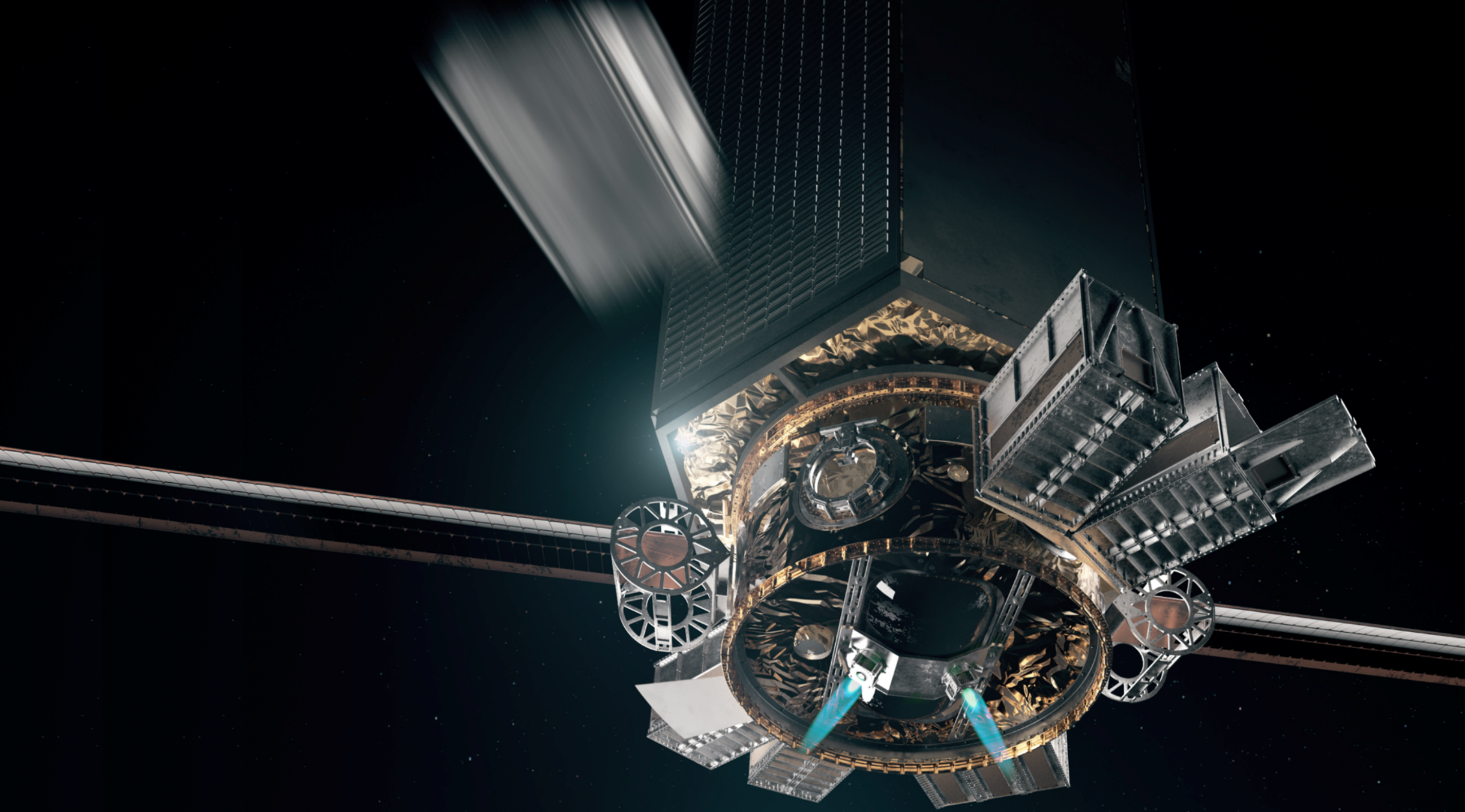

SPACE UTILITY VEHICLE

Payload User's Guide

FIREFLY AEROSPACE

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Overview

Firefly Aerospace Inc. ("Firefly") was founded to provide economical, high-frequency access to space for small payloads. The Firefly team addresses the market's need for flexible access to space with a "simplest, soonest" approach to technology selection.

Firefly's Alpha launch vehicle is scheduled for first launch in first quarter of 2021. This vehicle is capable of delivering 1000 kg to an altitude of 200 km. In order to achieve higher altitudes and greater mission flexibility, Firefly also offers an in-space vehicle, the space utility vehicle. The goal of this document is to provide summary information on this latter vehicle for the purpose of preliminary mission planning for payload customers. The contents found herein are not intended to be mission specific and are subject to change. Firefly welcomes detailed design data such as payload-specific requirements and interfaces, and operational plans once a launch service agreement is in place.

Contact Firefly

Please contact Firefly Aerospace Launch and Payload Services with inquiries into the suitability of the SUV for your mission.

