degree of freedom of orientation around the sun direction allows to optimize the Warm-up attitude for angular momentum reduction and effectively to save fuel[3]. The orientation of the spacecraft in Warm-up is chosen such that the attitude perturbation torques reduce the angular momentum load on the wheels. Consequently the thrusters need to be fired fewer times during the next WOL maneuver in order to reach the target wheel levels. One year of routine operations with Warm-up slots inserted, where possible, saves an amount of fuel which is approximately equivalent to three months of routine mission (85 g, equivalent to consumption in 86 days)[4].

B. Low Fuel Attitude - LowFAT

During solar conjunction, when the sun is passing through between Earth and Mars, communications between MEX and Earth can be impaired or even interrupted as the signals are travelling through the plasma of the solar corona. Furthermore, the one-way-light-time reaches its maximum in that phase. To avoid loss of science data or corruption of telecommands and to reduce the risk of other operational anomalies payload operations are suspended for up to 5 weeks around the minimum of the Sun-Mars-Earth angle. In those 5 weeks the spacecraft is constantly kept in Earth pointing with the auto guidance being flipped from the North option to the South option in the middle. For the solar conjunction of Mars on 04/02/2011 science payload operations were suspended from 17/01/2011 to 20/02/2011. The resulting monotonous attitude profile caused an accumulation of angular momentum approximately three times the amount accumulated during routine operations. A study was conducted before hand to explore possibilities of reducing the fuel demand during this idle period. This study lead to the discovery of the LowFAT.

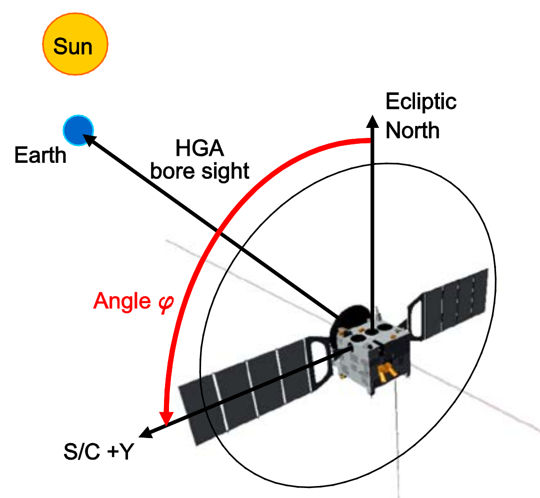

Figure 1: Illustration of the angle phi.

1. *Approach*

In contrast to the Warm-up approach, which aims to generate as much counter torque as possible to reduce already accumulated angular momentum in the RWA, the LowFAT approach aims to assume an attitude which generates a minimum net torque per orbit. During the target period of the solar conjunction it was mandatory to keep the HGA pointed to Earth in order to allow monitoring of the link quality. Under this given constraint there is only one degree of freedom remaining i.e. the orientation of the SA axis when the spacecraft is rotated around the HGA bore sight. In the following text this degree of freedom shall be denoted as angle ϕ, defined as the deviation angle of the spacecraft Y-axis from its nominal orientation in auto guidance with North option (see Fig. 1).

