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Leveraging Mars Aerobraking Experience for the Venus Environment*

Tung-Han You [1] and Mark S Wallace[1]

[1] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, 91109, CA, United States*

Abstract

Aerobraking was first demonstrated at Venus during the Magellan extended mission in 1993 and on every Mars orbiter since, from the Mars Global Surveyor (MGS) in 1997 to ESA's Trace Gas Orbiter (TGO) in 2017. This paper illustrates the differences between aerobraking at Venus and at Mars from both the astrodynamics and thermal perspectives. It shows how the periapsis velocity hammers the drag versus aerothermal heating relationship with comparable aerothermal heating limits and initial conditions at Mars and at Venus. Even though there are noticeable differences in the aerobraking environment between these two planets, the Mars heritage operations, processes, tactics, and strategy remain the same while addressing these differences in mission design and environment. Additionally, the spacecraft design requirements, capabilities, and thermal guards are retained across projects and planets. The operations processes and procedures developed over the 20 years of Mars experience can be equally applied back to the birthplace of aerobraking: Venus.

Keywords: Aerobraking, AB, Aerobraking Navigation, Aerobraking Mission Design, Venus Atmosphere, Aerobraking Mission Operations, Heating Rate, Dynamic Pressure, Thermal Limit, Aerodynamic, Glideslope, ABM.

Introduction

Aerobraking is a common technique used to reduce the orbit period of a planetary orbiter by dropping periapsis into the upper atmosphere of a planet and using the resulting drag. The use of this technique can reduce the required delta-v budget by well over a thousand meters per second. It was first demonstrated at Venus during the Magellan extended mission [1,2] in 1993 and on every Mars orbiter since, from the Mars Global Surveyor [3] (MGS) in 1997 to ESA's Trace Gas Orbiter [4] (TGO) in 2017 . The operations processes and procedures developed over the 20 years of Mars experience can be equally applied back to the birthplace of aerobraking: Venus.

Aerobraking Mission and Trajectory Designs

Aerobraking mission design has many drivers. For some missions, such as the Mars Reconnaissance Orbiter [5] there is a need to achieve the science orbit by a certain time so that the sun-synchronous ascending node can be at the right local solar time. For others, there is a desire to complete aerobraking as quickly as possible. Regardless of what drives the timeline, the aerobraking mission profile must send the spacecraft deep enough into the atmosphere to get enough drag to be useful, but not so deep that the resulting aerodynamic environment exceeds a subsystem. The aerothermal heating could overheat the spacecraft, the drag torques could exceed the spacecraft's control authority, or the simple dynamic pressure could exceed a mechanical limit. In addition, particularly in the end game, the spacecraft's orbital lifetime must be sufficiently long as to avoid undue risk.

When designing an aerobraking trajectory, all of these things must be considered. The aerodynamic environment can be parameterized as a limit in three factors: the dynamic pressure (Equation 1), the dynamic heating (Equation 2), and the integrated heating (Equation 3):

$$q = \frac{1}{2}\rho v^2 \tag{1}$$

$$\dot{q} = \frac{1}{2}\rho v^3 \tag{2}$$

$$J = \int_{t_1}^{t_2} \frac{1}{2}\rho v^3 dt \tag{3}$$

where ρ is the atmospheric density, v is the velocity, and the times t_1 and t_2, are the duration of a drag pass. The dynamic pressure, when multiplied by a ballistic coefficient (area/mass ratio) and a coefficient of drag, will yield the acceleration due to drag. The goal then is to tune the drag to meet the timeline requirement without exceeding the limits placed on the other parameters. These limits frequently have significant (100% or more) margin applied to them to accommodate uncertainties in the atmosphere, navigation uncertainties, and manevuer execution errors.

The next key parameter is the operations tempo and orbital lifetime. How often are we permitted to perform a maneuver to tune the trajectory? The more frequently manevuers are executed, the more active the operations team must be, but the better the trajectory can follow the variations in atmospheric density or, more importantly, counter gravitational perturbations. Solar tides can drive the periapsis altitude up or down and the more frequently a manevuer can be performed, the more this effect can be countered. For example, if solar tides are pulling periapsis out of the atmosphere, a maneuver could target the lowest altitude consistent with meeting the aerodynamic requirements, but the drag on each subsequent pass would be less and less. If the tides are strong enough, or the manevuer frequency is low enough, periapsis could be pulled entirely out of the atmosphere.

The question of orbital lifetime can be thought of as a missed-maneuver constraint. How long must the trajectory meet the dynamic pressure, dynamic heating, and/or integrated heating limits if a maneuver is missed for any reason? The longer this duration, the less risk is incurred by dipping into the atmosphere, but the longer aerobraking might take. For example, if solar tides are pushing periapsis down into the atmosphere, this factor would force each maneuver to target altitude higher than would otherwise be desired so that the aerodynamic limits would not be met until at least the end of the missed-maneuver "buffer."

The Venus environment is very different from that of Mars. First, and most obviously, Venus orbits the sun at approximately half the distance as Mars: 0.72 vs. 1.5 AU. The solar heating, then, is approximately four times as great. In addition to this heating, the planetary IR at Venus is much greater. Both of these effects have impacts on the spacecraft design. You cannot take a Mars spacecraft and expect it to work at Venus with no modification. Fortunately, these effects are well-understood and can be accommodated with standard design processes. The second effect of Venus being so much closer to sun is less obvious. Solar tides are significantly stronger at Venus than at Mars, as in Equation 4.

$$a_s = -\mu_s \left(\frac{\vec{d}}{d^3} + \frac{\vec{\rho}}{\rho^3} \right) \tag{4}$$

where a_s is the acceleration due to the sun, μ_s is the solar gravitational parameter, $\vec{d}$ is the sun-to-spacecraft vector (d is the magnitude), and $\vec{\rho}$ is the planet-to-sun vector (with ρ being its magnitude). In the case of a spacecraft that is 100,000 km from its respective planet in a direction orthogonal to the sun line, the solar tide acceleration is 10 times greater at Venus than at Mars. It does not require a particularly large orbit for this effect to be large enough to require consideration at Venus.

The second significant difference between Venus and Mars is the length of the sidereal day. Mars rotates just slightly slower than Earth and so it has a comparable J2 and familiar perturbations on the obit. The largest effect is that the spacecraft team must be prepared to deal with the resonances the orbit perturbations encounter as the orbit period becomes a rational fraction of the sidereal day [6,7]. Venus, however, rotates extremely slowly: once every 243 days. The result is that low orbits feel the same high-frequency perturbations revolution after revolution as the ground track moves only 10 km or so per orbit. As for lunar orbiters, [8,9], the effect is to drive significant eccentricity vector perturbations, which also drive significant periapsis variation. As a result of this and the solar tides, a Venus aerobraking trajectory changes from a tide-dominated periapsis variation to a non-spherical gravity periapsis variation as the orbit period is reduced and care must be taken in the design to account for both.

