Hummingbird: Versatile Interplanetary Mission Architecture

Christianna E Taylor (ctaylor@smad.com)
Anthony Shao (ashao@smad.com)
Nicola Sarzi-Amade (namade@smad.com)
Richard Van Allen (rvanallen@smad.com)
James Wertz (jwertz@smad.com)
Microcosm, Inc.
Hawthorne, CA 90250, United States

ABSTRACT

This paper will present the Hummingbird concept and its strengths that enable versatile interplanetary mission architectures. Interplanetary missions and system architectures for small satellites require a new type of thinking. Specifically, taking advantage of cubesat components, composite technology, and low cost approaches represents a paradigm shift essential to sending small satellites on interplanetary missions. Microcosm has worked with NASA Ames on a Small Business Innovative Research (SBIR) program called ***Hummingbird***, a low-cost (~ $3M recurring cost) small interplanetary satellite with 1.5-3.5 km/s delta V capability and sub-meter resolution applicable for many Earth/planetary science missions. These missions include orbiters/landers/sample return missions to Mars, Phobos/Deimos, near Earth asteroid/asteroid belt, Lagrange points, Venus, and Moon, and Earth science. The spacecraft is a unique all-composite, unibody structure in which the propellant tank itself is the structure. Quicker scouting missions to asteroids and planets are needed to assess their potential for both science missions and eventually human missions. Evolving small satellite travel to interplanetary destinations requires versatile scouting missions that provide quick turnaround, easy access, and multiple destination possibilities. Hummingbird serves as a low-cost alternative that can pave the way for larger, more in-depth missions to multiple destinations with multiple payload configurations. There is no one way to incorporate low-cost methods into a given mission. However, incorporating radiation hardened cubesat components and supporting multiple payload classes, while keeping mass low by utilizing composite tanks, is a start to expanding space exploration to include the small satellite community.

1. Introduction

As the needs for interplanetary exploration solutions evolve, certain challenges arise associated with utilizing smaller satellites for these missions. The chief amongst them are the generally large communications distances involved, launch vehicle selection, and cost. What are the fundamental limitations on the use of small satellites for interplanetary missions? Where do we want to go with small satellites (i.e., what interplanetary targets)? What small satellite technologies are required or need to be modified to achieve interplanetary travel? These challenges were addressed by looking at case studies of multiple destinations and determining if the Hummingbird spacecraft could target multiple destinations such as the Moon, Mars, Phobos, Deimos and the asteroid belt. These destinations represent an interesting range; however, the corresponding range of distances involved leads to significant communications challenges.

As the small satellite world expands from low-Earth orbit to interplanetary missions, radiation hard components that can handle long-duration missions become essential. Hummingbird has the ability to utilize cubesat components while also integrating larger components into its spacecraft bus. As time progresses and microelectronics become smaller, this will only further reduce the cost and mass budget. A trade study on the cubesat components (especially radiation hardened components) is not included as a part of the results presented in this paper; however, we have observed that this is as an area that will only improve over time. Along the same line of thinking, bus subsystems and some payloads also will become smaller as technology progresses. Small satellites may take advantage of these trends by enabling multiple scouting missions with a multitude of cubesat payloads to gather large amounts of information in an effort to enhance future larger missions. We chose as the baseline a visible sensor payload capable of taking pictures with submeter resolution based on an Exelis telescope already developed for a LEO application.

Finally, the challenges that all small satellite systems face are the launch vehicle options and cost. It does not make sense to launch a $3M satellite on a $30M launch vehicle as the primary payload. A first order analysis suggests that there is at least one very low cost option that is consistent with Hummingbird that will be discussed below.

2. Hummingbird Concept

The Hummingbird Spacecraft is pictured below in Figure 1. It is an 80 kg satellite, with a 25 kg dry mass that includes the Exelis telescope as the primary payload. Alternative payloads can be interchanged to support other missions; however, for initial scouting missions where the objective is to get a physical sense of the target object, Hummingbird was built around the Exelis telescope scheduled to launch on Kestrel Eye in 2013. The channels on either side can accommodate up to 12 cubesat sized payloads (6 on either side) and can be arranged in other configurations as a function of payload size or shape.

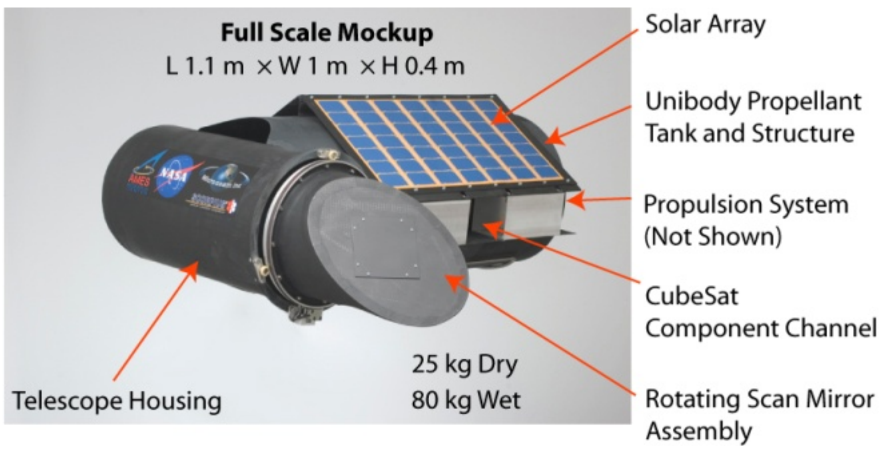

Figure 1. Hummingbird Full Scale Mockup.

Hummingbird's main advantage is its large hydrazine propellant tank leading to a delta V capability that enables the ambitious missions introduced previously while remaining within what still is a small satellite envelope. It is possible to add electric propulsion, for example, but with the penalty of added complexity and greater cost. The current design is flexible because it is easy to change the propellant tank (by elongating or shortening it or increasing or decreasing its diameter) to fit within a range of candidate launch vehicles and to reach a variety of targets.