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List of Acronyms

Acronym	Meaning
COTS	Commercial Off-The-Shelf
GEO	Geostationary Orbit
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
OD	Outer Diameter
SSO	Sun-Synchronous Orbit
SUV	Space Utility Vehicle
VAFB	Vandenberg Air Force Base

1 Vehicle Description

The Firefly Space Utility Vehicle (SUV) is a solar-electric third stage for the Alpha and Beta launch vehicles. The SUV is illustrated in Fig. 1 and shown schematically in the Alpha launch vehicle fairing in Fig. 2. This vehicle provides in space propulsion and can serve as a payload bus for missions lasting up to five years. The SUV enables missions that require:

- Higher altitudes than can be achieved using the launch vehicle alone
- Inclinations out of range of the launch vehicle
- Payload support and services for up to 5 years, including high power (0.4–5 kW), up to 150 Mbps downlink, and attitude control
- Multiple trajectory changes
- Deployment of payloads at multiple planes/inclinations (constellation deployment)
- Orbit tuning for launch vehicles using solid rocket motors
- Deorbiting the payload or second stage post mission
- Sustained super low altitude (250 km) orbits

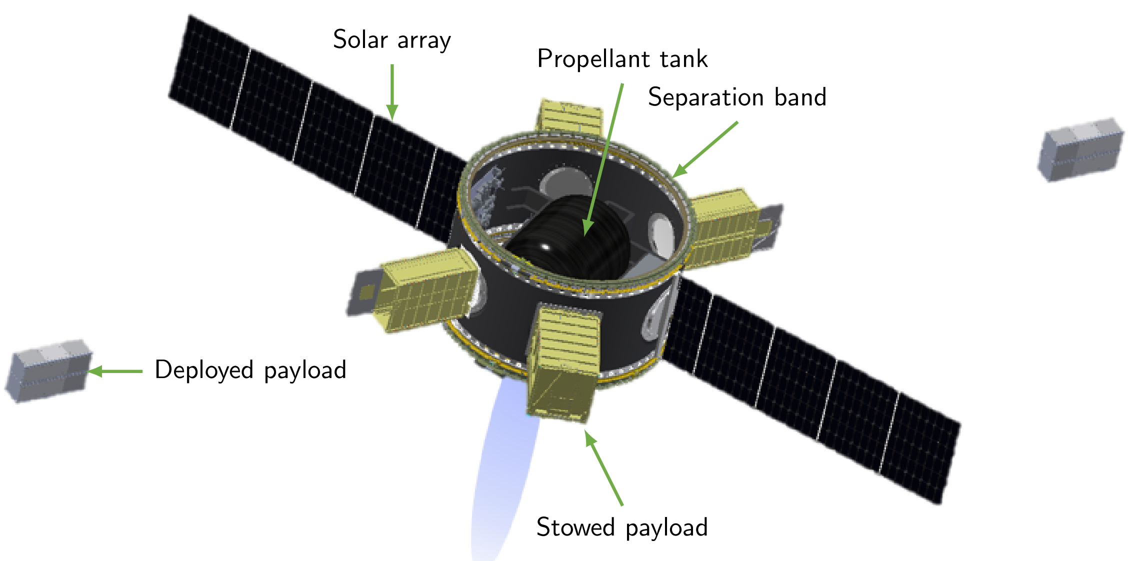

Figure 1: The Firefly Aerospace Space Utility Vehicle (SUV).

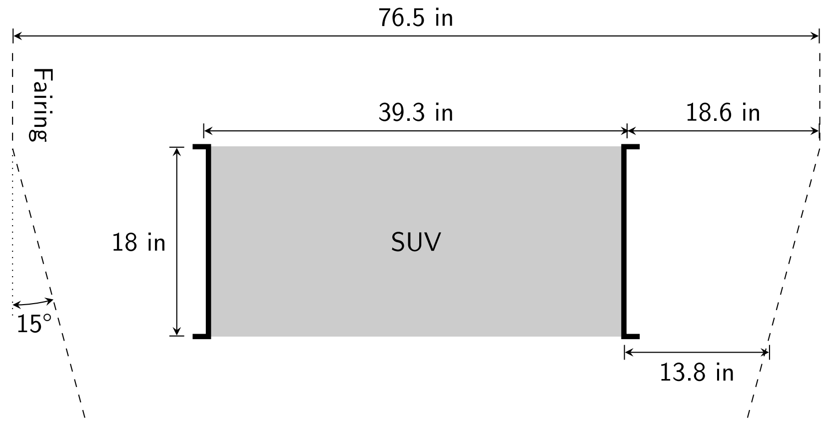

Figure 2: SUV cross section (side view).

