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AUTONOMOUS AEROBRAKING: A DESIGN, DEVELOPMENT, AND FEASIBILITY STUDY

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Aerobraking has been used four times to decrease the apoapsis of a spacecraft in a captured orbit around a planetary body with a significant atmosphere utilizing atmospheric drag to decelerate the spacecraft. While aerobraking requires minimum fuel, the long time required for aerobraking requires both a large operations staff, and large Deep Space Network resources. A study to automate aerobraking has been sponsored by the NASA Engineering and Safety Center to determine initial feasibility of equipping a spacecraft with the onboard capability for autonomous aerobraking, thus saving millions of dollars incurred by a large aerobraking operations workforce and continuous DSN coverage. This paper describes the need for autonomous aerobraking, the development of the Autonomous Aerobraking Development Software that includes an ephemeris estimator, an atmospheric density estimator, and maneuver calculation, and the plan forward for continuation of this study.

INTRODUCTION

NASA uses aerobraking to reduce the fuel required to deliver an orbiter into its desired final orbit around a target planet or moon that has an appreciable atmosphere. Rather than using the propulsion system to decelerate the spacecraft after initial orbit insertion, aerobraking decelerates the spacecraft using aerodynamic drag. An orbital spacecraft is not normally designed with aerodynamics in mind or with a thermal protection system to protect it from atmospheric heating. Therefore, while the spacecraft is aerobraking, it must traverse through the upper atmosphere of the planet or moon multiple times while keeping the aerodynamic loads and heating to very low levels during each pass. Small propulsive maneuvers at apoapsis are used to control the altitude at periapsis to maintain the spacecraft within its designed periapsis control corridor as illustrated in figure 1. The periapsis control corridor may in terms of dynamic pressure, a heat rate indicator, or even atmospheric density, but typically the corridor is constrained by spacecraft temperature, which is the limiting parameter on the vehicle. Using this multiple-pass through the upper atmosphere approach enables the spacecraft's design loads to remain within its designed parameters and while achieving an appropriate final science orbit.

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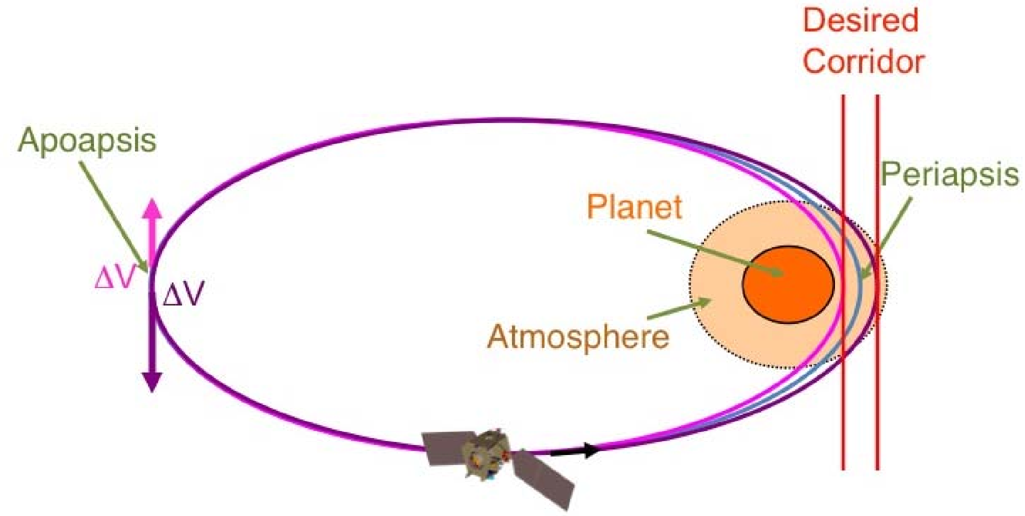

Figure 1. A spacecraft using apoapsis maneuvers to control periapsis altitude during aerobraking.

