MarCO: Flight Review and Lessons Learned

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ABSTRACT

Provide an informative abstract of no more than 200 words. The abstract should stand alone as a summary of the paper, not as an introduction (i.e., no numerical references). Type the abstract across both columns and fully justified.

INTRODUCTION

On November 26th, 2018, the MarCO spacecraft completed their journey to Mars, having flown 6.5 months and over 450 million kilometers. Both spacecraft encountered significant challenges during their journey, including safe-mode entries, a leaky thruster, and necessary software updates, but they successfully arrived to relay data for the InSight mission during its entry-descent-and-landing at Mars.

Vehicle Description

Each MarCO flight vehicle consists of a 6U CubeSat, approximately 36x24x10cm in size when stowed. The primary aluminum structure houses a Vacco cold gas propulsion system, with R-236FA propellant, a JPL Iris X-band transponder with UHF reception capability, Astrodev Command and Data Handling (CDH) and Electrical Power System (EPS), MMA deployable solar panels, Blue Canyon Technologies XACT attitude control system, JPL antennas (including high gain reflectarray), and two Gumstix boards & cameras. Together, each vehicle weighs approximately 14 kg and fits within a 6U Tyvak NLAS dispenser.

Onboard flight software (*protos*) was developed at JPL, and the ground system was adapted from NASA's Advanced Multi-Mission Operations System (AMMOS). These are used in conjunction with the Deep Space Network for communication with each spacecraft. The team has also partnered with Morehead State University for X-band data reception, and SRI for UHF broadcast during early flight test.

Mission Concept of Operations

MarCO, like most Mars missions, launched on a trajectory that intentionally aimed away from Mars for planetary protection purposes (this avoids having to decontaminate the entirety of the launch vehicle's upper stage, a likely impossible task as it is exposed to Earth's atmosphere). Upon deployment, approximately 90 minutes after launch, and subsequent to InSight's own launch vehicle separation, the two MarCO spacecraft powered on for the first time since completing dispenser stowage some two months prior.

Early planned mission operations consisted of spacecraft checkout and deployment of panels and antennas. Within several weeks of launch, both MarCO's were scheduled to perform a trajectory correction maneuver (TCM), steering the flight path toward Mars, and removing the launch vehicle bias. Follow-on TCMs (up to 4 additional) throughout the mission allow for minor correction of the final flyby trajectory.

After a 6.5-month cruise, both InSight and the two MarCO spacecraft arrived at Mars on November 26, 2018. Each MarCO spacecraft were programmed to relay telemetry data back from the InSight lander as it proceeded through EDL to landing on Mars. The Mars Reconnaissance Orbiter simultaneously recorded the broad InSight signal (including telemetry data) and subsequently sent this to Earth. During EDL, a UHF carrier tone was directly received by Earth, providing limited insight into descent events. Though the MarCO spacecraft were not required for InSight mission success, their presence and operations allowed for near-real-time telemetry downlink and health monitoring of the EDL process.

After EDL data relay, the MarCO spacecraft will have completed their demonstration objectives and primary mission.