Table 1: SUV characteristics

Height	18 in
Diameter	40 in
Dry mass	130 kg
Material	Carbon fiber
Propellant	Xenon
Propellant storage	70 L COPV, 17.3 in OD
Power	0.4–5 kW
Number of thrusters	1–4
Thrust	30–310 mN
Specific impulse	1150–1800 s

2 Vehicle Capabilities

Figure 3 illustrates the degree to which the SUV extends the capabilities of the Alpha launch vehicle. For missions exceeding 2000 km, the SUV delivers substantially more payload mass. Up to 600 kg can be delivered to GEO and up to 500 kg can be delivered to lunar orbit. The SUV is generally well suited to high-energy missions, such as those requiring substantial inclination changes. The SUV can carry a single primary payload as well as up to four secondary payloads (illustrated in Fig. 4). In addition, the SUV can be stacked with a number of deployment rings for a greater number of secondary payloads, or stacked with additional SUVs for increased mission capability.

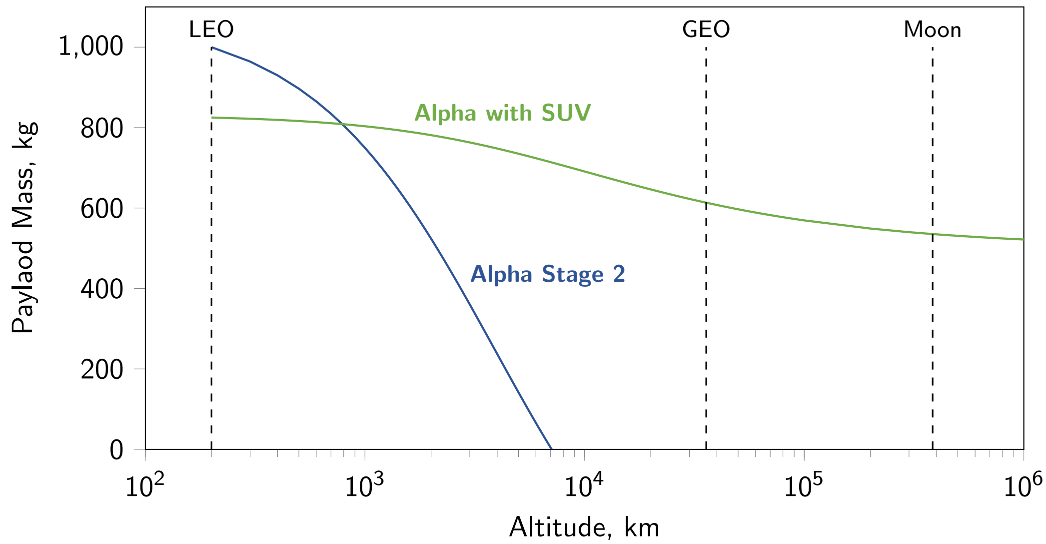

Figure 3: Comparison of Alpha payload delivered with and without the SUV third stage. All SUV trajectories are calculated from an initial circular orbit at 200 km.

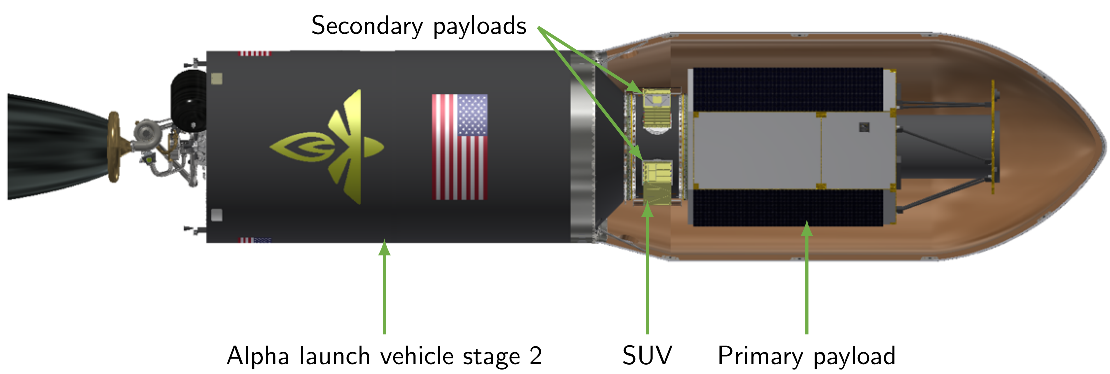

Figure 4: The SUV with primary and secondary payloads inside the Alpha launch vehicle fairing.

3 Vehicle Variants

3.1 LEO Vehicle

The LEO SUV employs a 400 W solar array and commercial off-the-shelf (COTS) avionics. This vehicle is a high-value low-cost solution for payloads operating in the low-radiation environment below 2000 km.

3.2 Extended-Range Vehicle

For payloads operating above 2000 km, or which require rapid transit between trajectories, we offer a high-power and radiation-tolerant vehicle. The extended-range SUV operates at 2–5 kW and is tolerant to radiation dosages exceeding 90 krad. This vehicle can operate at nearly any altitude or inclination as far as cislunar space.