NASA has used aerobraking four times to modify a spacecraft's orbit to one with lower energy, reduced apoapsis altitude, and smaller orbital period. Aerobraking was first demonstrated by the Magellan spacecraft at Venus[1]. For this spacecraft operations cycle, aerobraking was completed at the end of its primary mission, demonstrating the concept of aerobraking and reducing the orbital period from just over three hours to just under two. This successful demonstration led to the use of aerobraking as a mission enabling capability for three Mars orbiters: Mars Global Surveyor (MGS)[2], Mars Odyssey[3], and Mars Reconnaissance Orbiter (MRO)[4]. A brief comparison of these four missions can be found in Table 1.

Table 1. A comparison of aerobraking spacecraft.

	Magellan	MGS	Odyssey	MRO
Launch Year	1989	1996	2001	2005
Dry Mass (kg)	1035	677	380	968
AB Orbits	730	886	330	428
AB Days	70	17 months	77	149
AB Period Change (hr)	3.2-1.6	45-1.9	18-2.0	34-1.9
ΔV Savings (m/s)	1220	1220	1090	1190
Propellant Savings (kg)	490	330	320	580

Although aerobraking reduces the propellant required to reach the final orbit, this reduction comes at the expense of time, continuous Deep Space Network (DSN) coverage, and a large ground staff currently required for aerobraking operations. This combination of DSN and workforce results in aerobraking being an expensive operational phase of a mission[5]. The first aerobraking demonstration, Magellan, held the shortest aerobraking operations phase completing in 70 days. With such a small orbital period change in this duration, however, it is understood that a mission-enabling aerobraking phase to reduce a large-period orbit to a small science orbit at Venus would be considerably longer. If holding to the same relatively benign (low dynamic pressure, low heat rate indicator) periapsis corridor, aerobraking a Venus spacecraft could take years.[6]

With the development of Autonomous Aerobraking (AA), much of the daily operations could be moved to the spacecraft, thus reducing the cost of the aerobraking phase by several millions of dollars. The concept of autonomous aerobraking has been studied in depth over the past decade[7,8,9]. A first step in autonomous aerobraking occurred with the implementation of a periapsis timing estimator on MRO[10] that was tested during Mars Odyssey aerobraking operations. Further development that includes maneuver execution is required and is the subject of further discussion here. In the AA development described in this paper, the spacecraft would calculate and predict its own ephemeris (all aerobraking activities are referenced to a periapsis time and all periapsis altitude correction burns are performed at apoapsis). Using the subsequent orbit's predicted periapsis, the spacecraft would estimate its next predicted periapsis density using an onboard atmospheric model. If the predicted parameter control value (dynamic pressure, heat rate, temperature) is predicted to fall outside of the corridor, the spacecraft would determine the maneuver strategy to remain within the specified corridor. The spacecraft would design and execute any required maneuvers. Ground based weekly activities such as corridor updates (the operational corridor may change weekly if the spacecraft is off of its intended schedule), updates to model parameters (e.g. AADS gains), and overall mission strategy would remain as ground-based activities. Not only would providing this functionality of moving daily maneuver assessment to the spacecraft save significant cost in staff and DSN usage, but because the spacecraft would no longer be tied to the work schedule of the ground personnel (e.g., previously, maneuvers were ideally performed during staff's prime shift and outside of weekends and holidays), autonomous aerobraking also has the potential to reduce risk, as the maneuver could be conducted at the optimal time and executed even if DSN or other required ground elements were unavailable.

AA has been developed with support of the NASA Engineering Safety Center (NESC) over the past year and has demonstrated preliminary concept feasibility. This initial feasibility study is the first phase of an anticipated 4-year, three-phased study to develop and test the Autonomous Aerobraking Development Software (AADS). The concept study and overview of the AA development will be discussed in this paper.