2.1 Alternative Missions and Payloads

Hummingbird is primarily designed to scout possible targets, with more in depth exploration left for later and likely more ambitious missions. As mentioned previously, the payload is assumed to be the Exelis telescope to image candidate targets. .

Alternate payloads need to be examined in terms of which ones make sense to add or replace the imaging payload. One interesting candidate payload class that could easily be added is an ultrastable oscillator/clock that would use the Doppler shift associated with the target's gravitational attraction in conjunction with the imager that would provide volume data to determine asteroid mass. Another candidate payload is an alpha particle X-ray spectrometer. It is a passive instrument that requires little care. It would require contact with the surface of a body of interest. For an asteroid target, since the touchdown velocity would be approximately at most several cm/s, this appears to be achievable.

Relative to determining other physical properties of asteroids an anchoring test could be performed by ejecting one or various types of probes connected to reels that pull Hummingbird to the surface. This test would be useful relative to determining how to anchor astronauts during human exploration missions. Small masses also could be ejected from Hummingbird at various velocities, and the effects of the impacts could be imaged to determine surface and subsurface material characteristics. These masses could be simple solid masses or they could be explosive to see if they could trigger landslides (this applies both to asteroids and to Phobos/Deimos). The charged particle environment around various bodies of interest could be measured with a Langmuir Probe. This would involve an extended boom that could be spring loaded and would be expendable. Very low data rates would be involved, a non-trivial factor given the communications distances to Mars and to asteroids. Finally, other types of low-cost, low-mass sensors could include radiation sensors to determine secondary radiation, along with sensors to measure electrostatic forces.

2.2 Launch Vehicles

An *Orbit Cost Function (OCF)* was developed to gain a better understanding of the launch vehicle aspect of the mission and to identify and rank existing or needed capabilities relative to enabling Hummingbird interplanetary missions. This function will be further developed in Section 4. The results show that from a delta V capability viewpoint, the propellant tank will support Hummingbird missions to the Moon (1.04 km/s) and Mars (1.89 km/s). (It has been assumed that there is a delta V contribution from the launch vehicle and possibly an upper stage.) Even a Phobos mission is not much beyond the existing capability and can be accomplished with only a minimal increase in the tank length to achieve the necessary 2.89 km/s. Only an asteroid class mission would require a substantial change to the baseline Hummingbird tank size (increase in length, increase in diameter, or a combination) because of the 4.62 km/s needed. Given the ease associated with changing composite tank dimensions, being able to support asteroid missions will not be difficult technically or add much to mission cost. In addition, assuming that more efficient propellants will be available (e.g., “green” propellants), the performance can be improved further in later missions.

Regarding launch vehicles, over the range of Hummingbird masses calculated to span lunar to asteroid missions (118 kg to 1,168 kg), existing candidate launch vehicles are available, including Pegasus, Minotaur I, Athena 1c, Minotaur IV, Taurus, and Delta 7320. Others in development that should be considerably less costly than any of the above have been identified.

3. Mission Versatility

Three mission classes were examined: Lunar, Mars, and asteroid. Estimating the sizing for a Hummingbird spacecraft for these three mission classes required an orbit analysis to size the propellant tank that would provide sufficient delta V to accomplish each mission.

3.1 Mars Missions Preliminary Analyses

Analyses were conducted to design trajectories from the Earth to Mars. It was assumed that Hummingbird departs from an Earth parking orbit. The astrodynamics model that was used was based on a few simplifying assumptions that are explained below.

An iterative method was used to obtain the results in terms of start date and arrival date. First, results were generated assuming circular and coplanar orbits for the Earth and Mars. Then, the results were extended to address realistic orbits (non-zero eccentricity and non-zero relative inclination). For the transfer to succeed, Hummingbird must intersect Mars’ orbit when Mars is passing by that position. The departure from Earth was assumed to be tangential to Earth’s orbit as seen in heliocentric space, which takes full advantage of the Earth’s velocity around the Sun to obtain the desired departure delta V. Looking at the heliocentric portion of the transfer, it was assumed that the transfer was a direct one: Hummingbird will intersect Mars at the first intersection between the spacecraft trajectory and Mars' orbit, to reduce the transfer time. This type of direct transfer (with tangential departure) is called a "T1" transfer.

Different delta Vs can be selected for the Earth departure. For the preliminary analysis, the minimum energy delta V was assumed, which is very close to a Hohmann transfer delta V, but not exactly the same, due to the eccentricities and different inclinations of the planets' orbits. To simplify the passage to real orbits and to analyze the separate effects of eccentricity and inclination, eccentricity alone was considered first, and the effect of inclination was added as a second step. An iterative process based on circular orbits as the starting point was used. The calculations of transfer times are dependent on the selection of a particular opposition date around which the round trip occurs. The analysis was done for the opposition date of July 27, 2018, which represents the closest approach between the Earth and Mars, in order to minimize the delta V and the corresponding amount of propellant required.

The iterative procedure consists of calculating the start date for the circular orbits case first, which is called Iteration 1. Iteration 2 introduced the eccentricity of the planets' orbits, and was used to find the actual intersection with Mars' orbit. Given a precise opposition date, a transfer delta V, and a trajectory type (T1 in this case), there is only one departure point that works. Therefore, the transfer must start at a precise date, which is unknown at first. However, thanks to the iteration process, it is possible to make a first guess considering the start date to be equal to the one previously found for circular orbits. Such a date, although not yet exact, is close enough to assume that when Hummingbird intersects Mars' orbit, Mars will be in that vicinity within a reasonable approximation. At the end of this second iteration, it is then possible to measure by how much the intersection misses the actual position of Mars, and start a new iteration with an improved start date, and repeat this process until convergence.