Using the disturbance torque model

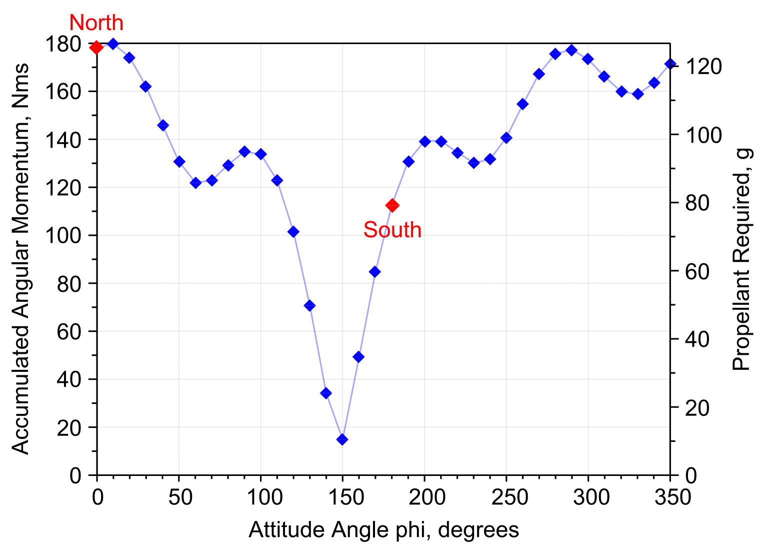

Figure 2. Angular momentum accumulated at different values of the angle phi. *Calculated for the conjunction period from 17/01 to 20/02/2011. The scale on the right shows the amount of propellant necessary to neutralize the accumulated angular momentum.*

(Eqs. 6,7) we can now calculate the expected total accumulated angular momentum if the spacecraft is kept Earth pointed at a fixed value of ϕ for the duration of the whole conjunction phase. This is repeated for a series of different values of ϕ covering the full circle. Figure 2 shows the result for the 2011 conjunction phase with a sampling resolution $\Delta\phi = 10$ degrees. The figure shows that there is an optimum angle at about $\phi = 150$ degrees at which the accumulated angular momentum and therefore the fuel consumption could be minimized to about 9% of what would be required by the North option or about 14% compared to the South option. It also shows that using the South option for the whole period would be approximately by a third cheaper than the North option.

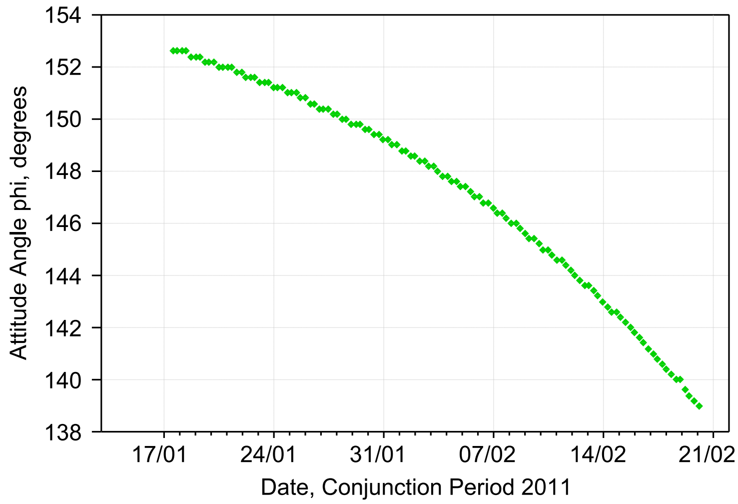

Figure 3. Optimized attitude angle phi as function of time. *Calculated for the conjunction period from 17/01 to 20/02/2011.*

Using a higher sampling resolution $\Delta\phi$ around the minimum the optimum ϕ can be calculated per orbit. This results in a fully optimized attitude profile which reduces the total accumulated angular momentum to less than 5 Nms for the whole conjunction period (approx. 5% of South option). Figure 3 shows the optimized angle per orbit for the 2011 conjunction phase with a sampling resolution $\Delta\phi = 0.2$ degrees.

2. In-Flight Verification

New operational concepts and methods are not easily introduced and adopted as routine operations in practice. Especially not during mission phases like the conjunction period during which commanding is not guaranteed and possibilities to react to a critical situation are limited. For this reason the LowFAT was not implemented throughout the whole conjunction period in 2011 but the South option of the auto guidance was chosen instead. To provide in-flight verification of the calculated predictions and to gain operational confidence for a full adoption in later conjunctions, the LowFAT was implemented for five orbits near the end of the 2011 conjunction idle period. At this time the probability of communication link disruptions had reduced to normal levels. Figure 4 shows the evolution of all four RW angular momentum levels as recorded from spacecraft telemetry during the test period including nine orbits before and two orbits after the test. On four occasions the reset of the wheel speed levels by WOL maneuvers can be observed. It is noticeable that during the LowFAT test orbits the wheel levels just oscillate around a relatively constant mean level close to ±5 Nms. In contrast to this the mean wheel levels show a steady linear increase/decrease of momentum in the orbits before and after the LowFAT test when the spacecraft was in auto guidance with South