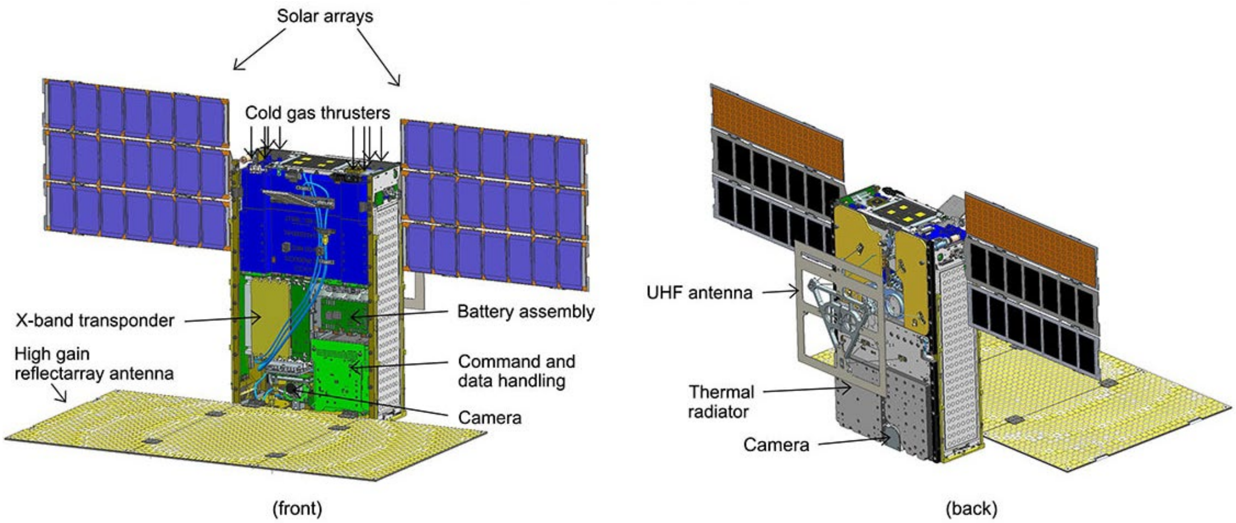

Figure 1: Schematic of the Mars Cube One spacecraft (front and back) with front panel removed.

CRUISE OPERATIONS

Both MarCO spacecraft followed InSight to Mars in a loose formation for much of cruise, separated by roughly 10,000km. MarCO-A completed three trajectory correction maneuvers in May, August, and October in preparation for Mars flyby. MarCO-B performed an additional TCM in November to better align for flyby.

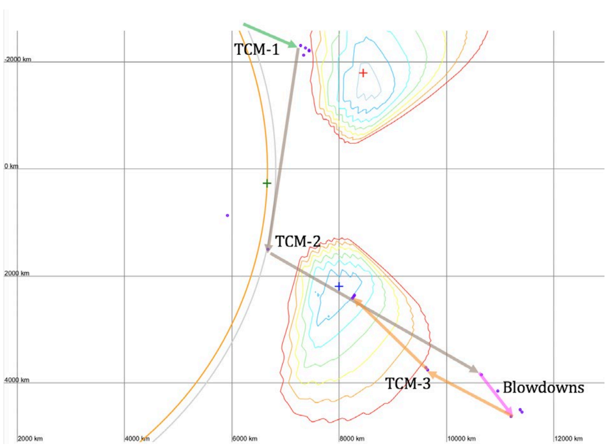

Figure 2: MarCO-A path to Mars, including TCM-1, TCM-2, and TCM-3. Mars is shown by the circle on the left. The contours represent the best trajectory for relay at a specific point of time as shown in the B-plane.

During cruise MarCO-B developed a propulsive leak, which required constant maintenance and monitoring. Prior to launch, the team observed a slight leak from the tank to the plenum chamber, but accepted the risk for flight (the observed leak filled the plenum chamber over approximately four days). In flight, a second leak developed through a thruster valve, causing a continuous moment on the spacecraft attitude.

To handle the leak, the team altered the spacecraft behavior to empty the plenum every 15 to 30 minutes, significantly reducing the overall impulse, but causing a near continuous thrust (adjustments to TCMs were required to accommodate). The leak from the tank to the plenum continued to fluctuate over the course of the mission, leading to occasional periods of “high” leaks that tended to slow as the tank increased in temperature, over the course of a few days. Accommodation of the leak led to a continued effort to reduce usage of the prop system, most notably by successfully dumping momentum accumulated by the reaction wheels through solar radiation pressure moments on the large high gain antenna and solar panels. By experimenting with different orientations of the panels with respect to the sun, the team derived a set of attitudes that could transfer or reduce momentum from the wheels, negating the need for propulsive desaturations. This reduced the before-flight estimate of 1-2 propulsive desats per day to almost none across the entire mission and both spacecraft.