Finally, and most critically, Venus is significantly larger than Mars, with a gravitational parameter an order of magnitude larger. As a result, the spacecraft's velocity at periapsis, for the same orbit period and periapsis altitude, is about 2.1 times as large, as illustrated in Figure 1. Since drag goes as the square of velocity (Equation 1) this is advantageous to the designer. However, the heating goes as the cube (Equations 2 and 3), and so the same heating is experienced at 10% of the density, and so for a constant permissible heat rate, the spacecraft can only go as deep as about 10% of the density and about 2.1 times less drag.

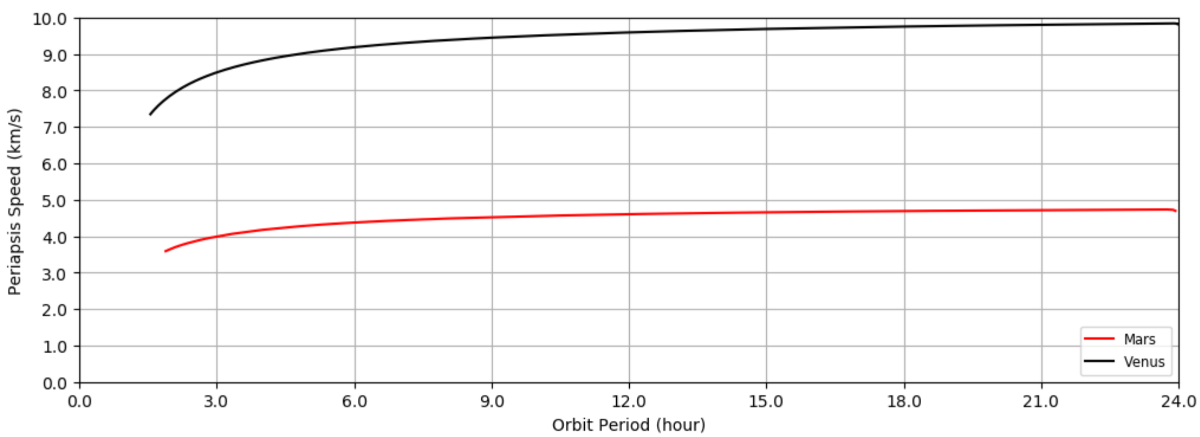

Figure 1: Periapsis Velocity at Mars and at Venus

Consider a simple case of two 2000 kg spacecraft with 50 m^2 of drag area, one at Mars and the other at Venus. Both are in 92° inclined, 24-hour orbits around their respective planets and want to reduce their apoapsis altitude to 486 km. For the Mars mission, aerobraking would accomplish the equivalent of 1140 m/s of ΔV, while the Venus example requires more than twice that: 2500 m/s. Both spacecraft can accept a maximum dynamic heating of 0.12 W/cm^2 and are willing to do a maneuver every 24 hours so as to minimize the duration of aerobraking and apply a 48-hour missed-maneuver buffer. We ignore, here, the fact that *solar* heating at Venus is four times that at Mars. The assumption is that these two spacecraft have been appropriately engineered for their thermal environments. The time history of dynamic heating is illustrated in Figure 2, the per-pass drag ΔV in Figure 3, with the resulting orbit period vs. time is illustrated in Figure 4. All three figures also illustrate the effect of doubling the allowable heating rate for the Venus case.