AUTONOMOUS AEROBRAKING SUPPORT

The Autonomous Aerobraking development team consists of core members from three NASA centers, industry, and academia. The NESC provided programmatic support; NASA Langley Research Center provided study team leadership, thermal modeling, aerodynamic modeling, trajectory analysis, and simulation support. NASA Johnson Space Center provided aerodynamic and aerothermodynamic support. NASA Marshal Space Flight Center provided atmosphere modeling. Kinetx provided the Ephemeris Estimator. The Johns Hopkins University Applied Physics Laboratory (APL) developed a MESSENGER-based high fidelity simulation. The National Institute of Aerospace provided atmosphere models and analysis. Outside of this core development team, NESC support consisted of several technical fellows as consultants to the AA development work. In addition, a peer review consisting of a review board of technical fellows is scheduled for November 2011 to assess the results of Phase 1.

AUTONOMOUS AEROBRAKING: PHASE 1

During Phase 1 of the AA development study, atmospheric[11,12], aerodynamic[13], and thermal models[14] for a representative spacecraft were developed for both the onboard AADS as well as a ground-based "truth" simulation that is developed for testing purposes. An autonomous ephemeris estimator was developed and incorporated into the AADS[15]. In previous aerobraking mission experience, an increase in error in predicting the time of periapsis passage requires frequent (daily) ephemeris updates from the ground using tracking data from DSN. If high quality ephemeris estimation can be performed onboard, the number of required updates will be reduced. The goal for AA is the capability to allow over one week before requiring a ground update. This eliminates the requirement for continuous DSN coverage.

The "truth" simulations were developed using two separate tools: Program to Optimize Simulated Trajectories II (POST2)[16] at NASA Langley Research Center and a MESSENGER-based simulation at APL, the Autonomous Aerobraking High Fidelity Simulation (AA-HFS)[17]. The AADS is the onboard set of models and algorithms that is called from and tested against both "truth" simulations. This suite of models and algorithms within the AADS consists of the ephemeris model, an atmospheric density predictor, a thermal model (for Venus only), and maneuver logic. The maneuver logic was an adaptation of that which was developed for the ground-based Mars Odyssey mission analyses and refined for the Mars Reconnaissance Orbiter for mission design and operations[18]. This logic is used for onboard determination of daily maneuver decisions and execution based on AADS algorithms.

Three versions of the AADS were tested during Phase 1: one that carried a baseline heat-rate indicator (1/2 * atmospheric density*velocity^3) corridor at Mars, the second was a solar-panel temperature corridor at Venus, and a third held a dynamic pressure corridor at Titan. At each destination, nominal and some stressing aerobraking situations were designed to stress-test the software. For example, the benign polar orbit that was originally used for testing the AADS was not sufficient in identifying potential errors in the software. Modifying the orbit to cross the Tharsis Ridge over mars uncovered small, simulated gravitational differences that might not have been noticed over the "nominal" simulated state.

During Phase 1, performance was analyzed of the AADS against the "truth" simulations[19]: POST2 and the AA-HFS. Detail of the initial performance of the AADS-Mars against the POST2 simulation can be found in reference 19.

AUTONOMOUS AEROBRAKING: PHASE 2

Pending project approval, a second phase (14 months in duration) of development will follow Phase 1 that includes the transportation of the AA modules to a flight-like processor and for additional testing of the AADS. This hardware-in-the-loop processor will provide an interface by which it can be determined if a spacecraft is capable of processing and transmitting the necessary data for AADS computation and if that spacecraft can successfully execute the maneuvers dictated by the AADS. In addition phase 2 will determine the necessary processor characteristics, including storage requirements. The ephemeris and atmospheric density estimator require the accelerometer time history during the atmospheric pass, and the ephemeris estimator also requires the accelerometer history during any propulsive maneuver.