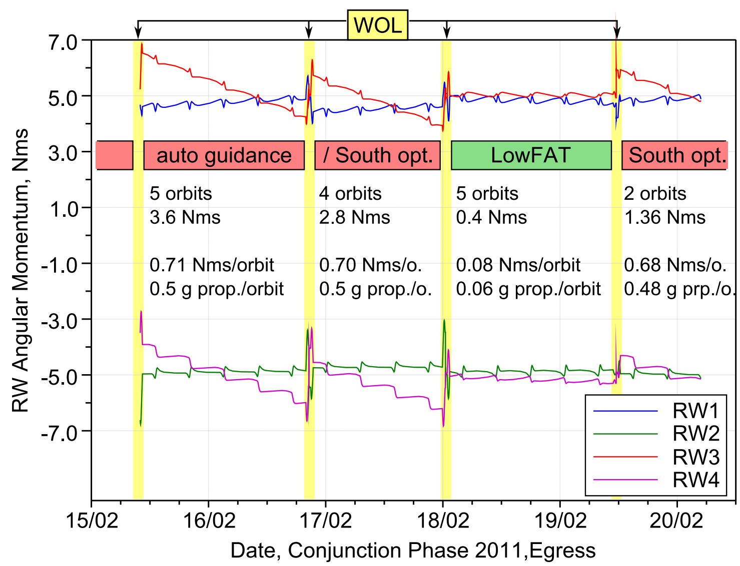

Figure 4. Reaction wheel levels during LowFAT test from s/c telemetry. *For periods between wheel off-loadings additional information is displayed: number of orbits, total angular momentum build-up, build-up per orbit and propellant required per orbit. In LowFAT the build-up of angular momentum is significantly smaller than in the adjacent auto guidance phases.*

option. While the oscillation is caused by the high eccentricity of MEX' orbit around Mars and the dynamic nature of the GG torque which is strongest at pericenter, the linear change can be attributed partially to both GG and SRP. The optimized LowFAT attitude causes the residual part of the GG over one orbit to neutralize the SRP.

3. Efficiency

The in-flight verification allows to conclude that an implementation of the LowFAT throughout the whole conjunction period could have saved up to 75 g propellant (with respect to the auto guidance South option, Fig. 2) which is equivalent to about 2.5 months of the yearly budget for WOL. Assuming similar results for future conjunctions and taking into account that solar conjunctions with Mars occur only every 2 years we can infer that the LowFAT has the potential to extend MEX' science operations by about 38 days per year. This is nearly half as efficient as the Warm-up approach which allows – if routinely applied - to save approximately 85 g propellant per year, equivalent to a lifetime extension of about 86 days. Although the LowFAT has a stronger immediate effect than Warm-up it is applicable only for very limited periods of time as it does not support science operations in parallel. In contrast to that, the Warm-up attitude can be integrated in routine operations without interfering with the payload operations plan.

C. Applicability of LowFAT to other Spacecraft or other Mission Phases

1. LowFAT for other Spacecraft

Any spacecraft in Mars orbit which was designed to endure an aerobraking phase should be able to apply the LowFAT principle during a solar conjunction of Mars. But in general the following conditions should be met for other spacecraft, be it in Mars orbit or around any other planet, in order for the LowFAT to be useful.