4 Payload Interfaces

The interfaces for the primary and secondary payloads are described in Table 2 and illustrated in Fig. 5. There are six secondary payload attachment interfaces vertically centered on the SUV at 60° intervals about the axis of symmetry. Custom adapters can be made to mate between the circular SUV interface and the payload interface.

Table 2: SUV payload interfaces

Payload Type	Bolt Circle Diameter	Number of bolts	Payload Constraints
Primary	38.81 in	60 0.25-in bolts	800 kg max (mission dependent, see Fig. 3)
Secondary	8 in	12 0.25-in bolts	40 kg max with center of gravity 10 in from attachment plane

5 Payload Support

The SUV can provide support to the payload during transport to and following arrival at the payload's destination orbit. Typical parameters for services provided are indicated in Table 3. Of particular note is that once the destination orbit is reached and the propulsion system is powered off, a significant amount of power—up to 5 kW—is available to the hosted payloads.

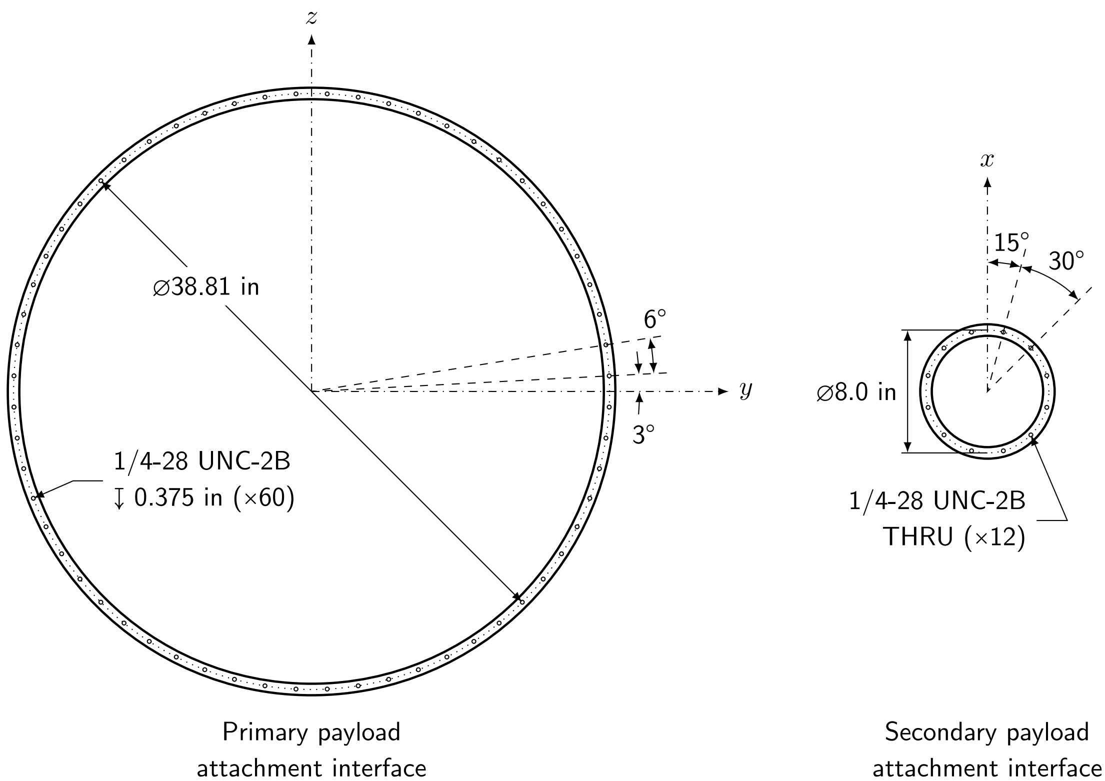

Figure 5: Payload interface dimensions in launch vehicle coordinate frame (see Alpha launch vehicle Payload User's Guide).

Table 3: SUV payload services

Power	0.4–5 kW
Downlink	Up to 100 Mbps X-band, 50 Mbps Ka-band
Uplink	200 kbps S-band
Pointing Control	50 arcsec
Stability	5 arcsec/sec
Mission Duration	5 years

6 Example Missions

In this section, we provide examples of specific missions that are achievable using the SUV in conjunction with the Alpha launch vehicle. While the possible destination trajectories are only weakly dependent on available power and payload mass (assuming that the payload mass is under the maximum allowed), the travel time for a given trajectory is strongly dependent on both power and payload mass. As a result, we separately provide figures indicating maximum payload delivered and figures indicating mission duration.

6.1 Orbit Raising

We show the maximum payload achievable for a given altitude and inclination in Figs. 6 and 7 for Cape Canaveral launch and for Vandenburg Air Force Base launch respectively. In Figs. 8, 9, and 10, we provide mission duration for different payload masses and power levels. All missions are assumed to begin at 400 km circular orbits. Larger payloads are possible by beginning at lower altitudes, but the drag at low altitudes makes lower power missions (<1 kW) infeasible.