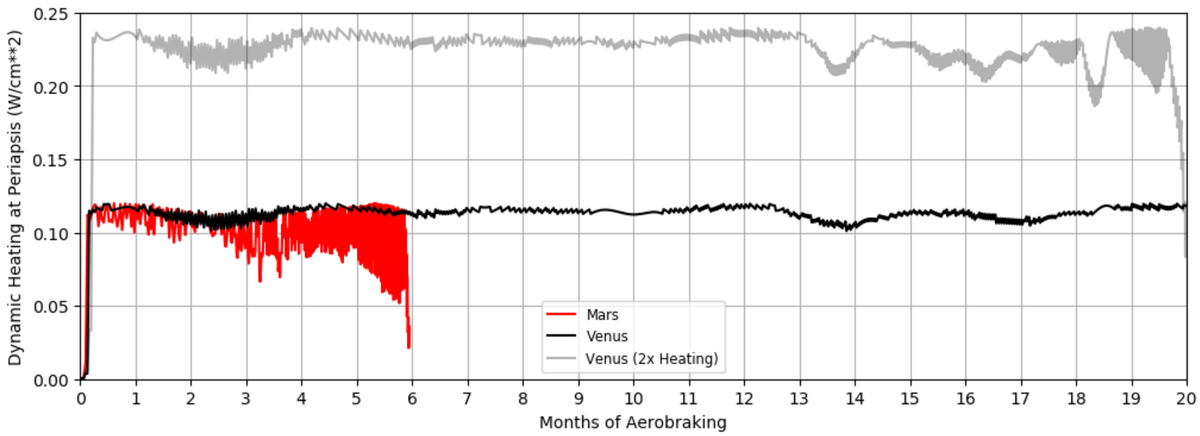

Figure 2: Comparison of Heating Rates for Example Aerobraking Trajectories

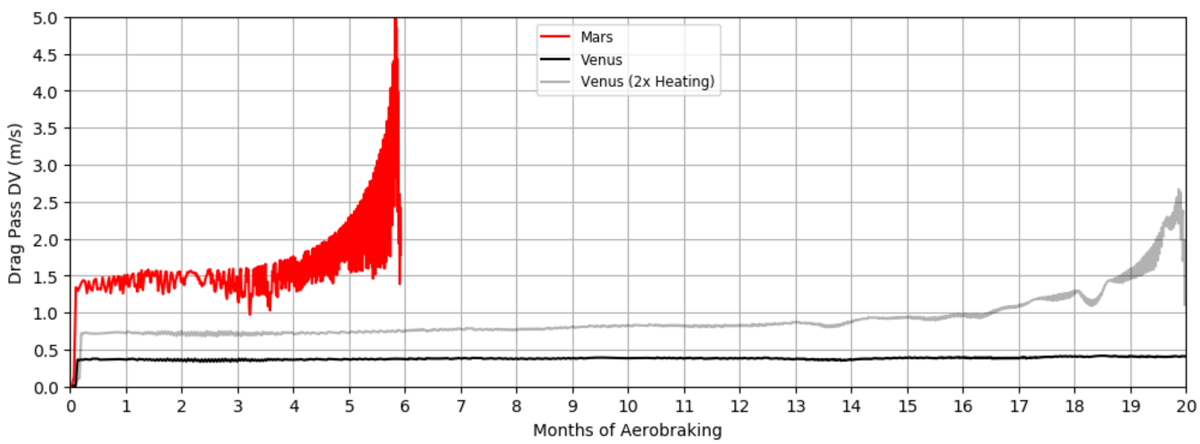

Figure 3: ΔV Due to Drag for Example Aerobraking Trajectories

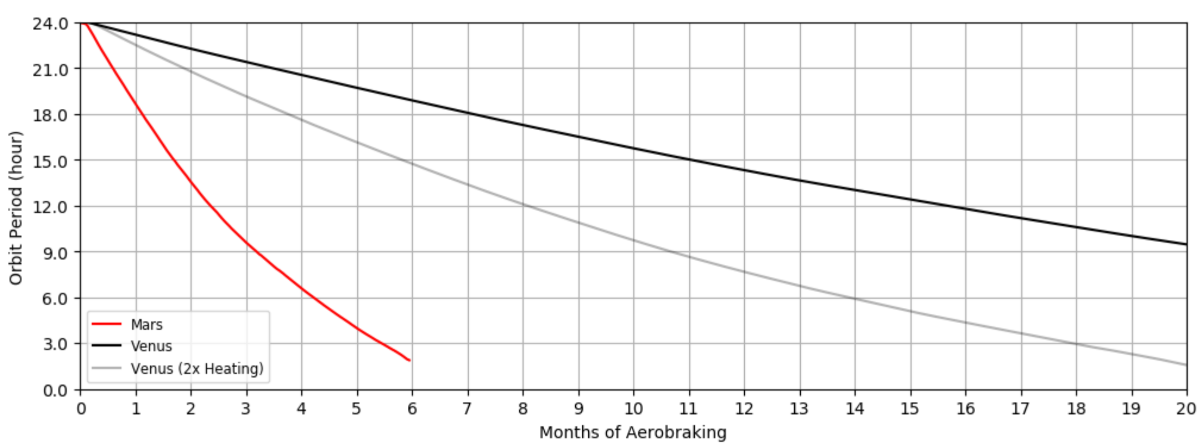

Figure 4: Orbit Period vs. Time for Example Aerobraking Trajectories

Clearly, the reduction in the drag ΔV, coupled with the need for more ΔV in the first place, leads to very long aerobraking campaigns at Venus, all else being equal. The 0.24 W/cm^2 case required 20 months, compared to the six-month campaign at Mars with half the allowable heat rate (0.12 W/cm^2). Holding the heat rate constant requires an additional 10 months, at least. As a result, Venus aerobraking campaigns will generally be much longer than the typical Mars mission, requiring significant period reduction contributions propulsively (e.g. by stepping down the orbit), higher acceptable heating rates, or all three.

All of these differences between aerobraking at Mars, where we have a wealth of experience, and Venus, the birthplace of aerobraking, are important. However, once they are properly considered in the trajectory design, they do not impose dramatically different processes and procedures for mission operations than those honed over the decades.

Mission Operations

Aerobraking Operations Overview

The first planetary aerobraking mission was performed on NASA's Magellan (MGN) mission in 1993 jointly by Jet Propulsion Laboratory and Martin Marietta (now Lockheed Martin). Even though Magellan flight systems were not specifically designed for conducting aerobraking and the Venus atmospheric model was primitive, it successfully reduced its orbit from ~8500 km to ~540 km in a little more than two months. It saved more than 1.3 km/s of ΔV that it did not possess at the time [10]. This made high-resolution gravity science possible.

Magellan's breakthrough in aerobraking techniques enabled missions to benefit from free ΔV in the form of atmosphere drag. It served as a foundation for the follow-up aerobraking missions, basically all aerobraking missions thereafter, including the recent successful ESA aerobraking mission - ExoMars Trace Gas Orbiter. It not only greatly influences the operation, configurations, and processes, but also affects the spacecraft design. All aerobraking missions to date were successfully carried out regardless if it took place at Mars or Venus.

One of the important factors making aerobraking operations routine and effective is the utilization of heritage processes. From the dawn of the aerobraking operations, the community clearly understood aerobraking challenges and risks. Despite the fact that there were a handful of aerobraking and aerobraking-like (e.g. Mars Atmosphere and Volatile EvolutioN, MAVEN) executions at Mars since the Mars Global Surveyor mission, there was no identical atmospheric profile experienced. Every flight path was different in terms of space environment. Volatility and uncertainty are the natural *a priori* of the aerobraking operations. A successful implementation does not rely on how short the aerobraking duration is or the maturity of the atmospheric model. It depends on how well the processes are comprehended and executed with margins.

Configurations, Interfaces, and Capabilities

Aerobraking Phases

Traditionally, since the Magellan era, aerobraking operations have been mainly divided into Walk-in, Main, and Walk-out phases. Although there are slight variations in phase divisions or naming convention among missions, the core contents and features of the aerobraking-phase definition are similar. Mars Odyssey (ODY) split the Main phase into the Main and End-game phases [11]. MRO's "End-game" was part of its "Walk-out" phase. ESA's TGO used a different naming convention for the Main phase.

The walk-in period typically lasts from a few days to several weeks, depending on the spacecraft's capability and the space environment. Magellan completed its walk-in in 3 days while ExoMars Trace Gas Orbiter spent 47 days in its first Walk-in phase. There are no absolute rules to dictate the walk-in duration. The key is to gradually lower the orbit periapsis altitude comfortably in a series of steps carried out by executing propulsive maneuvers at the apoapsis. The "test-the-water" approach has two major purposes. First is to conservatively find the adequate atmosphere "layer" (i.e. to acquire the desired periapsis altitude) for the aerobraking main phase. Secondly, prior to committing to the Main-phase operations, it provides an excellent "first-look" opportunity to characterize the atmospheric conditions, gauge the spacecraft design and capability, and verify the aerobraking operation readiness state. Many "first time" events or activities are exercised in this phase, such as operation processes, interfaces, spacecraft and ground systems configurations, aerobraking command sequences, and atmospheric model correlations. This phase offers a chance to evaluate if operations are ready to initiate the Main phase.

A majority of the energy is removed during the Main phase. It typically takes a few months to a year to execute depending on the initial conditions, design approaches, target, environment, and trajectory geometry. Main-phase is characterized by using small propulsive aerobraking maneuvers (ABMs), executed at apoapsis, to fine-tune periapsis altitude to satisfy a defined corridor parameter (e.g. heating rate, dynamic pressure). The periapsis altitude needs to be low enough to produce adequate drag to achieve desired orbit within time constraints imposed by energy balance concerns relative to trajectory requirements. It also needs to be high enough to avoid violating spacecraft heating limits and/or maximum allowable dynamic pressure requirements.