Onboard behaviors were modified to handle the leak mitigation, including modifying safe-mode, nominal mode, fault detection, and even which telemetry points were recorded (the navigation team desired more insight into the propulsive events). The flight software ran eight independent sequence engines to execute up to eight sequences simultaneously, and could store up to another eight in onboard memory. Together, this led to significant flexibility of the system – even allowing for “brain-surgery” on the spacecraft without the need (or capability) to swap to an alternate processor.

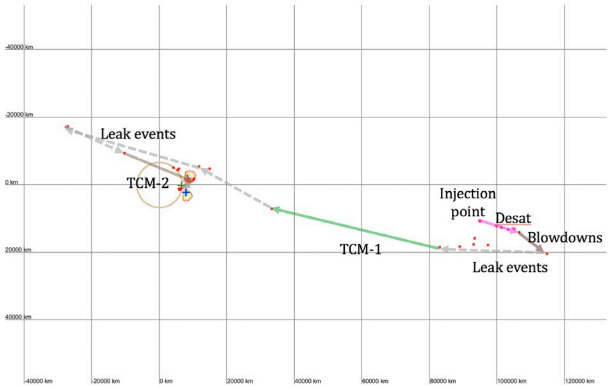

Figure 3: MarCO-B path to Mars (TCM's 1 & 2). Mars is shown by the circle on the left. The small contours represent the best trajectory for relay at a specific point of time as shown in the B-plane.

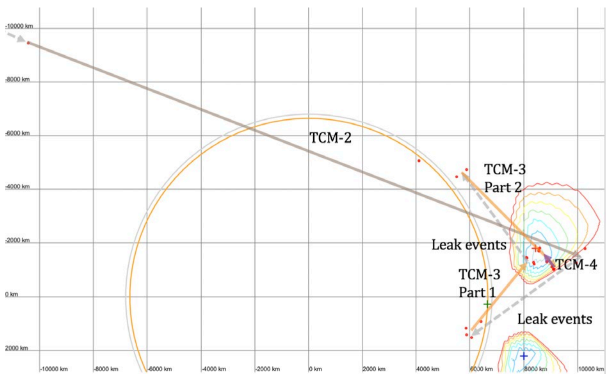

Figure 4: MarCO-B path to Mars (TCM-3 and 4).

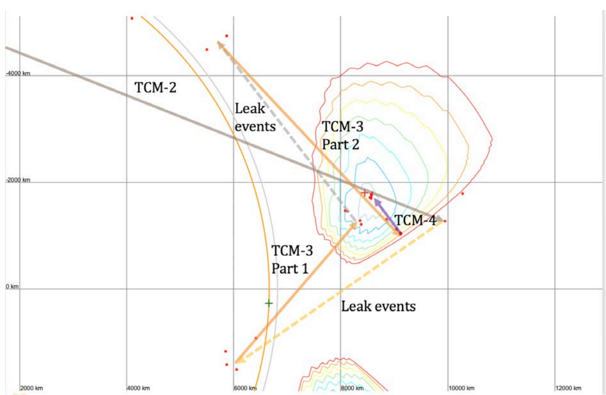

Figure 5: MarCO-B path to Mars. Final alignment for EDL.

MARS ENCOUNTER

On November 25th, 2018, both spacecraft approached Mars. With only twenty-four hours until EDL, MarCO-A reported in healthy, however MarCO-B missed a pass, with a likely entry into safe mode. InSight donated several uplink passes, however no signal was detected throughout the afternoon. Should the spacecraft have had a radio or attitude control issue, rather than a safe-mode entry, the command-loss timer would cause a safe-mode entry late night (the timer had been reduced to a several hours in anticipation that the team might need to recover from safe-mode quickly prior to EDL). Though half of the team worked late into the night, no signal was detected. This led to two paths – either MarCO-B would wake up according to the wake-up table Monday morning, or the spacecraft was in an unrecoverable state.

