# Interplanetary Rideshare Cost/Benefit Analysis: A Mars Mission Approach

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## ABSTRACT

In recent years the popularity of rideshare missions has increased dramatically. Rideshare missions have become the primary launch mechanism for small satellites and have provided high cost and logistical benefits for spacecraft developers. Rideshare launches are now available on even the most oversized vehicles, such as Falcon 9. In addition, rideshare opportunities are becoming available beyond launch, with several companies providing shared transportation services using transfer vehicles to deploy spacecraft in different orbits in LEO or beyond. The rideshare launch model can easily be expanded to interplanetary missions, and some launches, such as SLS-1 (Artemis 1), are already planned to deploy several spacecraft beyond LEO. However, as in LEO, the rideshare concept can be expanded beyond the launch phase in interplanetary missions using a carrier vehicle. In this approach, spacecraft heading for destinations beyond Earth obit would share a carrier vehicle to deliver them to their destination. This paper analyzes the implications of such an interplanetary carrier vehicle in a Mars transfer scenario. Mars is chosen due to its popularity as a destination for scientific missions, but the analysis is relevant to other potential destinations such as Venus or the asteroid belt. The paper analyzes the effect of the rideshare concept in Interplanetary Transfer Operations: the need for individual spacecraft operations in transit is eliminated since a single carrier vehicle is taking care of the trip to Mars. Operations include tracking and deep-space communications as well as navigation and maneuvering. The paper ends with a call for action for funding agencies interested in interplanetary missions to empower the definition of new standards needed to ensure high levels of commonality.

## INTRODUCTION

In recent years, small satellites have become a critical part of the space industry, with thousands of spacecraft in LEO supporting every mission type, from communications to state-of-the-art scientific research. Moreover, the low cost associated with smaller size and mass production has made mega-constellations possible, adding many thousands of smallsats to the global inventory. Now smallsats are being considered for interplanetary missions to different celestial bodies. Examples of these missions include the twin-spacecraft EscaPADE,[1] the dual space probe JANUS, and many CubeSats planned for missions to the Moon and beyond.[2] While the numbers of smallsat interplanetary missions are currently minimal, they can be expected to follow a similar evolution to the LEO missions, with a significant increase in numbers over that next decade. Reviewing the story of small satellite evolution in LEO may help predict and prepare for the emergence of small satellites as key enablers beyond Earth orbit.

Earth-orbiting small satellites went through three distinct development phases:

1. *Feasibility demonstration*: In LEO, this phase took a long time. It started with satellites built by AMSAT, a small number of universities, and a few small companies like SSTL. The purpose of the spacecraft in this phase is primarily technology demonstration as well as education. The explosion of university CubeSats in the early 2010's represents the end of this phase with a clear consensus that small satellites were capable of operating in space.
2. *Utility Demonstration*: In this phase, commercial and government operators accepted small satellites as mission-capable systems and developed mission-capable spacecraft. SSTL, Orbcomm, Planet, Spire, and Skybox are examples of commercial success stories, while the NASA AMES series of exobiology CubeSats

are an excellent example of early government applications.

3. *Wide adoption*: In this phase, we witnessed an explosion of small satellite missions in all traditional space applications from communication constellations (Starlink, OneWeb, Swarm Technologies) to remote sensing and science (RapidEye, Spacety, Satellogic, SpaceWill). This phase sees the entry of many new players to the space industry and many new mission concepts enabled by the reduced cost associated with small satellites. Many of these new concepts incorporate constellations or swarms of spacecraft to perform missions not feasible with single spacecraft systems.

Along with these phases in the development of spacecraft and missions, the space transportation methods available to small satellites also followed three distinct phases.

1. *Piggyback phase*: In this phase, small satellites were launched as secondary payloads with traditional spacecraft as primary payloads. In this approach, the primary payload has ownership of the launch, and the small satellites must follow the primary payload's schedule and orbit parameters. In addition, launch opportunities are limited by the number of primary payloads willing to accept secondary payloads. These constraints challenge all small spacecraft developers, but they become more problematic for small spacecraft missions with specific commercial and scientific goals. Some of the most popular systems in this phase include the Ariane ASAP rings,[3] NASA GAS-Can,[4] and early CubeSats, including the first NASA ELaNa missions.[5]

2. *Dedicated Small Launches and regular Ride-Share*: Once small satellites demonstrated their utility, many commercial and scientific missions demanded control over their launch parameters. As a result, a new launch vehicle class was developed to support this new market (SpaceX Falcon 1e, Rocket Lab Electron, iSpace Hyperbola-1). Dedicated small satellite launch vehicles reduce schedule and orbit constraints but have higher per kilogram launch costs. As a lower-cost alternative to dedicated small launch vehicles, rideshare missions on larger rockets became available (PSLV, Vega, Falcon 9, Sherpa, Soyuz Fregat). Here, many small satellites share a larger vehicle. This approach provided frequent, low-cost launch opportunities, but still providing access to limited orbital destinations.