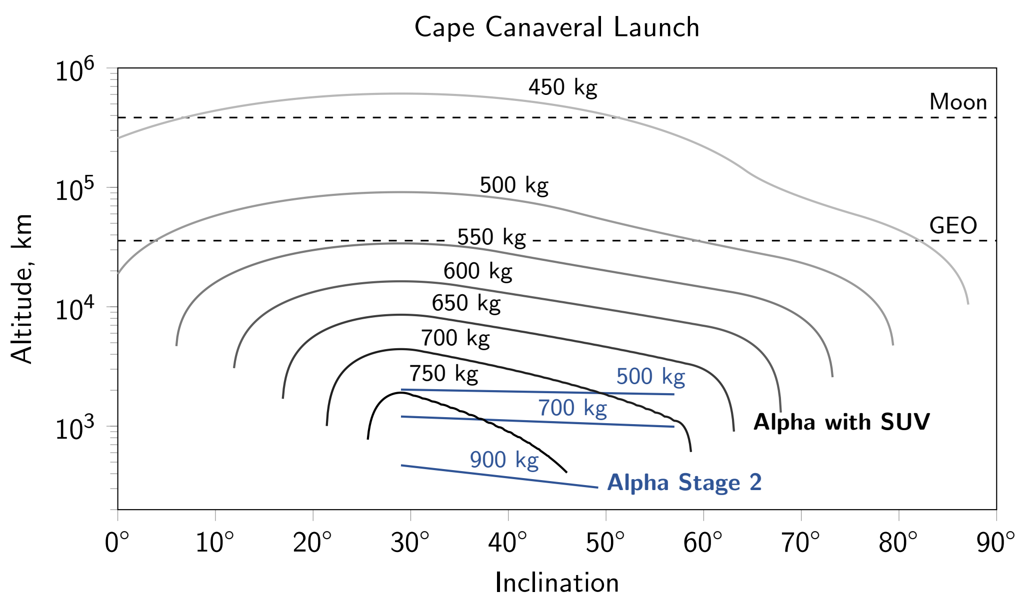

Figure 6: Comparison of Alpha payload delivered with and without the SUV third stage from a Cape Canaveral launch. All SUV trajectories are calculated from an initial circular orbit at 400 km.

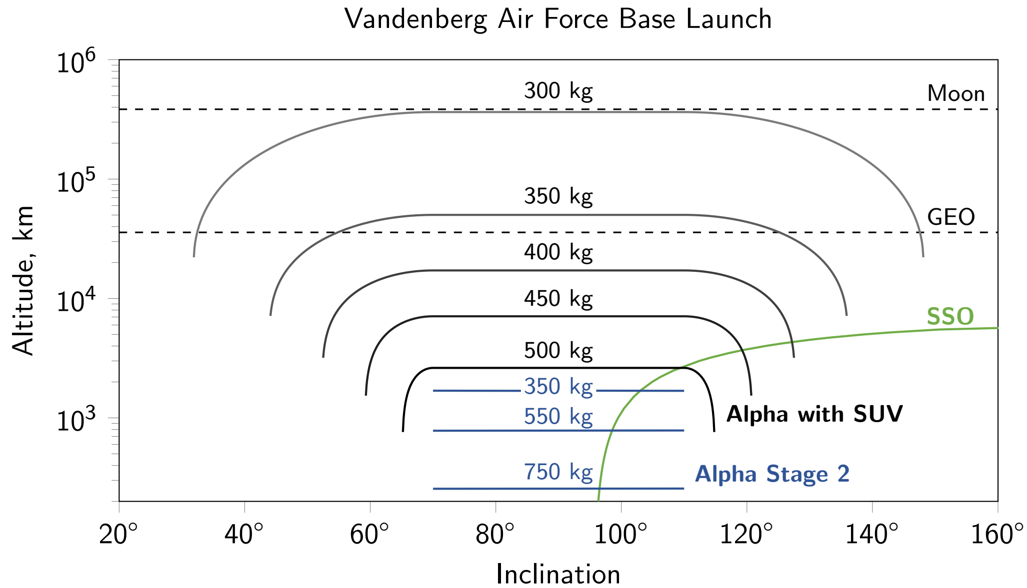

Figure 7: Comparison of Alpha payload delivered with and without the SUV third stage from a Vandenberg Air Force Base launch. All SUV trajectories are calculated from an initial circular orbit at 400 km.