At 6:05am, Monday morning, November 26th, MarCO-B's signal was received by the DSN. Telemetry indicated that several commands had been received the previous day by the broad MGA, however it was likely the spacecraft was off-pointed, so the narrow-beamed HGA transmit signal did not reach Earth. At the 6:30am tagup, MarCO-A and MarCO-B were reported "GO" for EDL support.

Just after 7:15am, MarCO-A's carrier signal rolled-off. With four and a half hours to EDL, MarCO-A was missing and MarCO-B had disappeared once in the last day.

Telemetry indicated that the star tracker was likely being blinded by "Mars-shine". At 11:14 and 11:16am (Earth receive Pacific time) respectively, MarCO-B and MarCO-A signals were received by the DSN. Each spacecraft reported healthy telemetry, though MarCO-A's star tracker was not yet in fine-tracking mode. Because of Mars-shine, the spacecraft was forced to propagate on gyros, causing the spacecraft attitude to slowly drift away from pointing at Earth. MarCO-B rotated to image Phobos at 11:16 and turned back at 11:31am. MarCO-A's again lost signal after telemetry indicated that the star tracker was still not in fine-pointing, but several minutes later, both MarCO-B and MarCO-A reported they had entered EDL mode, were at Bent-Pipe attitude, and had star trackers in lock – once the star trackers were "looking" past Mars, shine was no longer an issue.

At 11:41am, both spacecraft sent telemetry indicating UHF carrier had been detected. This was confirmed with the Earth-based UHF receivers which could receive the UHF carrier, but not decode data due to the low link margin. UHF telemetry began at 11:46am, and both MarCO's started the relay. Woven within the relay was the limited health, safety, and RF telemetry for mission support.

InSight soon entered the period of expected plasma blackout. MarCO-B dropped the carrier for only 15 seconds, while MarCO-A lost 38 seconds of data. It then deployed its parachute at 11:51am, indicated in the RF signal by a Doppler shift. Lander separation from the backshell occurred at 11:53am, indicated by a brief change to carrier-only, and the lander touched down on Mars at 11:54am, November 26th, 2018.

Five minutes later, the InSight UHF signal turned off – in that time, the first image InSight took of Mars was relayed to Earth from the MarCO's. All telemetry showed a healthy EDL with a spacecraft ready to extend its solar arrays and begin the science mission. Overall, MarCO-A sent 93% of all InSight EDL data. MarCO-B sent 97%.

In the subsequent hours, MarCO-A performed a radio occultation experiment with it's X-band signal being occluded by Mars to characterize the atmosphere. MarCO-B attempted photos of Mars and its moon Deimos. And both spacecraft repeated their transmissions of UHF data for redundancy – these were not needed, as no frames were lost in the initial transmission to Earth.

Over the following days, MarCO-B transmitted several images of Mars taken by its wide field of view camera, including those showing Elysium Planetia, where InSight landed; the poles of Mars, white from the ice caps; several volcanoes; and even two dim and small images of Phobos. Unfortunately, most of the attempts to image Phobos and Deimos failed. Even so, the limited effort spent on the cameras paid off as the team was able to provide a "Farewell" image of Mars, with the MarCO high gain antenna and feed prominent in the view. MarCO's primary mission was a success.

Figure 6: Mars, as imaged by MarCO-B, just following InSight's entry-descent-and-landing. The right hand side of the image shows the high gain reflectarray, while the left has the high-gain feed. The image was taken by MarCO-B's wide-field-of-view camera.

EXTENDED MISSION

While MarCO's primary objective was complete following InSight's successful landing on Mars, as a technology demonstration mission, there was significant interest in further characterizing the hardware in each spacecraft. Both spacecraft remained healthy in the days after EDL. The first focus was on retrieving as much onboard data as possible for use in system characterization. This included onboard telemetry history, telemetry points not usually downlinked, and in-focus images taken before or after Mars.

Prior to EDL, each MarCO took advantage of MSPA (multiple spacecraft per aperture) opportunities with InSight (and eachother) to maximize the track time, with numerous downlink-only opportunities. After Mars, there was no InSight to partner with, and the two different flyby trajectories caused each MarCO to begin separation from the other. For the first time, tracks could not be shared between the vehicles.