Throughout aerobraking, a minimum orbit lifetime is maintained. During the walk-out phase, periapsis altitude is raised to satisfy orbit lifetime constraints, should problems occur during the final days of aerobraking. This may result in more frequent ABMs to meet this requirement. The walk-out phase lasts approximately a few weeks and is terminated with a periapsis raise maneuver (Aerobraking Exit maneuver, ABX) as part of the transfer to the target orbit.

Aerobraking Maneuvers

An aerobraking orbit is divided into three distinct segments – ABM block, telemetry downlinking/power recharging block , and drag-pass block.

An ABM block is illustrated in Figure 5; a "down" ABM is used to lower the periapsis altitude into the desired operations corridor, while an "up" ABM is executed to keep the spacecraft from exceeding the heating rate limit or other spacecraft constraints. Usually, a daily ABM opportunity is allocated. Most of the missions performed ABMs every other day or less.

An ABM ΔV is selected from a small pre-determined and pre-tested menu, typically about 10 – 20 ΔVs with spacing carefully chosen. Typically, the menu ranges from a few cm/s to several m/s. This is the only way to efficiently support rapid maneuver sequence development. The "up" and "down" directions are implemented using on-board orbital ephemeris. The thruster axis is ether along or opposite the inertial velocity vector. The heritage ABM configuration and process can be applied to aerobraking at Mars or at Venus as seen in Figure 5.

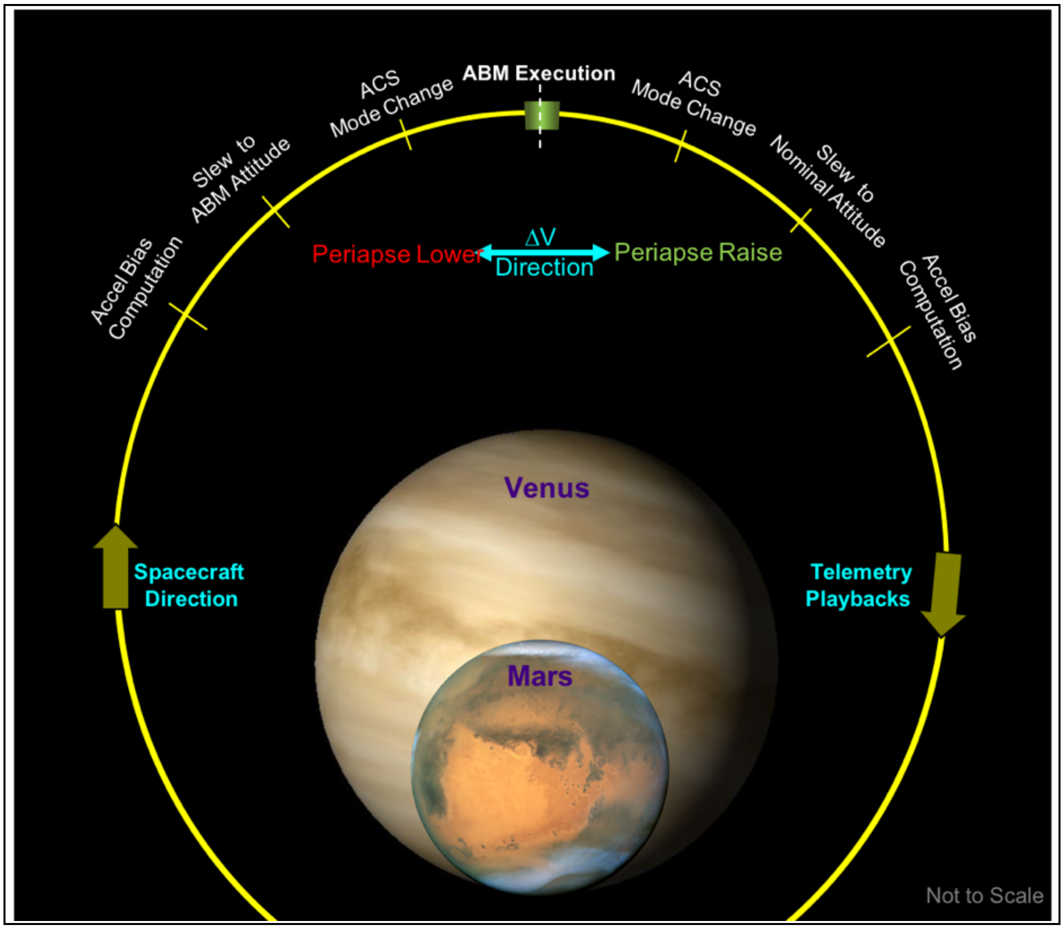

Figure 5: Typical Aerobraking Maneuver (ABM) Block

Mission	AB Duration, Month	Period Reduction, Hours	Corridor Control Parameter	Orbit Lifetime, Hours	Key Glideslope Parameters	Onboard Timing Adjust	Pop-up ABM[a]	No. ABM[b]	Remark
MGN (Venus)	**2.4** (1993)	3.2 to 1.5	Dynamic Pressure	N/A	Period	No	0	14	First Planetary Aerobraking
MGS (Mars)	**10.5** (1997-99)	45.0 to 2.0	Dynamic Pressure	48 hours	Period (LMST, Inclination)	No	0	92	Excluded 5.5-month break
ODY (Mars)	**2.7** (2001-02)	18.6 to 2.0	Aerodynamic Heating Rate	24 hours	Period	No	0	33	
MRO (Mars)	**5.0** (2006)	35.0 to 2.0	Aerodynamic Heating Rate	48 hours	Period, (LMST, Inclination)	Yes	0	27	First mission performed PTE[c] in ops
TGO (Mars)	**9.0** (2017-18)	24.0 to 2.0	Aerodynamic Heating Rate	48 hours	Period	Yes	1	67	Excluded 2-month break

Table 1: Aerobraking Statistics from Historical Missions

[a] Contingency ABMs due to spacecraft anomalies or exceeding flight allowable limits
[b] Included all types of ABMs (corridor control, contingency, collision avoidance, ABX, etc.)
[c] Periapsis Timing Estimator – onboard autonomous capability adjusts timing on aerobraking sequences

One advantage of conducting aerobraking at Venus over Mars is that there are no collision avoidance maneuvers required for a Venus mission. The late comers at Mars (e.g. MRO, TGO) spent significant efforts in deconflicting the potential collision events. This resulted in a more complicated aerobraking process for a Mars mission.

During aerobraking, the spacecraft is particularly vulnerable to a safe-mode event or a sudden space environment change such as unexpected local dust storms (Mars) or uncategorized atmospheric behavers. Contingency pop-up ABMs are specifically designed to safeguard against such events that either breach pre-defined criteria concerning spacecraft allowable capabilities (e.g. thermal limit), or those that are induced by onboard anomalies.