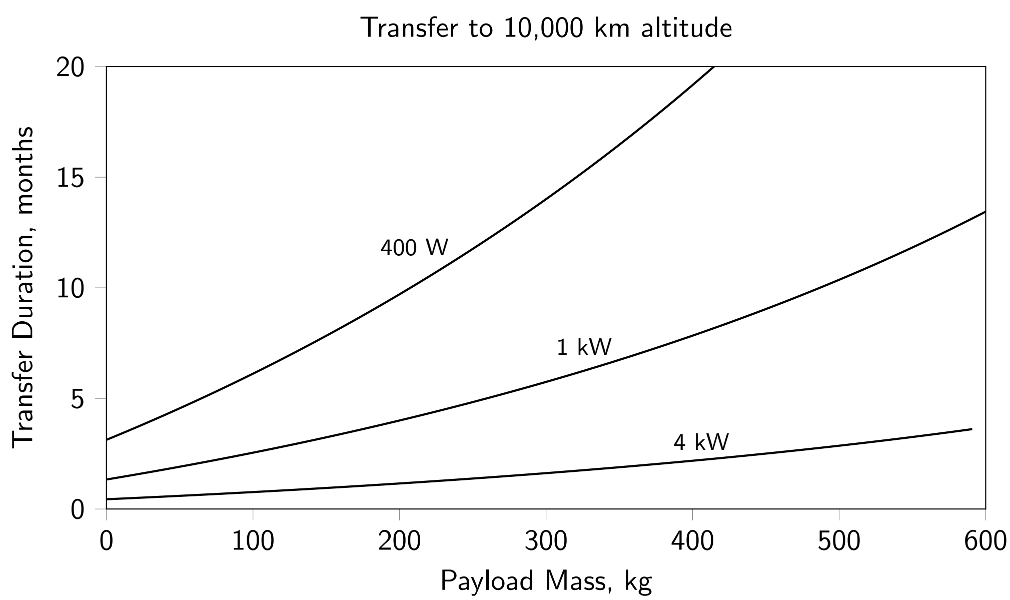

Figure 8: Minimum travel time to 10,000 km as a function of payload mass for different power levels.

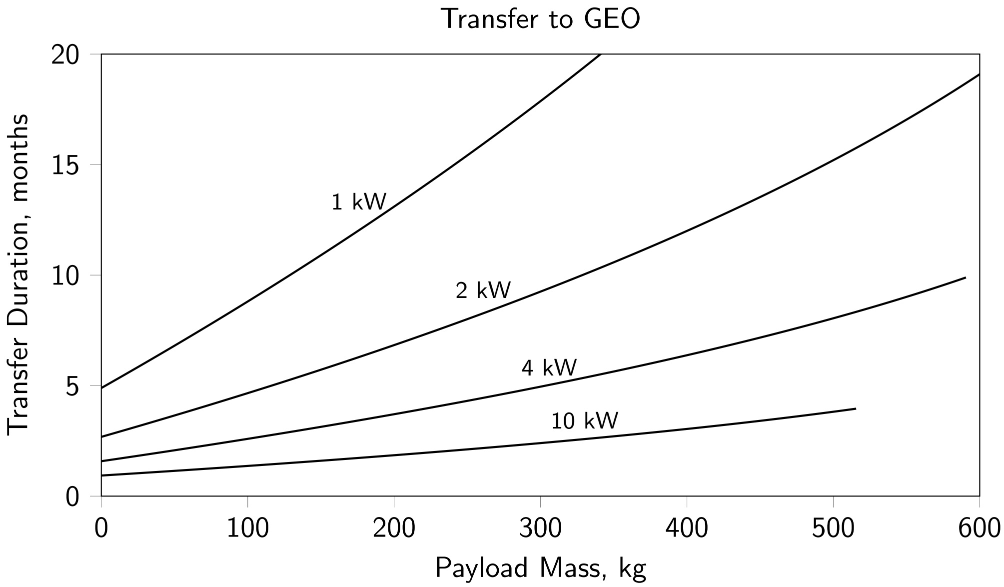

Figure 9: Minimum travel time to GEO, including a 29° inclination change, as a function of payload mass for different power levels.