3. *Last-mile Space Tugs*: To increase the range of orbits available to small satellites in low-cost rideshare launches, some companies are developing orbital transfer vehicles, or space tugs, to provide small satellite developers a ready-made solution for orbit adjustments after a rideshare launch. These companies include Momentus (Vigoride), UARX Space (OSSIE), SpaceFlight (Propulsive Sherpa), Rocket Lab (Photon), DOrbit (ION). Space tugs allow small spacecraft developers having specific orbit requirements to use low-cost rideshare opportunities without incorporating the complexity of orbit transfer systems into their spacecraft. Here, the propulsion systems and operational requirements are incorporated into the space tug and shared by several spacecraft, thus reducing the overall cost for the individual spacecraft.

## ***Next Step: Going Beyond LEO***

The next step in the evolution of the small satellites involves missions beyond Earth's orbits. We can expect that the development of these missions will follow similar steps as in LEO. So far, the number of missions is minimal. We are clearly in a feasibility demonstration phase. The primary objective of the missions is to test the compatibility of smallsat systems with planetary missions. However, the success of small satellites in LEO is accelerating the timeline for interplanetary missions. The MarCO[6] twin-spacecraft were a major step towards feasibility demonstration. In addition, many interplanetary missions are in development and getting ready to launch. These include 13 CubeSats being ready to launch with the first SLS mission,[5] and ESA's Hera Asteroid Impact mission.[7] It is expected that these upcoming missions will complete the feasibility and utility demonstration phases for interplanetary small satellites and will lead to a broad adoption phase with similarities to the LEO experience. The number of players in the interplanetary space business is expected to increase significantly along with the number of spacecraft flying beyond Earth orbits. Moreover, the lower cost of small satellites is already generating interest in constellations beyond the Earth, like ESA's Moonlight Project to provide lunar navigation and communications, resulting in a further increase in the numbers of spacecraft launched.

The launch strategies for interplanetary satellites seem to be following a similar timeline as in LEO launches. Initially, missions are using piggyback opportunities (MARCO, the 13 CubeSats on the SLS, EscaPADE). However, these missions are finding similar schedule and orbit problems as small satellites in early LEO, as was the case of delays on the launch of the SLS or the change of trajectory of the Phsyche spacecraft that left EscaPADE waiting for another piggyback flight. Other great examples of rideshare missions beyond LEO are NASA lunar lander missions, where multiple lander providers offer sharing the lander to deploy rovers and instruments on the Moon.

Looking at the current evolution of smallsat interplanetary missions, we will likely reach a similar launch state as LEO spacecraft. In addition, a number of dedicated small launch vehicles with interplanetary capabilities will be available soon. These dedicated vehicles will likely have to compete with lower-cost rideshare opportunities on larger rocket providers like SpaceX and Arianespace. However, a few small rocket launchers are already considering providing dedicated interplanetary launch opportunities, as is the case of Rocket Lab with the Photon upper-stage or FireFly Aerospace.

## INTERPLANETARY TUGS: A BETTER WAY TO TRAVEL

In LEO, Space tugs are eliminating many of the orbital constraints for rideshare missions. As a result, they are becoming great enablers for spacecraft developers and companies since they provide more flexible orbit insertion and rapid constellation deployment. Space tugs in LEO also remove the complexity associated with maneuvering capabilities from the individual spacecraft and reduce overall cost. When considering ride share interplanetary missions, the specific characteristics of these missions make space tugs an even more attractive solution. The following are some of the relevant characteristics of interplanetary missions that support the use of space tugs:

### *Schedule constraints*

Favorable interplanetary trajectories are only available for small, infrequent time windows, as is the case for Mars missions, for example. As a result, the launch schedule for missions to the same celestial body tends to be the same for many different missions, making rideshare launch cost benefits even more attractive than in LEO.

### *Long and complex cruise phases*

The travel time to targets beyond earth orbit is very long. In addition, navigation during the cruise phase is a complex problem requiring highly specialized know-how and access to the DSN for orbit determination and communications. A space tug requires a single navigation solution for all spacecraft onboard, providing significant cost savings. In addition, new players entering the interplanetary mission domain are unlikely to possess the skills required to complete this phase of the mission independently. The long cruise phases do increase the complexity of the tug since it must keep the transported spacecraft comfortable during the trip. At a minimum, the space tug must provide power, a safe thermal environment, and a communication interface to confirm vehicle health. Fortunately, many of these capabilities are already available. For CubeSats, companies such as Innovative Solutions in Space (ISIS) and UARX Space have deployers with these options already implemented and designed for interplanetary missions, with solutions from 3U to 12U. Moreover, Cal Poly's P-POD offers an improved version of its deployer[8] with these capabilities. For small satellites other than CubeSats, the available separation systems (such as clamp-bands) provide an umbilical with power and data capabilities as a standard option too.