A plot representing the outbound arc for the opposition of July 27, 2018 is presented in Figure 2. Earth and Mars orbits are shown in black. The transfer orbit is in green. The blue markers indicate the positions of the Earth at the start and arrival dates, and the red markers represent the positions of Mars at the start and arrival dates. The black dotted lines represent the direction of perihelion for the Earth and Mars, and the black solid line coming out from the Sun represents the direction of opposition. It is clear from the plot that on July 27, 2018 opposition occurs relatively close to Mars perihelion.

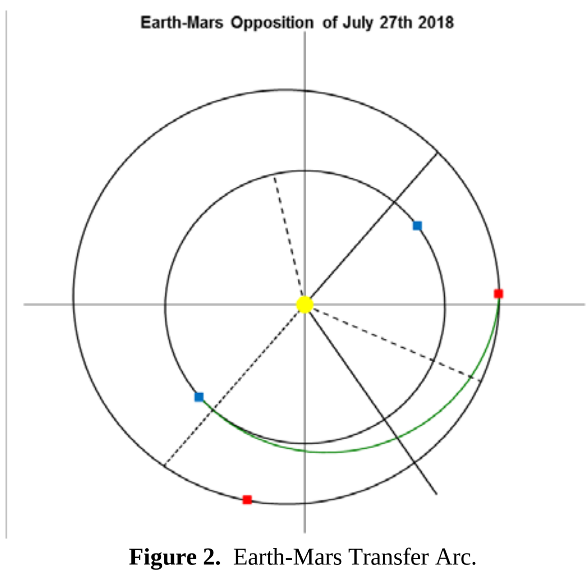

Figure 2. Earth-Mars Transfer Arc.

The inclination of Mars orbit with respect to the ecliptic plane has been taken into account and the actual delta V for the Mars transfer has been calculated. The Mars orbital plane has an inclination, i, of 1.85º with respect to the ecliptic plane. Modeling real orbits means performing a plane change in a way that minimizes the propellant usage. The main assumption is that the departure and arrival dates calculated in 2-D do not change. Equivalently, the transfer durations and the transfer arc lengths do not change. These assumptions are true within a few hours, as was estimated analytically. Thus, the goal is to calculate the additional delta V required for the plane change. The second assumption is that Hummingbird makes the inclination change in its heliocentric orbit 90º before arriving at its destination, which is the point where the inclination change is a minimum. Consequently, the portion of the transfer arc off the ecliptic plane is 90º, while the portion in the ecliptic plane is given by the difference between the total arc length, calculated in 2-D, and 90º. [0]

The results of this study are that for the opposition of July 27, 2018, the departure from Earth is on May 2, 2018, and the arrival at Mars is on October 28, 2018. The transfer time is 179 days, and the delta V's in heliocentric space are 2,647 m/s at Earth, 3,403 m/s at Mars, and 701 m/s for the deep space plane change, for a total of 6,750 m/s. To calculate the more correct delta V's, the departure and arrival techniques at the Earth and Mars, respectively, need to be accounted for. The Earth departure delta V is accomplished with a hyperbolic maneuver, provided partially by the upper stage of the launch vehicle and partially by Hummingbird. The hyperbolic delta V needed at the hyperbola perigee (400 km altitude) is 3,496 m/s, and it was estimated that the launch vehicle can provide about 60% of this amount (2,098 m/s), while Hummingbird provides the remaining 40% (1,398 m/s). Mars orbit insertion requires a nominal hyperbolic periareion delta V of 2,491 m/s, at 300 km altitude. Most of this delta V can be attained by performing aerobraking at Mars. An accurate assessment of how much delta V can be provided by aerobraking was completed and is covered in the *OCF.[0]* For reference, earlier in the program it was assumed that 80% of the 2,491 m/s of delta V needed was provided by aerobraking (1,993 m/s), which left 498 m/s to be provided by Hummingbird. As a consequence, the total delta V supplied by the Hummingbird propulsion system was 2,597 m/s, which already is within the propellant capabilities of Hummingbird.

The more accurate assessment of aerobraking reduced the aerobraking delta V from 498 m/s to 90 m/s and was based on estimating the initial apoareion altitude of the highly elliptical insertion orbit, and to calculate the time needed for circularization. Several papers, mostly from NASA, were found on this topic and were evaluated to find information relative to real missions (Mars Odyssey, Mars Global Surveyor, and Mars Reconnaissance Orbiter). [3,4,5] This gives a total delta V for Hummingbird of 2,189 m/s.

3.2 Asteroid Missions Preliminary Analyses

Research continued relative to missions to near Earth asteroids (NEAs). The study model for these types of missions was very similar to that used for Mars. However, in the case of the asteroids, aerobraking cannot be used for capture, since the asteroids do not have atmospheres. Therefore, in the asteroid case a completely propulsive maneuver has to be performed. In addition, asteroids have negligible gravitational forces due to their relatively small mass. As a result, the NEA case was modeled as rendezvousing Hummingbird with an empty point in space. Thus, this mission requires a full rendezvous between the Hummingbird transfer orbit and the asteroid orbit, which also includes an additional heliocentric plane change at the location of the asteroid. After the rendezvous with the asteroid is accomplished, the orbital mission around the asteroid can begin.

Preliminary calculations have been made for the total delta V needed for NEA exploration missions. The delta V was considered as the sum of the delta Vs necessary for transferring from Earth to the asteroid and the delta V to orbit the asteroid during the mission. The transfer delta V depends on the chosen destination asteroid. The delta V to orbit the asteroid depends on how far from the asteroid the spacecraft is and the duration of the mission.

A few asteroids were selected for preliminary calculations and are listed in Table 1, in order of average distance from the Earth.

Table 1. Asteroid List.