With three planned tracks per week, each spacecraft has limited communication opportunity. In addition, with the distance between the spacecraft and Earth quickly increasing, data rates begin to significantly decrease. While pre-launch datarates only included 62.5 bps, 1 kbps and 8kbps downlink and 62.5 bps and 1kbps uplink, further rates were tested and implemented during cruise. This allowed for a stepped decrease as range increased. By the end of December, 2018, the spacecraft were downlinking at 1 kbps and used a 500 bps uplink.

In the months leading up to EDL a small team examined possibly flyby targets once the vehicles had passed Mars. While numerous small body objects exist, few were accessible within the constraints of MarCO, most notably the limited propulsive capability. Though the flyby might have been altered to make use of a gravitational slingshot, this would have added significant constraints to InSight support, and was considered ill-advised. Once options were identified (and the list was re-evaluated following each maneuver), they were evaluated for propulsive feasibility, duration of journey, and orbit condition code (the certainty of the trajectory of the small body object). More targets were accessible to MarCO-B rather than MarCO-A.

With EDL support complete, and potential extended mission under discussion, focus turned toward updating parameters onboard the two vehicles. On December 24th, MarCO-B began to indicate the return of mid-size leaks (larger plenum pressure measurements of approximately 400 Torr were taken between slow-blow events), and by December 28th, strong blowdowns with no significant plenum pressure drop, along with repeated automatic wheel desaturations showed that the vehicle was again in the strong blowdown regime. Due to the in-progress desaturations, parameter updates were postponed.

On January 2nd, no transmissions were heard from MarCO-A. Previous contacts had shown a healthy spacecraft, with primary activities downlinking historical telemetry. There were some initial indications that the star tracker had occasional loss of lock, but no other adverse behavior.

In follow-on scheduled passes, the DSN was unable to detect telemetry or carrier for either vehicle. Attempts to command-in-the-blind, specifically to reset the attitude control subsystem and put the radio in a low-data-rate mode were unsuccessful. By mid-January, both wake-up tables had run out, and the command-loss timer had expired, guaranteeing that each vehicle would be in safe mode, cycling through data rates and antennas, with periods of charge in between.

Throughout the month of January, the team undertook parallel campaigns of command-in-the-blind along with long listening periods and examining downlinked telemetry and. In addition to the usual 34 m apertures, 70 m dishes at high power levels were utilized to attempt to “break-in” to the spacecraft, even if the onboard attitude or antenna selection led to a low link margin. Of the last data downlinked, including historical data from the days preceding loss of contact, both spacecraft indicated occasional, but increasing, star tracker loss-of-lock. This corresponded with coarse sun sensor telemetry showing occasional inability to find the sun.

The coarse sun sensors detect the sun by comparing the measured light value on each individual photodiode, assuring that the levels are above a pre-set threshold (intended to ignore reflections, glint, or other spurious light). Should light not be detected on any of the photodiodes, and the star tracker is not in lock, the system will propagate attitude knowledge based on the onboard gyro (which can cause significant drift with no absolute attitude reference). After a pre-set timeout, without star-tracker or sun detection, the ACS (attitude control system) will attempt to rotate the vehicle to perform a sky search and re-lock on the sun. Each commanded attitude change can be faster than the maximum rotation rate of the star tracker, decreasing the likelihood of lock. The frequent attitude changes also cause an increasing rate of momentum build-up in the reaction wheels due to inevitable friction within the system.

In early January, analysis of coarse sun sensor telemetry indicated that the levels of sunlight on the craft were at the edge of the software-set threshold for spurious light protection. While the threshold had been predicted to be suitable for some months ahead, updated comparisons had not been performed. If the coarse sun sensors had been unable to find the sun, causing the vehicle to enter sun-search mode, the spacecraft would spend less time with solar panels charging, likely leading to the spacecraft entering a power-negative state, and the radio unable to appropriately point toward the Earth.