Table 1 summarizes the ABM statistics from past missions. In average, the ABM frequency historically ranges from every other day (e.g. ODY) to once per week (e.g. MRO, excluding collision avoidance maneuvers). The frequency is highly correlated to aerobraking margins and atmosphere uncertainty. There were no pop-up maneuvers performed in NASA's missions. ESA's TGO conducted one pop-up maneuver due to a heating-rate violation.

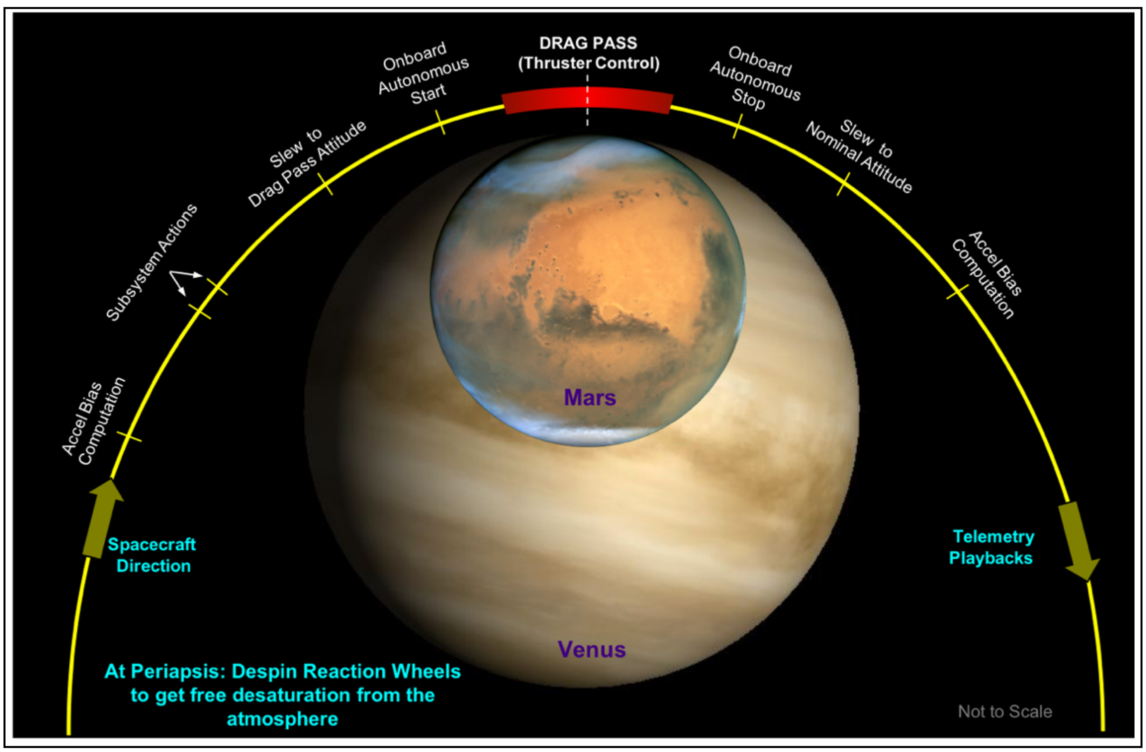

Figure 6: Aerobraking Drag-pass Configuration

Drag Pass

All NASA aerobraking missions to date were performed jointly by JPL and LM. Figure 6 illustrates a simplified drag-pass configuration adopted by these missions. The configuration is inherited and evolved from the MGN mission. Spacecraft subsystem actions (e.g. accelerometer-bias calibration) are initiated prior to the slew to the drag-pass attitude. Effective drag duration ranges from a few minutes at the start of aerobraking, to about 0.5 hours prior to the end depending on the initial orbit conditions and the final target. A typical 5 minutes "guard band" is allocated on each side of the predicted drag-pass. This is to account for the inability to accurately predict atmospheric behaviours. Prior to MRO, to ensure onboard aerobraking sequences worked properly, multiple ephemeris updates were required when orbital period became small. The update process increases workload noticeably on the flight teams. Only once the onboard automation was introduced on MRO in 2006, did the situation improve significantly. The drag-pass configurations and enhanced capabilities can be easily exported to any future missions including aerobraking at Venus.

Aerobraking Duration

In most cases, if there are no spacecraft capability or trajectory constraints, it is a good practice to complete aerobraking operations before the solar conjunction. This will potentially save propulsive ΔV and avoid prolonging aerobraking operations. However, it is not an unusual implementation for an aerobraking mission to cross a solar-conjunction event. Both MGS and TGO successfully demonstrated aerobraking operations with solar-conjunction breaks. Although, in some cases, paying a ΔV penalty is undesired, there are many other advantages of taking an aerobraking break during a solar conjunction event.

Missions (especially applicable to the typically-longer campaigns of a Venus aerobraking mission) can utilize the additional time to:

- Perform science activities and observations during the quiescent period if it is permitted
- Enhance operation processes and procedures
- Improve atmospheric model based on the latest data
- Juvenilize operation teams and train new staff
- Achieve trajectory/orbit phasing strategy to meet trajectory requirements (may save ΔV)
- Rehearse and perform operation readiness tests for the remaining aerobraking
- Adjust design and glide-slope control strategy
- Increase robustness of the aerobraking interfaces and system configurations

As Table 1 illustrated, MGS took about 10.5 months to complete its aerobraking operations in addition to spending 5.5 months for a solar conjunction break. The long-break provided MGS much needed time to complete its science-orbit phasing, which saved significant ΔV. It also allowed time to evaluate its broken solar-array conditions. TGO took about 9 months, excluding a 2-month solar-conjunction break, to conclude its aerobraking, owing to spacecraft system constraints. Similarly, the break provided opportunities to greatly enhance the overall aerobraking system.

Glideslope Parameters

Aerobraking glideslope trending is one of the most effective methods measuring current states and the progression of aerobraking operations. The simple tracking method compares baseline to the reconstructed and predicted slopes. Orbit-period glideslope is the most important parameter that reveals if the current operations are ahead or behind the desired target. Other major glideslopes include inclinations, local mean solar time, and apoapsis altitude, which impact the propulsive ΔV consumptions for the science-orbit establishment. Flight teams make tactic and strategic adjustment based on these trending results. Figure 7 demonstrates MRO aerobraking glideslope trending results. The glideslope approaches can be fully adopted by any future aerobraking missions.