Parameter	4769 Castalia	2008 HU4	1620 Geographos	25143 Itokawa	433 Eros
Semi-major Axis (a) (AU)	1.063	1.097	1.245	1.324	1.458
Eccentricity (e)	0.4831	0.079	0.335	0.28	0.223
Inclination relative to the Ecliptic (deg)	8.89	1.326	13.341	1.622	10.829
Diameter (m)	1300	8	3500	400	17000
Mass (kg)	5.00E+11	6.20E+05	2.60E+13	3.55E+10	6.69E+15
Gravity Accel. at Surface (m/s)	7.90E-05	2.59E-06	5.67E-04	5.92E-05	6.18E-03
Circular Orbit Vel. at Surface (m/s)	0.2266	0.0032	0.9958	0.1088	7.25
Escape Vel. at Surface (m/s)	0.3204	0.0045	1.4083	0.1539	10.25
Aphelion (AU)	1.5765353	1.183366101	1.662075	1.69472	1.783134
Perihelion (AU)	0.5494647	1.010965424	0.827925	0.95328	1.132866

In terms of transfer delta V, a few assumptions were made to get preliminary estimates. The main assumption that was made is that the transfer orbit delta V is comprised of two components: 1) the delta V necessary for a near-Hohmann transfer from Earth to the asteroid (i.e., the Earth and the asteroid are in the same plane), and 2) the two delta Vs for the deep space plane changes (i.e., the delta Vs to rendezvous with the actual asteroid orbital plane). The sum of these components gives an estimate of the delta V needed for the transfer and rendezvous with the asteroid. The transfer orbit delta V also accounts for the energy required to escape the Earth on a hyperbolic trajectory. A sample asteroid mission is calculated in Section 4.4 later in the paper.

Relative to maneuvering around an asteroid, one option examined early in the program was to maneuver such that Hummingbird moved in a square pattern around the asteroid; however, results show that there was sufficient gravity to maneuver more conventionally as would be the case for bodies with larger masses. The delta V associated with orbiting a representative asteroid is provided in Table 1 above as a part of the asteroid mission discussion.

4. Orbit Cost Function (OCF)

An Orbit Cost Function *OCF* was defined to compare a range of different missions. The *OCF* is the ratio of the mass available in a certain mission orbit to that available in a reference LEO orbit, where the reference orbit is usually a 185 km circular orbit. The *OCF* represents a multiplier on the cost of putting a spacecraft into its mission orbit, or, for a fixed launch vehicle, an inverse multiplier for the amount of payload that can be put into the mission orbit. [0] The *OCF* is related to the required delta V by:

$$OCF = (1+K)e^{\Delta V / g I_{sp}} - K \tag{1}$$

where K is the fraction of the propellant mass assigned to tankage and other propellant hardware, typically 10%. The *OCF* corresponds to the delta V for multiple segments, so that the cumulative cost function, $OCF_{A+B+C...}$ is just the product of the individual *OCF*s A, B, C, and so on. Therefore:

$$OCF_{A+B+C\ldots} = OCF_A \times OCF_B \times OCF_C \times \ldots \tag{2}$$

For each of the missions we studied with respect to different destinations, an overall *OCF* has been calculated. The purpose of calculating the *OCF* is to be able to decide the size of the launch vehicle that is needed for a particular mission. A preliminary result in terms of launch vehicles is presented at the end of the whole *OCF* discussion. The different missions are described below.

4.1 Lunar Mission

Starting at a 185 km altitude parking orbit, and launched due East from Cape Canaveral (which is assumed to be the case with *OCF*=1), Hummingbird will need to perform multiple propulsive maneuvers to get into lunar orbit. The orbit has been defined as a 20 km circular orbit at different possible inclinations (including polar). The first maneuver is a combined transfer and plane change to transfer to the Moon, for a total delta V of 3.14 km/s. When Hummingbird reaches the Moon, it must perform a maneuver for hyperbolic capture, which will require another 834 m/s of delta V. In addition, there will be some delta V required for orbit maintenance and end of life deorbit, estimated at 200 m/s (over 2 years) and 5 m/s, respectively.

Since the Moon is inclined from the ecliptic plane 5.15 deg, and the parking orbit is 5.05 deg from the ecliptic, only a 0.1 deg plane change is necessary. A Hohmann transfer will minimize the delta V required to rendezvous with the Moon, and will only require 5 days for the transfer. Completing these two maneuvers in one combined maneuver saves Hummingbird 13 m/s compared with doing them separately. Assuming that the launch vehicle is responsible for the combined transfer and plane change maneuver to transfer to the Moon and that the remaining maneuvers are carried out by Hummingbird, and assuming a LOX/kerosene I_{sp} of 320 s, the *OCF* is 2.89. As Hummingbird approaches 20 km from the lunar surface, the geocentric speed of the spacecraft is about 187 m/s approximately at apogee of the transfer orbit. This velocity corresponds to a pericenter velocity on the hyperbolic capture trajectory of about 2.5 km/s in lunar-centric space at a distance of 20 km above the lunar surface. In order to place Hummingbird into the desired 20 km circular orbit, the velocity at pericenter must be reduced to 1.67 km/s. The capture maneuver will therefore require a delta V of 834 m/s. The desired inclination of the orbit around the Moon can be achieved simply by approaching the Moon from the appropriate side, while maintaining the same arrival asymptote direction, without the need to use extra delta V. The rendezvous maneuver has an *OCF* of 1.48, and is done assuming hydrazine propellant for the Hummingbird propulsion system, which has an assumed I_{sp} of 235 s.