1) Fuel/Propellant must be a potentially life limiting factor for the mission.
2) A major part of the fuel demand is caused by WOL. If most of the fuel is spent on orbit maintenance (e.g. Venus Express) then a few grams of fuel saved by a clever attitude are unlikely to make a difference in the mission lifetime.
3) At least two independent perturbation forces are causing attitude perturbation. Otherwise only the Warm-up approach works, i.e. alternating build-up attitude and counter acting attitude.
4) There must be at least one degree of freedom in attitude. If there is no degree of freedom in the attitude then there is no room for optimization.
5) The spacecraft must go through an idle period such as MEX in conjunction. Holding permanently a specifically optimized attitude should not clash with any on-going payload operations or earth communication.

2. A Hibernation Phase for Mars Express

The lander relay radio of MEX is still a valuable asset for ESA in Mars orbit as it can be used to support future lander missions[2,3]. In case this is required in a hypothetical scenario where the financial support for the MEX mission has ended before the arrival of the lander, the LowFAT could be considered as a possibility to keep MEX operational in a hibernation-like state. This way MEX could be conserved at minimum costs of on-board and ground resources to provide monitoring of the entry, descent and landing sequence (EDL) and relay support for a future surface mission. To maintain a degree of freedom for the attitude without violating thermal constraints outside of conjunction the permanent Earth pointing constraint would need to be lifted in such a phase. Instead, only a minimum frequency of regular ground contact would be scheduled for monitoring purposes.

V. Conclusion

The two different approaches "Warm-up" and "LowFAT" complement each other since the former allows to save fuel during routine science mission phases while the latter yields a high efficiency in extended periods of suspended payload operations, i.e. solar conjunction periods. Together they have the potential to extend Mars Express' lifetime from the fuel perspective in the order of 16 months. Assuming the mission support is extended by ESA until mid-2016 the LowFAT could be implemented in two future conjunction phases (2013 and 2015) yielding a lifetime extension of 5 months. Additionally the Warm-up attitude could be applied during four years of routine operations adding another 11.5 months lifetime extension.

While the LowFAT can help in the future to reduce an elevated fuel demand during conjunction periods to a level below average consumption in routine operations it has also been considered as an approach to potentially preserve the spacecraft beyond the end of its science mission in a hibernation-like state. This way it could be used to monitor EDL phases of future Mars landers and provide relay support while being kept operational at minimum costs of on-board and ground resources.

Appendix A
Acronym List

AOCS	attitude and orbit control system
CoM	center of mass
CoP	center of pressure
EDL	Entry, descent and landing
ESA	European Space Agency
ESOC	European Space Operations Centre
GG	gravity gradient
HGA	high gain antenna
LowFAT	low fuel attitude
MEX	Mars Express
MMH	Monomethylhydrazine, liquid rocket fuel
NTO	Dinitrogen Tetroxide, liquid oxidizer for MMH
RW	reaction wheel
RWA	reaction wheel assembly
S/C	Spacecraft
SA	solar array
SME	Sun-Mars-Earth angle
SRP	solar radiation pressure
WOL	wheel off-loading

Appendix B
Glossary

Aerobraking	Maneuver which utilizes aerodynamic drag forces to slow down a spacecraft at pericenter in order to lower its apocenter altitude at very low fuel cost.
Centre of pressure	Point of attack of aerodynamic forces on a body or surface.
One way light time	Time a signal takes to travel from the ground station antenna to the spacecraft or vice versa. Accordingly the two way light time is the time it takes to receive confirmation for the reception of a command sent to the spacecraft.
Solar conjunction	A phase during which the Sun-Earth-Planet angle is close to zero degrees such that the planet appears to be aligned with the sun. Occurs roughly every two years for the Sun-Earth-Mars system.
Solar opposition	A phase during which the Sun-Earth-Planet angle is close to 180 degrees such that the planet appears to be opposite of the sun. Occurs halfway between conjunctions for the Sun-Earth-Mars system.

Acknowledgments

J. Bauer thanks the German Aerospace Center (DLR) for the financial support he received in the frame of the German Trainee Programme, during which the numerical evaluation of the “Warm-up” attitude and the development and verification of the “LowFAT” was achieved.

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