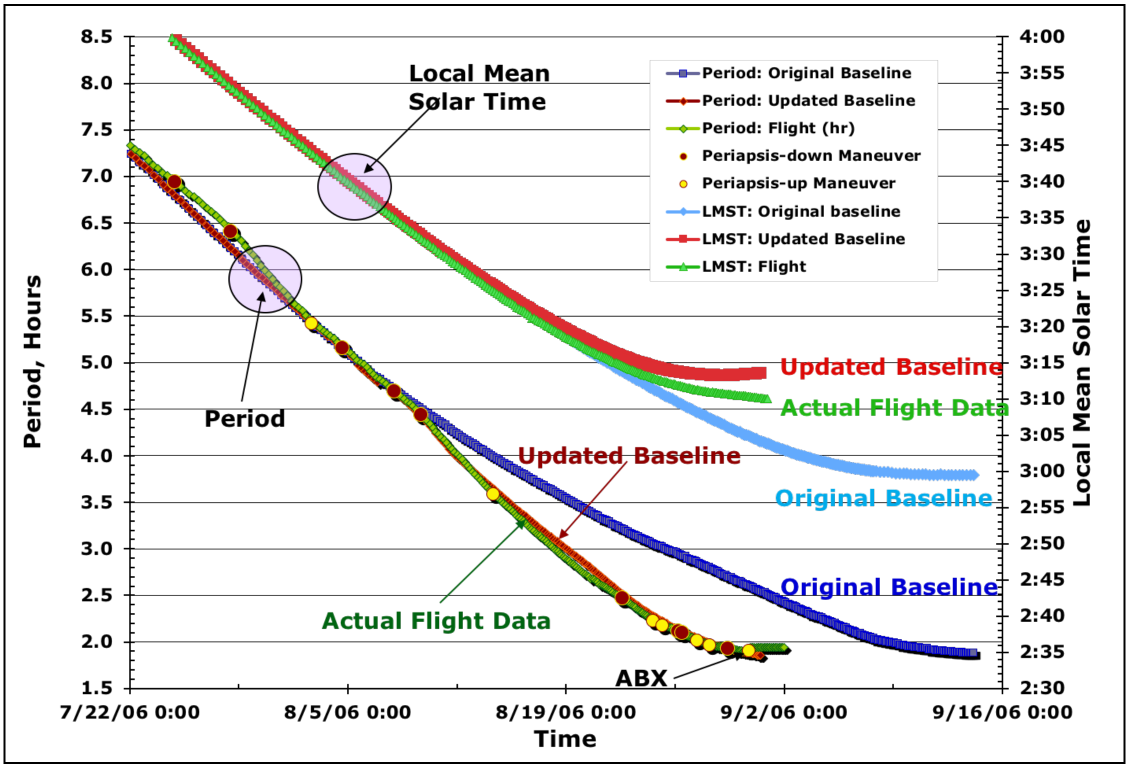

Figure 7: Aerobraking Glideslope Trending Example, MRO

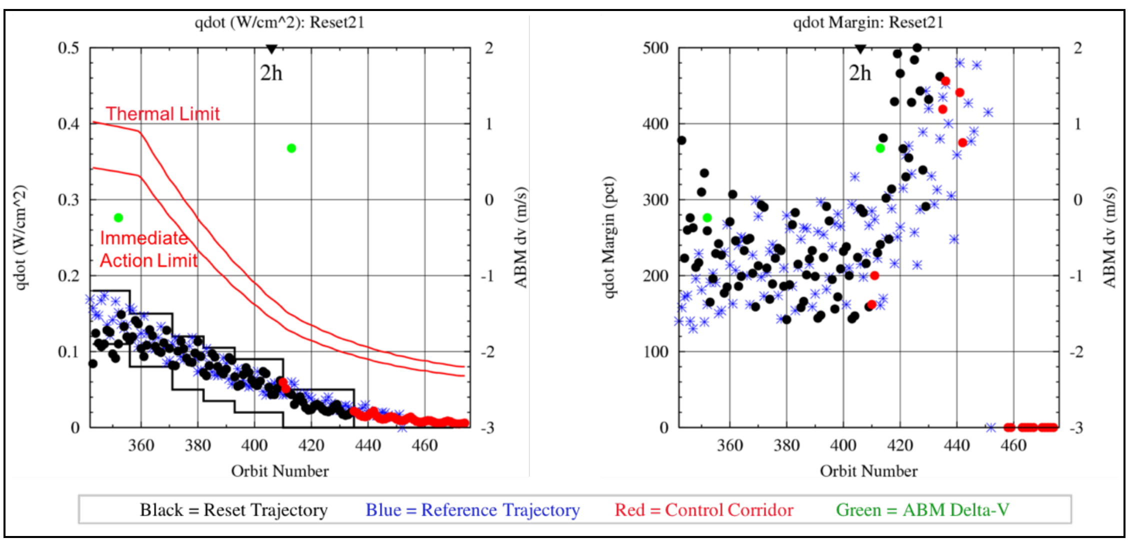

Figure 8: Corridor Control Example (near the end of aerobraking), MRO

Corridor and Margin

A corridor control parameter and the associated margin, dictate when and how frequently an ABM needs to be executed. In the past, missions either selected dynamic pressure or heating rate as the corridor control parameter (see Table 1). MGN and MGS were constrained by the rigidity of subsystem-structure rather than thermal limits, so the dynamic pressure was a logical selection as its corridor control parameter. The corridor margin is calculated from the upper-bound of the corridor. Figure 8 demonstrates the relationship of MRO corridor and “Thermal Limit” and “Immediate Action Limit”. As shown in the right figure, the minimum heating rate margin is about

120% and ranges as high as 500%. The margin gave the flight teams tremendous flexibility when making an ABM decision (leading to a less frequent ABM). It also allowed the teams to build the glideslope margin early in the operations, to allow for unexpected contingency events or permit an early aerobraking termination.

Operation Interfaces

Multiple disciplines are involved in aerobraking operations. A successful aerobraking relies on effectively connecting each team together. Figure 9 illustrates aerobraking interfaces in terms of processes and team interactions. The heritage processes and interfaces can be applied to any future Mars or Venus aerobraking mission.

Key participating teams and their roles and responsibilities are:

- Atmosphere Advisory Group (AAG): led by an atmosphere scientist. Onboard atmospheric engineering data (e.g. accelerometer data) and navigation density solutions are analyzed for atmosphere model updates. It also provides advice to flight teams regarding current and forecasted atmosphere conditions and potential threats.
- Navigation Team (Nav): performs orbit determination, updates spacecraft dynamic models, and trends glideslopes. It also conducts aerobraking trajectory and maneuver analysis to update aerobraking profile, corridor design, and ΔV menu. It presents aerobraking progress and recommends ABM location and magnitude for mission decisions.
- Flight Dynamic Team (FD): analyzes and validates aerodynamics and thermodynamics for key spacecraft subsystems. It also provides aerobraking trajectory validations.
- Spacecraft Team (SCT): leads and coordinates spacecraft activities including building aerobraking command sequences. It implements and carries out real-time uplink/downlink activities; monitors and reports spacecraft/payload health status; and implements and executes aerobraking anomaly recovery plan should it become necessary.