In addition to the flight-like processor analysis of autonomous aerobraking, the AADS will undergo further stress-testing in the POST2 and the high fidelity simulation environment. During Phase 1, the AADS was built for three destinations: Mars, Venus, and Titan. During Phase 2, more anomalistic environments will be introduced to ensure that the AADS is robust and will select the appropriate maneuver while considering spacecraft risk. For example, the AADS will select a maneuver that places the next periapsis within the designed corridor. Further development of the AADS will include additional error checks to ensure that this maneuver does not put the spacecraft in a situation in which a statistically feasible high-density could put the spacecraft at risk. These error checks and further investigation of 3-sigma atmospheric events will be a focus of Phase 2. Phase 2 will also incorporate emergency maneuver implementation into the AADS. As AADS is running after atmospheric exit, there will be a determination of the maximum heating of the drag pass just completed. If the heating is far higher than statistically anticipated and it crosses an “immediate action” pre-determined criteria, an overriding “up” maneuver must be made prior to the next drag pass to raise the periapsis altitude so that a ground based team can determine the next course of action. This emergency maneuver is something that has been calculated for every spacecraft aerobraking operations on the ground. For autonomous aerobraking, this contingency situation must be automated as well. These additions and improvements to the AADS will be ongoing within Phase 2 and Phase 3.

AUTONOMOUS AEROBRAKING: PHASE 3

Following the Phase 2 activity, Phase 3 is dedicated to determining the physical cost of aerobraking (e.g. dedicated processor, if required, implementation of autonomous aerobraking code within the MESSENGER-based code, etc.) as well as the limitations of autonomous aerobraking. Success is defined by the ability of AADS to maintain aerobraking effectiveness for up to one week at a time, without uploads from ground staff, for nominal as well as off-nominal aerobraking scenarios at Mars, Venus, and Titan. AADS improvements, tuning, and stress-testing will continue throughout Phase 3.

AUTONOMOUS AEROBRAKING: PHASE 4

It is anticipated that one of the next orbiters to use aerobraking to achieve science orbit will use AADS in a listen-only mode as a technology demonstration. This will be Phase 4 of AA. AADS, after three phases of ground-testing, will be implemented onboard an aerobraking orbiter, will employ AADS and will calculate desired maneuvers. It will not, however, execute these maneuvers. Aerobraking for this spacecraft will remain ground-based in which engineers in a mission control will continue to simulate trajectories and compute maneuver magnitude and timing. During aerobraking operations, the AADS-derived maneuvers, ephemeris and atmospheric density estimation capability will be compared to those determined by the ground-based staff. This will determine the efficacy and actual improvement over ground-based aerobraking operations that AADS could benefit a science mission. This Phase 4 shadow mode demonstration will also help identify any operational situations that would produce anomalous results that must be corrected before committing to flight.

The next aerobraking orbiter after this Phase 4 AA demonstration will then reap the benefits of autonomous aerobraking in reducing cost and risk to the orbiter mission.

CONCLUSION

Aerobraking is a long and arduous process that bears considerable cost and risk associated with ground-based analysis and maneuver determination. Autonomous Aerobraking is currently being developed in four phases that will lead to the elimination of millions of dollars in cost of a large aerobraking operations staff and continuous DSN coverage. Phase 1 will be completed in

November 2011 and will have produced three versions of the AADS for three periapsis control corridors at three potential destinations. Phase 2 is intended to test these modules in a flight-like environment, determining the physical cost of employing AADS on a spacecraft. Phases 2 and 3 will be spent stress-testing the software, ensuring that proper risk is assessed onboard. Phase 4 is a demonstration of the AA software in a shadow mode. This demonstration is intended to prove the efficacy of autonomous aerobraking and quantify the benefits to an aerobraking orbiter. The next orbiter to use AA in a flight operations environment should then see a comparable maneuver strategy with the spacecraft staying within the design corridor without the staffing burden of ground-based analysis and cost burden of continuous DSN coverage.

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NOTATION

AA	Autonomous Aerobraking
AADS	Autonomous Aerobraking Development Software
AA-HFS	Autonomous Aerobraking – High Fidelity Simulator
APL	Applied Physics Laboratory
DSN	Deep Space Network
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry and Ranging
MGS	Mars Global Surveyor
MRO	Mars Reconnaissance Orbiter
NESC	NASA Engineering and Safety Center
ODY	Mars Odyssey
POST2	Program to Optimize Simulated Trajectories

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