Orbit maintenance will be necessary to keep the spacecraft in the right orbit. An estimated delta V of 100 m/s will be required per year to account for perturbations, which are mostly represented by the lunar gravity field. For a 2 year mission, Hummingbird will therefore need about 200 m/s of delta V that corresponds to an *OCF* of 1.1. At the end of life, Hummingbird can deorbit with a controlled impact onto the lunar surface with about 5 m/s of delta V. Our preliminary results indicate that the total delta V required beyond the initial Earth parking orbit is 4.2 km/s, with Hummingbird responsible for less than 1.1 km/s of the total. The list of delta Vs and *OCF*s can be found in Table 2.

Table 2. Lunar Mission Summary.

Parameter	**ΔV (km/s)**	***OCF***	**t (days)**
Combined Maneuver*	3.135	2.887	5.0
Hyperbolic Capture	0.834	1.480	< 1
Maintenance	0.200	1.100	
End of Life / Deorbit	0.005	1.002	< 1
Total Delta V (km/s)	**4.174**	**4.709**	
Total Spacecraft Delta V (km/s)	**1.039**	**1.631**	

4.2 Mars Mission

By assuming we begin again from a 185 km altitude around Earth, with launch due east from Cape Canaveral, a total mission delta V of about 6.12 km/s will be needed for the entire mission. Hummingbird begins with a plane change that places it in the ecliptic plane, which will reduce the overall mission delta V. Next, it will perform a transfer that is tangential to Earth's orbit (what we call a T1 transfer) and then a heliocentric plane change. A hyperbolic capture will be done at Mars, followed by an aerobraking maneuver, which itself contains multiple phases. The purpose of aerobraking is to reduce the amount of delta V required by the spacecraft. These phases include a “walk in” phase, a main phase, and a “walk out” phase. After Hummingbird reaches Mars orbit, the delta V for orbit maintenance and end of life are determined as well. The delta Vs and respective *OCF*s for the Mars mission are listed in Table 3, and are explained below.

To take full advantage of the heliocentric velocity of Earth, Hummingbird will perform a 5.05 deg plane change to place itself into the ecliptic plane before transferring to Mars. This plane change has an *OCF* of 1.27 and requires 687 m/s of delta V. Once Hummingbird is in the ecliptic plane, a T1 transfer will be performed. Assuming launch on May 2, 2018, which is near the Earth-Mars opposition date of July 27, 2018 (most favorable opposition date in the 15-year synodic cycle), this transfer uses about 3.5 km/s of delta V and has an *OCF* of 3.30. These two maneuvers will be performed by the launch vehicle. When Hummingbird reaches 90 deg before Mars on the transfer trajectory, it will need to perform another plane change to intercept Mars. The maneuver is performed 90 deg before arrival because the plane change itself is minimized and the corresponding required delta V is close to minimum for the interplanetary transfer. The *OCF* for this maneuver is 1.39 and requires 701 m/s of delta V. The T1 transfer and the following plane change effectively reduce the amount of delta V required to reach Mars to a value close to minimum, as discussed in greater detail in Section 3.1. Figure 3 shows the orbit of the Earth, the orbit of Mars, the transfer orbit, the Sun, and the initial and final positions of both the Earth and Mars.

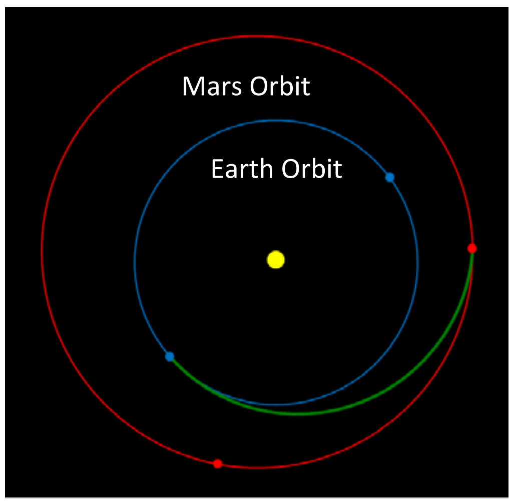

Figure 3. Mars Mission Profile. (The transfer orbit is shown in green.)

Hummingbird will ultimately be in a 300 km altitude circular orbit around Mars, at an inclination that will vary based on the mission. To achieve this end result entirely by propulsive maneuvers would require a delta V of 2.1 km/s. If time is not an issue, aerobraking is an option that can reduce this value significantly. Aerobraking is a technique that helps lower the apoapsis of an orbit by flying at a low enough periapsis altitude where the density of the atmosphere creates significant drag effects that slow down the vehicle at every pass. Eventually, the apoapsis will be lowered to a desired point, and then periapsis can be raised (“walked out”) to meet the final orbit. The first step is for Hummingbird to be captured into a highly elliptical orbit around Mars, with the altitude of periapsis at 300 km and the altitude of apoapsis at 54,000 km, where the latter is chosen based on the approach that was used for past Mars missions (e.g., MRO, Mars Odyssey, and Mars Global Surveyor). This initial orbit will have a period of 1.9 days. It costs less in terms of delta V to capture a spacecraft into an orbit of high eccentricity than one with lower eccentricity for a given periapsis altitude. [0] Hummingbird will take advantage of this idea, since aerobraking will provide essentially free delta V (i.e., by lowering the apoapsis altitude with multiple periapsis passages). During the initial capture maneuver, at the distance of closest approach to Mars, Hummingbird will perform a propulsive delta V maneuver of 829 m/s to slow it down from 5.5 km/s to 4.7 km/s in Mars-centric space. This hyperbolic capture maneuver has an *OCF* of 1.48. The desired orbital inclination at Mars can be achieved at no additional delta V cost by approaching the planet at certain locations around Mars, as explained previously for the lunar mission.