Key aerobraking processes include:

- Aerobraking Planning Process: consists of mission management, flight teams (Nav, FD, SCT), and AAG. The main objective of this process is to review current aerobraking states and to make an ABM "go-no-go" decision.
- Weekly Reset Process: this is an important process in terms of strategic planning and decision making. Long-term trending and aerobraking progress against baseline profile are analyzed and reviewed. Potential updates of the baseline strategy is recommended to the mission management. Flight subsystem and engineering performance is also examined with respect to the baseline configurations. A new set of maneuver menu, spacecraft configurations, and engineering parameters are updated through this process.
- Immediate Action Process: assesses if any contingency ABM or rebuilding aerobraking sequences are required in case of a spacecraft anomaly or violations of any pre-defined constraints.

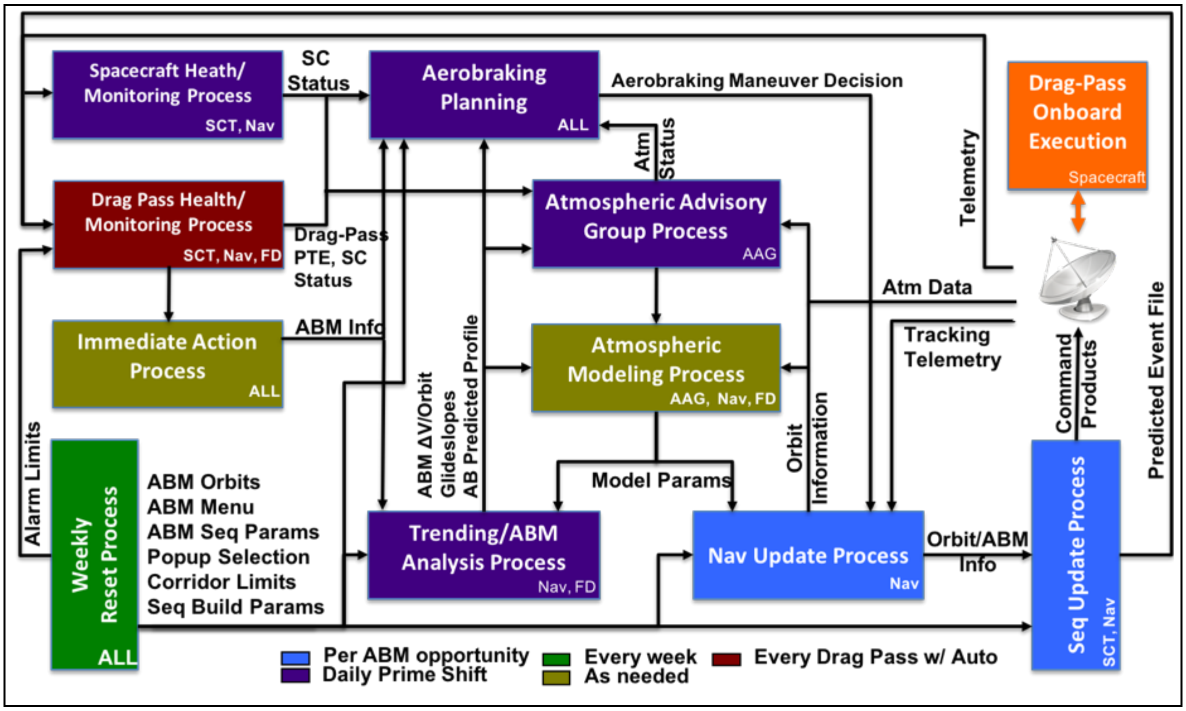

Figure 9: Aerobraking Operations Interfaces

Autonomous Operations

Prior to introducing an onboard timing-adjust capability, aerobraking was an intensive operation with heavily involved operations teams. Especially when the orbit period is less than 12 hours, an around-the-clock operation may be required. The Mars Reconnaissance Orbiter (MRO) was the first mission to utilize onboard automation to reduce the workload of the operation teams. The onboard automation was first conceived and discussed after the MGS aerobraking [12]. Lockheed Martin implemented and experimented its prototype Periapsis Timing Estimator (PTE) on ODY [13]. An enhanced version was successfully deployed on MRO for aerobraking operations. PTE continues evolving and is currently utilized by MAVEN for its aerobraking-like operations.

PTE controls the timing of sequence execution on each orbit via an onboard mechanism (drag-pass time based on centroid of drag profile, orbit period etc.). It senses atmosphere using accelerometer data and computes timing error relative to the onboard predictions (generated by the ground process) to adjust orbit ephemeris. With PTE, it can autonomously adjust timings of aerobraking sequences. Autonomous periapsis raise maneuver is only possible with PTE in the events of thermal limits and/or other flight constraint violations.

In addition to the onboard automation, a recently developed autonomous navigation capability, Traceable Automation with Remote Display and Interruptible Scheduler (TARDIS), [14] have been successfully deployed for Soil Moisture Active Passive (SMAP) science operations [15] and TGO aerobraking [16]. Normally, aerobraking operations is a repetitive process of determining orbit solutions and generating trajectory products. With TARDIS, orbit determination and ephemeris products can be scheduled 24/7 without a human in the loop. This proven capability can easily be adopted for future aerobraking operations.