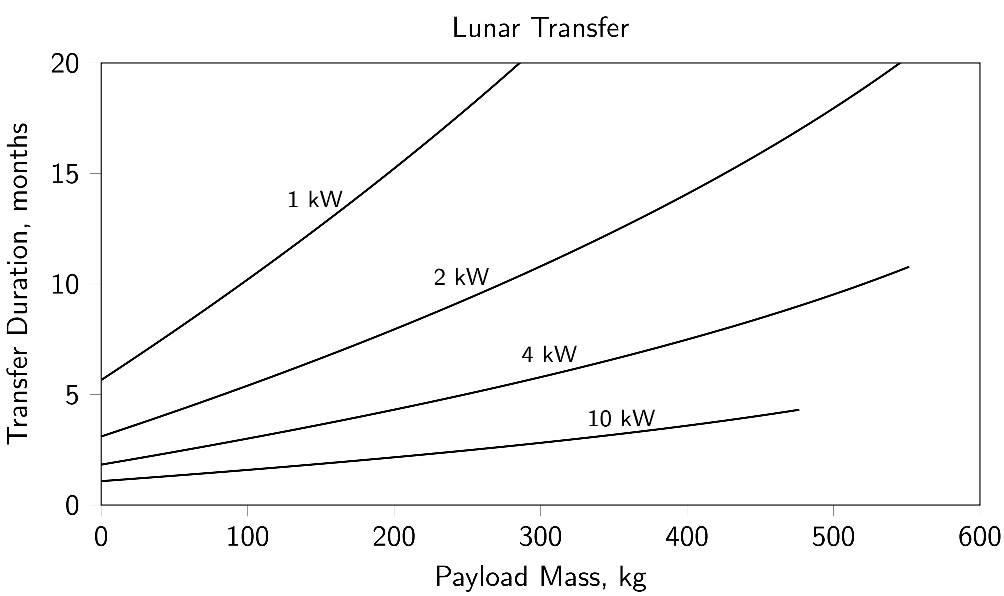

Figure 10: Minimum travel time to the Moon as a function of payload mass for different power levels.

6.2 Plane/Phase Changes and Constellation Deployment

In Fig. 11, we show the trajectories of three 17 kg 12U CubeSats, each in a unique sun-synchronous orbit plane separated by approximately 60°. Using the SUV, such a configuration is achievable in a single launch. At 2 kW, this mission can be accomplished in four months, a similar transfer time to an equivalent chemical propulsion mission. While the chemical propulsion mission is not possible from an Alpha launch vehicle, the electric propulsion version of this mission can both complete the CubeSat mission, and *also* deliver a 350 kg primary payload to offset mission cost.

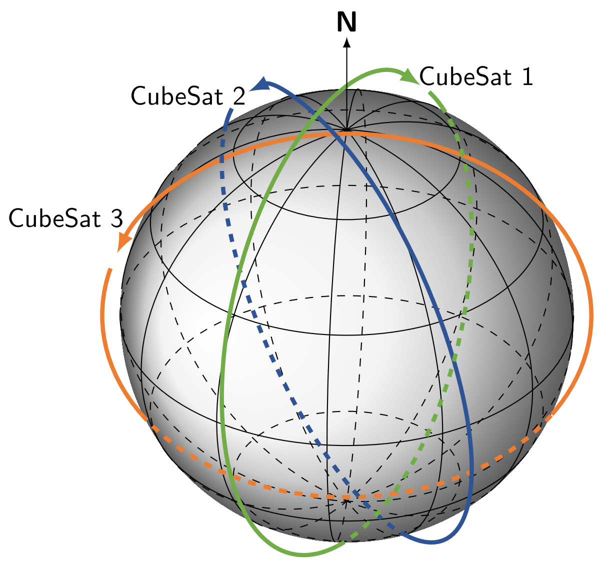

Figure 11: After being delivered to 500 km SSO by an Alpha launch vehicle, the SUV can deliver three 12U CubeSats to unique planes 60° apart. At 2 kW propulsion power, this mission can be accomplished in 4 months.

In Fig. 12, we show transfer time as a function of change in inclination for a 2 kW 500 km mission for various payload masses. Figure 13 shows transfer time for similar missions performed at GEO altitudes. Transfer time can sometimes be substantially reduced by taking advantage of the orbital mechanics at a particular altitude and inclination (as demonstrated in Fig. 11).

Orbital phase changes—either for a single satellite, or to deploy an array of satellites at unique relative positions—are easily accomplished by the SUV, typically in periods of 1 to 3 weeks per change of 90°. An example of such a mission is illustrated in Fig. 14, where four 17 kg 12U CubeSats are deployed at 90° phase intervals at 500 km. This mission is accomplished with 400 W propulsion power within 1 month using less than 1 kg of propellant. Heavier payloads may be accommodated with longer transit durations or higher power levels. Arbitrarily small amounts of propellant can be used when mission duration is not critical.