After capture into the highly elliptical orbit around Mars, Hummingbird is ready to start aerobraking. First, it will need to make a certain number of maneuvers at apoapsis to lower the periapsis ("walk in phase"). The reason why a lower periapsis is desired is that the greater atmospheric density at lower altitudes will reduce the overall time it takes to lower the apoapsis. Drag, reduces the eccentricity and lowers the apoapsis. During the walk in phase, Hummingbird will be lowered until periapsis reaches an altitude of 120 km. This maneuver will need 7 m/s of total propulsive delta V. When this phase is complete, the main aerobraking phase begins. During the entire main phase, the altitude of periapsis will remain at 120 km, but apoapsis will continuously decrease due to aerodynamic drag at every periapsis pass. The orbit period at the start of the main phase is 1.87 days. After each pass, the period will decrease, thus making the process faster and faster. Since this process is much slower at the beginning, aerobraking may take up to 5 months. Since the atmospheric density can be highly unpredictable at Mars, Hummingbird may not be continuously stable during the entire aerobraking duration. If uneventful storms or spikes in atmospheric density occur, periapsis may have to be raised for some short period of time, and then lowered back down again. To account for these events, an estimated 40 m/s of delta V has been added. Eventually, the altitude of apoapsis will reach 300 km, which ends the aerobraking main phase. The "walk out" phase is next. As soon as apoapsis reaches 300 km altitude, two propulsive maneuvers will be performed at apoapsis to raise the periapsis back to 300 km. The walk out phase requires 43 m/s of delta V. When this entire procedure is finished, Hummingbird will be in a circular orbit at 300 km altitude, with 1.17 km/s of propulsive delta V saved thanks to aerobraking.

Orbit maintenance will be required throughout the duration of the mission. A delta V of 100 m/s per year is estimated for Hummingbird. For a total mission life of 2 years, Hummingbird will therefore need 200 m/s of delta V, corresponding to an *OCF* of 1.1. At the end of life, Hummingbird can be raised to a safe altitude so as to not contaminate the Martian surface with about 73 m/s of delta V. As mentioned above, the entire mission to Mars has an estimated delta V of 6.12 km/s. The Hummingbird spacecraft will only be responsible for 1.89 km/s of the total, with the remaining will be provided by the launch vehicle. The list of delta Vs and *OCF*s can be found in Table 3.

Table 3. Mars Mission Summary.

	ΔV (km/s)	***OCF***	**t (days)**
Plane Change	0.687	1.269	< 1
T1 Transfer*	3.541	3.300	179
Plane Change (at 90 deg arc)	0.701	1.391	< 1
Hyperbolic Capture	0.829	1.476	< 1
Aerobraking	0.090	1.044	> 120
Walk In Phase	*0.007*	*1.003*	
Main Phase Maintenance	*0.040*	*1.019*	
Walk Out Phase	*0.043*	*1.021*	
Maintenance	0.200	1.100	
End of Life	0.073	1.035	< 1
Total Delta V (km/s)	**6.119**	**10.214**	
Total Spacecraft Delta V (km/s)	**1.892**	**2.439**	

* Assuming launch on May 2, 2018

4.3 Phobos Mission

A mission to Phobos will require maneuvers similar to those for the Mars orbiter mission, but will need about 1.0 km/s extra delta V overall. The first four maneuvers will be identical to those of the Mars mission (i.e., plane change to ecliptic, T1 transfer, plane change at 90 deg arc before Mars, and hyperbolic capture at Mars into a highly elliptical orbit). In terms of achieving an orbit around Phobos, it was found that the gravitational sphere of influence of Phobos is very small, in particular smaller than the average radius of the Martian Moon itself, effectively preventing a stable orbit around it. Therefore, orbiting Phobos will actually be accomplished via an orbit around Mars, with the Hummingbird orbit having the same semi-major axis as Phobos, in order to have the same orbit period. In addition, the target orbit will be such that when Hummingbird reaches the final apoapsis altitude, Phobos will also be at its apoapsis and along the same radial direction from Mars, except that the Hummingbird apoapsis will be at a slightly higher altitude than Phobos. This way, even though Hummingbird is orbiting Mars, its relative trajectory with respect to Phobos will be a full revolution around Phobos itself, at a relatively close distance from its surface, which will allow for accurate surface observations. In particular, the relative motion will be a 2:1 ellipse. Hummingbird's orbit apoapsis will be about 21 km from Phobos' center of mass, and on the side of Phobos farther from Mars. Since the semi-major axis is chosen to be the same for both Hummingbird and Phobos, the periapsis of Phobos also will be about 21 km farther from Mars than that of Hummingbird. Thus, both Phobos and Hummingbird will arrive at their relative periapses simultaneously, since they have the same period around Mars. Taking into account the actual dimensions of Phobos, Hummingbird will essentially be less than 10 km from the surface of Phobos at any given time in its final orbit around Mars. As Hummingbird orbits Mars, it effectively goes around Phobos once per orbit as well.

To place Hummingbird into this orbit, the satellite will still need to use aerobraking. The "walk in" phase is identical to the one proposed on the Mars mission, for a total delta V of 7 m/s. This delta V will place the periapsis altitude at 120 km above Mars. The main phase will then begin, lowering apoapsis to the desired distance of 9,540 km from the center of Mars (i.e., at an altitude of 6,144 km). Maintenance delta V during the main phase is again estimated at 40 m/s for events such as spikes in atmospheric density and Martian storms. As soon as the target apoapsis altitude is reached, the "walk out" phase can begin. This phase will raise the periapsis from a 120 km altitude out to 5,818 km and requires 575 m/s of delta V. At the end of the "walk out" phase, Hummingbird will be in the final orbit, which will produce effectively a final "science trajectory" around Phobos in the form of a 2:1 ellipse, as explained above. Aerobraking for this mission saves about 440 m/s of delta V. Orbit maintenance is estimated at 100 m/s per year, for a total mission life of 2 years. Hummingbird can be raised to a safe orbit around Mars with about 565 m/s of delta V. Therefore, the total mission delta V sums up to 7.1 km/s, but Hummingbird will be responsible only for 2.89 km/s of it, since the remaining amount can be provided by the launch vehicle. In a possible next phase of the program, Microcosm will design a mission to Deimos as well. The list of delta Vs and *OCF*s can be found in Table 4.