### *Large injection maneuvers*

The high delta-V associated with planetary injection maneuvers require spacecraft to incorporate large propulsion systems. Low thrust transfers can reduce the demands on the propulsion system, but low thrust interplanetary trajectories are highly complex, with increased travel times and challenging navigation requirements. As a result, most interplanetary missions opt for simpler but more massive chemical systems. A space tug would concentrate the propulsive requirements for many spacecraft in a single system. This approach reduces the system's overall complexity and significantly reduces the cost and size of the individual spacecraft.

## MARS MISSION SCENARIO

While the characteristics of the transfer orbits are fairly standard given a specific interplanetary target, analysis of the mission after arrival depends on the specific mission requirements for the individual spacecraft. Therefore, it is not easy to reach general conclusions. In order to illustrate the potential benefits of the interplanetary space tug concept, we will present a specific Mars mission example. Ten small satellites, weighing 100kg each, are to be injected into a single Low Mars Orbit in this mission. In one scenario, the smallsats are to be carried by a space tug that will perform the orbit injection maneuvers. The tug utilizes chemical propulsion with an Isp of 250s and a propulsion system structural mass ratio of 10%. This scenario can then be compared with the ten spacecraft being released into a Mars transfer trajectory from a rideshare launch and flying to Mars independently. The specific characteristics of the proposed mission are summarized in Table 1. The estimated launch mass for the Mars rideshare mission is 3,440kg. This mass is well within the launch capabilities of many launch vehicles, including Falcon 9,[9] Atlas V, or Ariane 5.

**Table 1: Space Tug Mission Characteristics**

| Description | Value |
|---|---|
| Initial orbit | Mars Transfer Orbit |
| Destination orbit | 500km (Low Mars Orbit) |
| Propulsion type | Chemical (Isp=250s) |
| Payload mass | 10 x 100kg small satellites |
| Space tug dry mass | 445kg (without payloads) |
| Required delta-V | 2.1 km/s |
| Required fuel | 1,995kg |
| Total launch mass | 3,440kg |
| Propellant mass fraction | 58% |

For the alternative mission of a free-flying spacecraft, the spacecraft's total mass includes a 100kg dry spacecraft, plus an appropriate propulsive system. The propulsion system assumes an Isp of 250s, and a structural mass ratio of 15% since a smaller propulsion system is less efficient. The resulting parameters for the system are displayed in Table 2. The final mass for ten spacecraft is 3,140kg, very similar to the mass of the tug system. Minor changes to the assumed Isp and propulsion system mass could change the numbers slightly and provide a mass advantage to either mission. However, the takeaway from this simplified analysis is that the tug system provides no clear launch mass advantage.

**Table 2: Free-flying Spacecraft Parameters**

| Description | Value |
|---|---|
| Effective spacecraft mass | 100kg |
| Propulsion system mass | 32kg |
| Spacecraft total dry mass | 132kg |
| Propulsion type | Chemical (Isp=250s) |
| Required delta-V | 2.1 km/s |
| Required fuel | 182kg |
| Launch mass per spacecraft | 314kg |
| Total launch mass (x10) | 3,140kg |
| Propellant mass fraction | 58% |

It should not come as a surprise if we perform a similar analysis for small LEO spacecraft. For many years CubeSats have launched encapsulated in deployers (PODs) with huge masses compared to the spacecraft they carry. Moreover, LEO space tugs also require subsystems and structural components that increase mass compared to free-flying spacecraft. However, these LEO systems have been highly successful. The performance and cost advantages of these systems are not to be found in mass savings. In LEO the benefits provided by standardized deployers or rideshare tugs are found in operational and integration, assembly, and test activities. The same advantages would be found in an interplanetary system as follows:

**Reduced spacecraft delta-V**: Spacecraft developers do not need to incorporate high delta-V propulsion systems since that functionality is incorporated into the tug. The reduced complexity of the spacecraft provides significant savings in development and testing for each of the spacecraft by incorporating a single propulsion system with a single development and testing program. In addition, the logistics involved with spacecraft fueling at the launch site are significantly reduced. Note that, due to the risk associated with large propulsion systems, integration, assembly, and testing costs for such systems are very high.

**Centralized licensing and certification**: A significant enabler for rideshare launches in LEO has been the role of experienced launch aggregators that provide a single interface between a launch provider and spacecraft developers. This reduction in documentation complexity results in significant cost savings for small satellite developers. Interplanetary rideshare using space tug missions presents similar benefits.