Other scenarios might also have played out: MarCO-B was clearly in a high-leak state at the time of loss of contact and may have been unable to desaturate reaction wheels, eventually entering into a spin state accelerated by solar radiation pressure. Either vehicle might have had a failure of a single-string component due to radiation or a high-energy particle. Even a few corrupted bits within the CDH’s boot sector could have prevented a reboot or safe-mode entry. While these scenarios would lead to a sudden loss of contact, having both spacecraft lost within days of each other indicates a likely systemic failure.

If the spacecraft were lost due to an incorrect coarse sun-sensor threshold, there is a chance the vehicles drained their batteries and are continuing along their elliptical trajectories powered off. Even with minimal power (the CDH only requires approximately 3.3V to boot), both the radio and reaction wheels need voltages greater than 8V and significantly more current to power on. But as the trajectories will again bring the spacecraft closer to the sun, NASA may elect a short re-contact campaign in the autumn of 2019 to attempt communications when more power is available to the vehicles and the coarse sun-sensors would detect the sun at levels that exceed the current threshold.

Due to the loss of communication, the MarCO's primary mission was declared complete on February 2nd, 2019, with any extended mission pending reestablishment of communications and subsequent approval.

With the primary focus of the mission on technology demonstration and support of InSight, management and preparation of the extended mission was minimal. As the ACS parameters were working for both TCMs and flight, there was little appetite for the additional risk of altered onboard parameters prior to the flyby. The nature of low-cost small spacecraft requires focus on primary objectives given the relatively small team size. For MarCO, this also required a limitation in ongoing analyses and trending that might have identified a forthcoming threshold violation for the coarse sun sensors. It was a tradeoff accepted for MarCO's mission that (likely) led to both primary mission success and eventual loss of communications.

CONCLUSIONS

MarCO, the smallest spacecraft to ever complete an interplanetary mission, has enabled a new class of planetary exploration. With low cost and fast schedule, MarCO demonstrated the feasibility of a constraint-driven interplanetary small spacecraft. The technology developed for MarCO, including the critical Iris radio, modified commercial hardware, and the flight software, are all available for use from the mission partners and commercial entities. Continued investment from NASA, ESA, JAXA, and others implies a bright future for solar system exploration with small spacecraft, however, as with MarCO, significant challenges, set-backs, and failures will occur.

MarCO was successful because of a narrow focus, an acceptance of risk, and significant support of lab and NASA leadership. It built upon technology developed over many missions, and was motivated directly from the success of the world-wide CubeSat community. While the mission was never required for InSight success, ultimately over seven million world-wide observers watched the near real-time descent of the lander through the seven-minutes of terror, with all telemetry relayed through the two MarCO spacecraft. Even InSight's first image of Mars was sent via MarCO – subsequent media metrics showed more than five billion "impressions" from articles, interviews, social media postings and replays in the follow-on days.

MarCO's key lessons stem from the deliberate development of systems with excess capability that could be used in flight operations, and the use of a small multidisciplinary (and co-located team). A streamlined governance model served to oversee and understand the risks undertaken by the mission, mitigated through extensive end-to-end testing and multiple high-fidelity testbeds. The engineering model spacecraft, serving as a testbed, was critical to mission success, and ultimately was used in all aspects of mission operations – checkout, nominal cruise, failure recovery and EDL planning.

It is our hope that MarCO is only the first of many new small spacecraft exploring the solar system. The choices made by the MarCO team can be traced back to previous missions like RAX, INSPIRE, and ASTERIA, through the testing and development of parts, the slow acceptance of risky choices, and the creation of operational procedures and behaviors. Some early choices, like RAX choosing to design a simplistic set-point controller for its power system, directly led to the robustness of the MarCO design. Others ended up being constraining, like the eventual need to utilize 2.5 kg of tungsten ballast. Yet the evolution of the MarCO project shows that an in depth understanding of where design choices come from – not just the choice itself – leads to an opportunity for exploitation toward mission success.

Acknowledgments

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