Table 4. Phobos Mission Summary.

	ΔV (km/s)	***OCF***	**t (days)**
Plane Change	0.687	1.269	< 1
T1 Transfer*	3.541	3.300	179
Plane Change (at 90 deg arc)	0.701	1.391	< 1
Hyperbolic Capture (at Mars)	0.829	1.476	< 1
Aerobraking	0.592	1.322	> 120
Walk In Phase	*0.007*	*1.003*	
Main Phase Maintenance	*0.040*	*1.019*	
Walk Out Phase	*0.545*	*1.294*	
Maintenance	*0.200*	*1.100*	
End of Life	*0.565*	*1.306*	*< 1*
Total delta V (km/s)	**7.114**	**16.321**	
Total Spacecraft Delta V (km/s)	**2.886**	**3.897**	

* Assuming launch on May 2, 2018

4.4 Asteroid Mission:

Near-Earth Asteroids offer an interesting opportunity for near-term robotic exploration and longer-term human exploration, as demonstrated recently by the creation of private asteroid mining companies Planetary Resources and Deep Space Industries. These small bodies are of particular interest because they hold clues to the origin of the solar system and the formation of the planets. Primitive type asteroids can provide additional insights and also resources. A mission to a near-Earth asteroid shows the versatility of the Hummingbird spacecraft.

The standard parking orbit of 185 km launched due east of Cape Canaveral is used once again for the asteroid mission. Hummingbird will first perform a 5.05 deg plane change into the ecliptic plane using 687 m/s of delta V. This maneuver corresponds to an *OCF* of 1.27. From here, Hummingbird will escape Earth and enter a transfer orbit by using 3.28 km/s of delta V, corresponding to an *OCF* of 3.03. Just after escape, a plane change in heliocentric space will be performed so that the transfer trajectory will intercept the asteroid. The heliocentric plane change in this case is performed right after escape because the transfer arc is smaller than 90 deg. The calculated launch date is Dec 5, 2021, which is before the opposition date of February 8, 2022, i.e., the closest approach between the Earth and the asteroid system during their nearly 12-year synodic cycle. The transfer time to the asteroid is approximately 89 days, and the transfer itself is done at minimum energy (it is the closest approximation to a Hohmann transfer based on the real orbits of the Earth and the target asteroid system). The plane change maneuver produces an *OCF* of 1.50. This transfer approach assumes that Hummingbird will go directly to the asteroid with no gravity assists around other celestial bodies. Figure 4 shows the orbit of the Earth, the orbit of the asteroid system, the transfer orbit, the Sun, and the initial and final positions of both the Earth and the asteroid system.

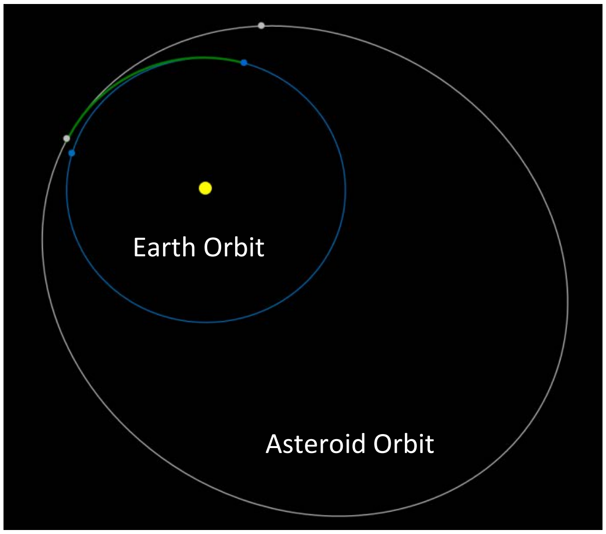

Figure 4. Asteroid Mission Profile. (The transfer orbit is shown in green.)

The rendezvous maneuver with the asteroid requires 3.82 km/s due to the change in velocity from the transfer orbit. In addition, a plane change is necessary in order to end up in the asteroids' orbital plane; assuming for now a 3.34 deg plane change (half the inclination of the asteroid's orbit with respect to the ecliptic), the required delta V is of 1.70 km/s. However, we have assumed that when we combine the rendezvous and the final plane change maneuvers into one maneuver, we can save some delta V. Based on this assumption, we estimated that about 20% of the total asteroid rendezvous delta V can be eliminated by performing the combined maneuver, giving an overall rendezvous delta V of 4.42 km/s, with an *OCF* of 7.37. For the moment this value is an estimate given that the final plane change inclination has not been exactly calculated.

Once Hummingbird completes its rendezvous with the asteroid system, an orbit maintenance delta V will be needed for the life of the spacecraft. It is estimated that 100 m/s/year, for a total of 200 m/s over two years, will be sufficient to maintain the orbit (*OCF* is equal to 1.1). A paper presented at the 2011 AAS/AIAA Astrodynamics Specialists Conference showed that the relative orbital velocities of the asteroid are in the cm/s range. [7] It also showed that an exploration approach consisting of a flyby of one of the three asteroids in the system would require a delta V of approximately 10 cm/s, small enough to allow accurate observations and measurements. As a consequence, a circular orbit around the same asteroid, which is the approach we assumed, would have an even smaller velocity. Thus, we consider the maintenance delta V of 200 m/s for a 2 year period assumed above to be a conservative estimate. A detailed analysis of maintenance velocities is being considered by Microcosm as an internal study. An end-of-life delta V of 3 m/s was calculated to de-orbit the spacecraft into the asteroid system from the 1 km orbit altitude assumed. The *OCF* corresponding to the end of life and reserve maneuver equals 1.00.