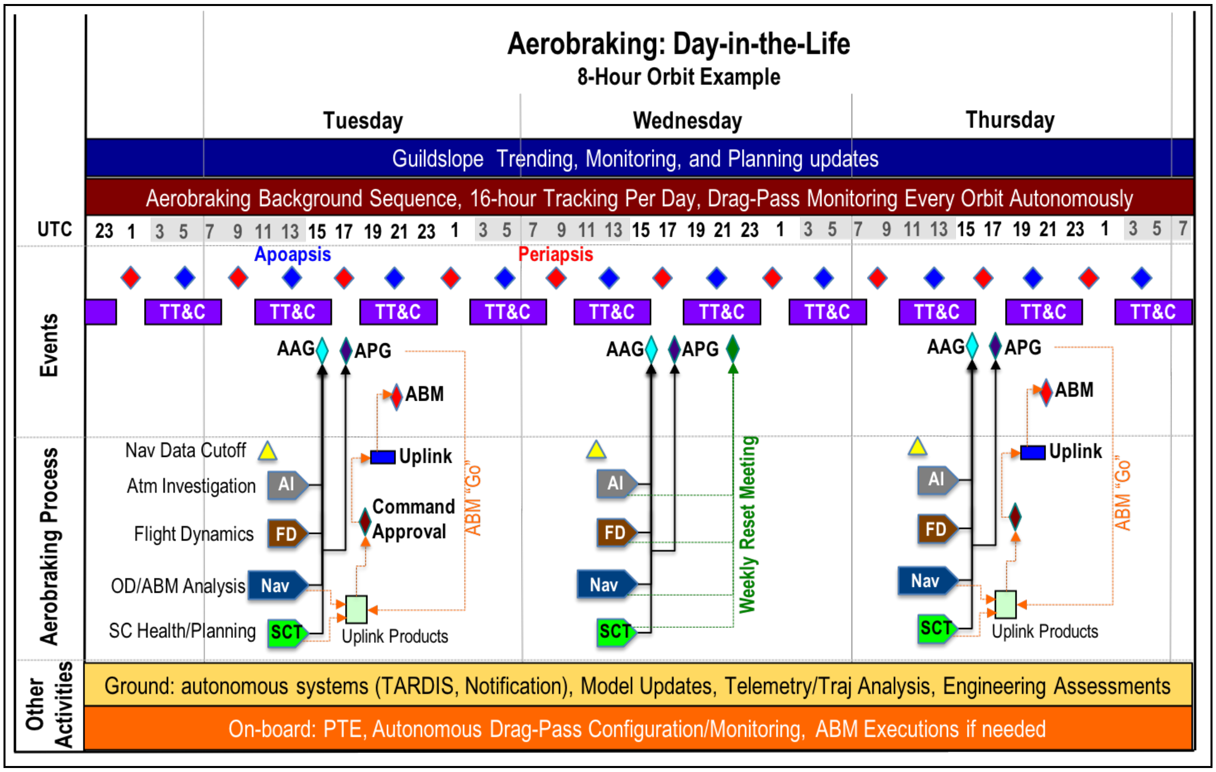

Figure 10: Aerobraking Day-in-the-Life with Prime Shifts; Off-Prime Shifts Are Handled by the Ground And Onboard Automations.

The biggest advantage of the onboard and ground automation is to reduce the daily or multiple per day product builds required. It significantly offloads the burdens of the flight operation teams. Figure 10 illustrates an aerobraking "Day-in-the-Life" scenario with automations in mind. Only the prime shift is required for flight activities such as ABM decisions, weekly resets. The off-prime shift can be performed by aerobraking autonomous capabilities with enhanced notification system [17].

Conclusion

Venus is not Mars. It's bigger and lies closer to the sun, and this has notable impacts on the design of an aerobraking trajectory. This is well understood. Equally well understood is how to fly an aerobraking mission. Past missions have demonstrated that long-duration aerobraking is not necessarily an undesired practice and there are great advantages of it given that an intermittent break is permitted. The aerobraking processes were invented at Venus and honed over the decades at Mars. Aerobraking processes have become systematized and mature. The additions of autonomous capabilities both onboard and in the ground systems have significantly reduced the risks of aerobraking and improved the operational intensity. Future Venus aerobraking missions will absolutely benefit from the advancements of these standardized capabilities and processes.

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References

1. S. K. Wong, T. H. You, et al. "Navigating Through the Venus Atmosphere", AAS-94-116, AAS/AIAA Spaceflight Mechanics Meeting, Cocoa Beach, Florida, Feb 14-16, 1994.

2. J. Giorgini, S. K. Wong, et al. "Magellan Aerobrake Navigation" British Interplanetary Society Journal, Vol 48, No 3, p 111-122, March 1995.

3. M. D. Johnston, et al. "Mars Global Surveyor Aerobraking at Mars" AAS Paper 98-112, AIAA Space Flight Mechanics Meeting, Monterey, CA, Feb 9-11, 1998.

4. M. Denis, P. Schmitz, et al. "Thousand Times through the Atmosphere of Mars: Aerobraking the ExoMars Trace Gas Orbiter", AIAA, SpaceOps Conferences, Marseille, France, May 29 – June 1, 2018.

5. T. H. You, A. Halsell, et al. "Navigating Mars Reconnaissance Orbiter: Launch Through Primary Science Orbit," AIAA SPACE 2007 Conference & Exposition, AIAA-2007-6093, Long Beach, California,18 - 20 Sep 2007.

6. A. C. Halsell, T. H. You, et al. "Mars Reconnaissance Orbiter: Aerobraking Control" 17th AAS/AIAA Space Flight Mechanics Meeting, AAS 07-243, Sedona, Arizona, January 28 – February 1, 2007.

7. D.T. Lyons, "Mars Reconnaissance Orbiter: Aerobraking Reference Trajectory," AIAA/AAS Astrodynamics Conference, AIAA 2002-4821, Monterey, CA, August 5-8 2002.

8. Sweetser, T. H., et al. "Design of an Extended Mission for GRAIL." AIAA/AAS Astrodynamics Specialist Confer-ence, Minneapolis, Minnesota, August 13-16, 2012.

9. Wallace, M. S. et al. "Low Lunar Orbit Design via Graphical Manipulation of Eccentricity Vector Evolution," AIAA/AAS Astrodynamics Specialist Conference, Minneapolis, Minnesota, August 13-16, 2012.

10. D. Lyons, S. Sauners, et al. "The Magellan Venus Mapping Mission: Aerobraking Operations", 44th International Astronautical Federation Congress, Acta Astronomica Vol. 35. No. 9-11 pp. 669-676, Graz, Austria, October 16-22, 1993.

11. J. Smith, J. Bell "2001 Mars Odyssey Aerobraking", Journal of Spacecraft And Rockets, Vol. 42, No. 3, May-Jun 2005.

12. D. T. Lyons, "Aerobraking Automation Options." AAS-01-385, AAS/AIAA Astrodynamics Specialist Conference, Quebec City, California, 2001.

13. J. D. Chapel, M. A. Johnson, et al. "Aerodynamic Safing Approach for the 2001 Mars Odyssey Spacecraft During Aerobraking", Journal of Spacecraft and Rockets, Vol. 42, No. 3, May-Jun 2005.

14. I. M. Roundhill, R. M. Kelly “TARDIS: An Automation Framework for JPL Mission Design and Navigation”, SpaceOps 2014 13th International Conference on Space Operations, Pasadena, California, May 5-9, 2014.

15. R. Haw, M. Chung, et al. “Navigation Automation for the Moisture Active Passive Observatory”, AAS 17-578, 2017 AAS/AIAA Astrodynamics Specialist Conference, Columbia River Gorge, Stevenson, Washington, August 20-24, 2017,

16. D. Han “Aerobraking the ExoMars TGO: The JPL Navigation Experience”, 27th International Symposium on Space Flight Dynamics 2019 (ISSFD), AIAC18 Conference, Melbourne, Australia, February 24-26, 2019.

17. M. Mizukami, C. G. Ballard, et al. “Automated Spacecraft Operations During Soil Moisture Active Passive Prime Mission”, 2019 IEEE Aerospace Conference, Big Sky, Montana, March 2-9, 2019.