**Reduced cruise operations**: A high mission cost during the cruise phase of any interplanetary missions is using the Deep Space Network (DSN) for tracking and communications. The space tug concept centralizes communication requirements to a single system. In our sample mission, this would represent a ten-fold saving in DSN access time. In addition, the cost associated with a navigation team to develop navigation and maneuvering solutions is eliminated for the spacecraft developers and is again concentrated on the tug. An estimated of the operations cost savings involved in the sample Mars mission is provided in Table 3. In addition, the DSN is facing serious congestion problems as large numbers of small spacecraft become operational beyond Earth orbit. Centralizing the cruise phase for several spacecraft traveling to the same target would significantly reduce operational requirements on the DSN. Note that since the tug is already designed to support DSN communications, it may be possible to utilize it as a communications relay after arrival. This would reduce the need for the spacecraft to incorporate large antennas for direct high-speed communications with Earth, further simplifying their design.

**Table 3: Operational cost savings of using a space tug over free-flying small satellites**

| **Space tug** | **Time [hs]** | **Cost [USD]** |
|---|---|---|
| Planning | 1,920 | $180,000 |
| Execution | 500 | $50,000 |
| DSN fees | 500 | $2,500,000 |
| **Total Space tug** | | **$2,730,000** |
| **Free-flying** | **Time [hs]** | **Cost [USD]** |
| Planning | 1,440 | $81,000 |
| Execution | 500 | $30,000 |
| DSN fees | 500 | $2,500,000 |
| **Sub-total free-flying** | | **$2,611,000** |
| **x10 spacecraft** | | **$26,110,000** |
| **Space tug savings** | | **$23,380,000** |

**Reduced overall spacecraft complexity**: The rideshare tug concept provides simpler small satellites (with low delta-V) access to launch opportunities currently limited to much larger missions. This possibility is mainly due to the larger launch vehicles and their capability of reaching interplanetary transfer orbits. LEO systems have demonstrated the cost reduction associated with smaller spacecraft with significant savings in logistics, development time, and integration, assembly, and test operations. These savings increase further when spacecraft standards are incorporated into the system, as CubeSats and ESPA class spacecraft demonstrated. Moreover, the large propellant mass fraction required for interplanetary orbit injection makes many small satellite form factors unsuitable for many interplanetary missions. For instance, a 12U CubeSat with a mass of 24kg would require 14kg of fuel, leaving only 10kg from the entire bus and payload systems. Therefore, for the smallest spacecraft reaching most interplanetary targets, an interplanetary tug is a key enabler.

**Economies of scale**: Small satellites in LEO have demonstrated significant cost savings when utilizing standardized systems and developing multiple spacecraft with a single design in swarms or constellations. This savings also applies to space tugs where a single design can be utilized for many missions with different spacecraft. Again, standardized form factors greatly facilitate the reuse of system designs and the cost savings associated with economies of scale. It is clear that the development of standardized accommodations in the space tug would provide significant cost savings from the tug and the transported spacecraft alike.

While it is not possible to provide an exact value to the savings described above, the experience in LEO makes it clear that standardization and radish are opportunities are an attractive launch solution for small spacecraft. Moreover, the DSN and navigation cost savings alone represent a significant incentive to consider interplanetary space tugs as an option for the deployment of small spacecraft beyond Earth orbit.

## Conclusions: The Path Forward

The simplified analysis above indicates that interplanetary tugs have the potential to enable small satellites to perform critical science missions beyond Earth orbit successfully. The space tug provides potential savings in all areas of operations and logistics. In addition, the use of a tug dramatically simplifies the design and development of the spacecraft it carries. Development simplicity and low cost are critical to enabling new developers to contribute to interplanetary exploration and enable the deployment of constellation missions beyond Earth orbits. However, in order to facilitate and accept the development of these new class of space tugs, funding agencies should consider the following areas for further research and analysis:

**Detail analysis**: Clearly, a more detailed analysis of the space tug's specific characteristics and payloads is required. However, this effort should not be approached in isolation. The scientific community should be involved in developing desired orbital configurations as well as payload requirements.

**Development of accommodations**: The benefits of standard spacecraft accommodations in the tug can not be understated. Experiences in LEO have demonstrated the utility of standards and have provided some guidelines to make those standards successful. First, the standards must be developed early enough to allow the development of spacecraft without schedule pressures. Standards must also be stable, and once defined, no changes should be allowed until the standards are proven and well understood. Given the long timelines associated with interplanetary missions, at least a decade of standard stability should be required. Finally, to encourage global participation, the standards should be international and ideally supported by space agencies across the world.

**Target Expansion**: The economies of scale benefits of the space tug increase with the number of launches. Therefore, the system should be designed to accommodate a variety of targets. For example, Mars, Venus, and the asteroid belt may be serviced by tugs with high levels of commonality.

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