The total delta V is 9.45 km/s, with Hummingbird expected to provide 4.62 km/s of this total, while the rest of the delta V is expected to come from the launch vehicle. The total *OCF* for the mission is 47.6. This result is just outside of the expected capabilities of Hummingbird. However, this maneuver sequence should be considered as an unfavorable case scenario. In fact, planetary flybys around other celestial bodies would increase the spacecraft velocity without using onboard delta V during the transfer phase. Also, the use of an additional upper stage or a cruise stage attached to Hummingbird would further reduce the amount of delta V required of the spacecraft. Additional analyses of the rendezvous plane change, the design of planetary flybys, and accurate orbit maintenance calculations are on the list of additional analyses to be performed either through Microcosm IR&D or through funding from potential follow-on contracts.in future phases of the program. Our preliminary findings show that Hummingbird is expected to be capable of getting to the asteroid and carry out its mission. The list of delta Vs and *OCF*s can be found in Table 5.

Table 5. Asteroid Mission Summary.

	ΔV (km/s)	***OCF***	**t (days)**
Plane Change to the Ecliptic	0.687	1.269	< 1
Transfer**	3.279	3.027	89
Plane Change to Asteroid	0.861	1.498	< 1
Combined Maneuver*	4.416	7.374	
Maintenance	0.200	1.100	
End of Life	0.003	1.001	< 1
Total Delta V (km/s)	**9.445**	**46.727**	
Total Spacecraft Delta V (km/s)	**4.619**	**8.120**	

* Maneuver combines rendezvous and plane change at the asteroid

** Assuming launch on Dec 5, 2021

4.5 Launch Vehicle

Based on the above results for the *OCF*, we have estimated the size of the launch vehicle needed for each of the four missions previously described. By assuming a Hummingbird dry mass of 25 kg, the initial mass, M_{LEO}, required in LEO for each of the four mission scenarios is the following:

- Moon (*OCF* = 4.709): M_{LEO} = 118 kg
- Mars (*OCF* = 10.214): M_{LEO} = 255 kg
- Phobos (*OCF* = 16.321): M_{LEO} = 408 kg
- Asteroid (*OCF* = 46.727): M_{LEO} = 1,168 kg

The above results show that the initial mass in a 185 km circular orbit with launch due east is relatively small for all four missions, especially for the first three. As a consequence, relatively small launch vehicles would be good candidates to launch Hummingbird for the missions described by the four cases above. In particular, the Moon mission could be achieved by most launch vehicles, especially Pegasus (M_{LEO} = 443 kg), Minotaur I (M_{LEO} = 580 kg), and Athena 1c (M_{LEO} = 820 kg). The same launch vehicles would support Mars and Phobos missions. The asteroid system mission could be accomplished via the Minotaur IV (M_{LEO} = 1,720 kg), Taurus (M_{LEO} = 1,350 kg), and Delta 7320 (M_{LEO} = 2,776 kg).

5. Conclusions

This paper has presented a small satellite concept that can accommodate a wide range of interplanetary class missions. (Missions to Venus were not analyzed, but could be included as a candidate target in future analyses.) In order to accommodate these missions Hummingbird, a small composite satellite was evaluated as a possible solution to the need for rapid scouting missions that could provide significant science return at low cost. Hummingbird has the ability to enhance its primary optical telescope payload with the addition of multiple CubeSat payloads. As microelectronics become smaller, the opportunities to utilize these improvements in small satellites will expand. The spacecraft bus utilizes this fact by incorporating CubeSat channels on the sides to expand the possible scientific return. These smaller payloads provide valuable precursor information to future larger missions at a fraction of the cost. Hummingbird provides a standard spacecraft bus with a primary optical telescope combined with the ability to accommodate a range of candidate CubeSat payloads. It overcomes the very real limitations by providing the necessary propellant to get CubeSat payloads to interplanetary destinations. From the work presented in the paper, Hummingbird would roughly be 100kg – 500 kg to arrive at the destinations presented. This creates low-cost small satellite options for scouting targets of interest. Interplanetary missions are a real possibility for small spacecraft and the Hummingbird architecture offers a solution to the limited range of CubeSats while utilizing their innovative capabilities.

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References

[1] Sarzi-Amade, Nicola. 2010. *Mars Rapid Round Trip Mission Design*. Ph.D. Thesis, University of Southern California, August

[2] Wertz, James R, David F. Everett, and Jeffery J. Puschell. 2011. *Space Mission Engineering: The New SMAD*. Hawthorne, CA: Microcosm Press.

[3] Dwyer, Alicia M.. 2001. *Modeling the Mars atmosphere for Monte Carlo simulations of the Mars 2001 Odyssey aerobraking mission*. Thesis (M.S.), George Washington University, 2001.

[4] Gladden, R. E. “Mars reconnaissance orbiter: aerobraking sequencing operations and lessons learned.” *Space Operations Communicator* 6, No. 1 (2009): 1–10.

[5] Cichocki, Filippo, Stefania Cornara, M. Sanchez, and J. L. Cano. “Aerobraking Mission Analysis Tool for Mars Exploration Missions.” IPPW7 conference, June, 2010.

[6] Tolson, R. H., A. M. Dwyer, J. L. Hanna, G. M. Keating, B. E. George, P. E. Escalera, and M. R. Werner. “Application of accelerometer data to Mars Odyssey aerobraking and atmospheric modeling.” *Journal of Spacecraft and Rockets* 42, no. 3 (2005): 435-443.

[7] Bellerose, J., et al, “Dynamics and Stability in a Triple Asteroid System: Applications to Mission Design”, AAS 11-404, AAS/AIAA Astrodynamics Specialist Conference, July 31 – August 4, 2011, Girdwood, Alaska.