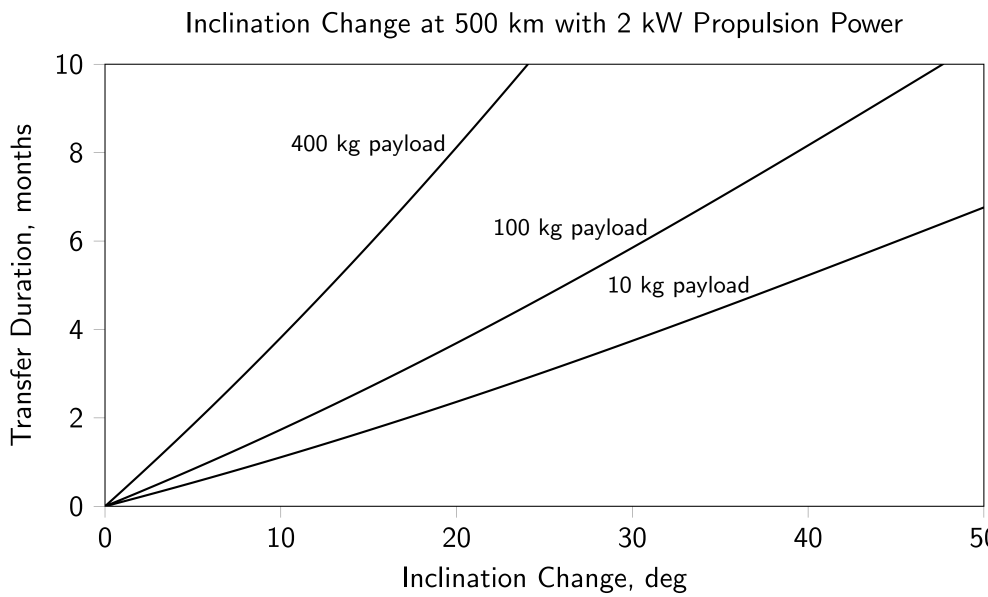

Figure 12: Transfer time for inclination changes at 500 km altitude with 2 kW of propulsion power for different payload masses.

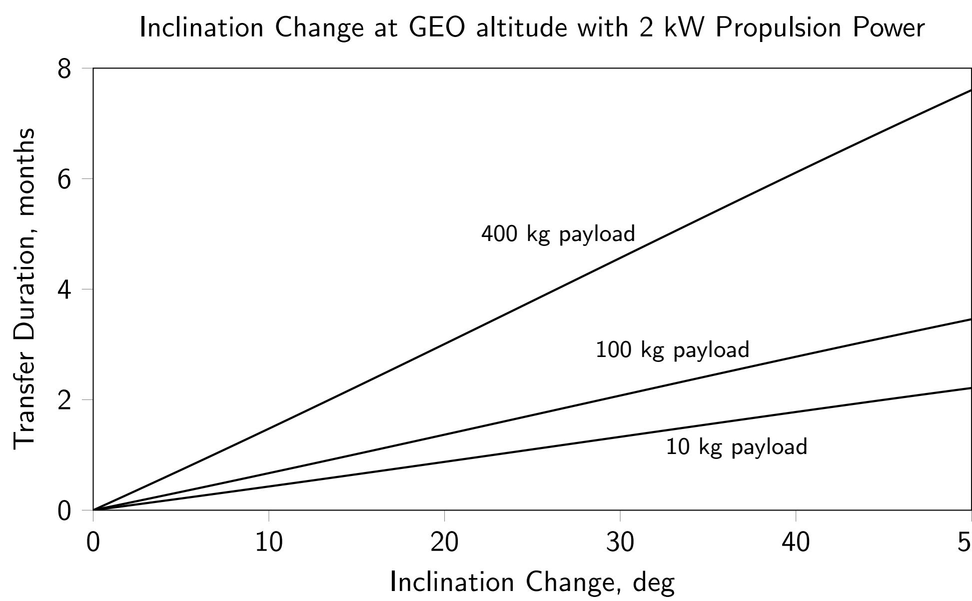

Figure 13: Transfer time for inclination changes at GEO altitude with 2 kW of propulsion power for different payload masses.

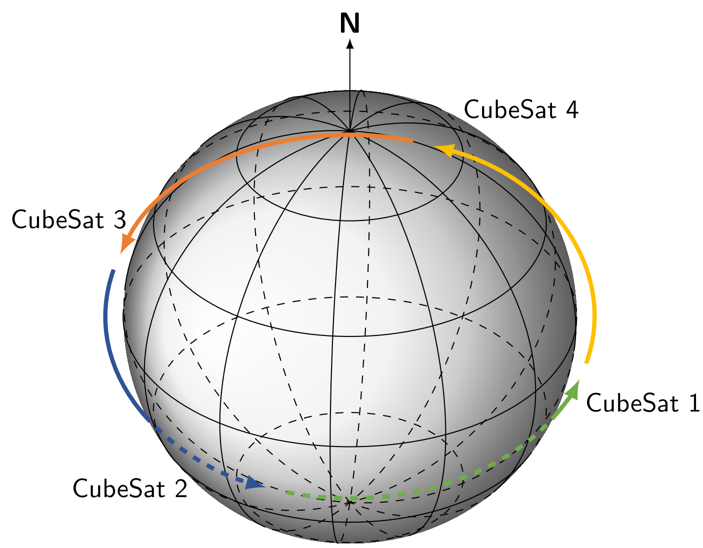

Figure 14: After being delivered to 500 km SSO by an Alpha launch vehicle, the SUV can deliver four 12U CubeSats at 90° phase intervals. At 400 W propulsion power, this mission takes less than 1 month to reach the final orientation and uses less than 1 kg of propellant.

6.3 Deorbiting

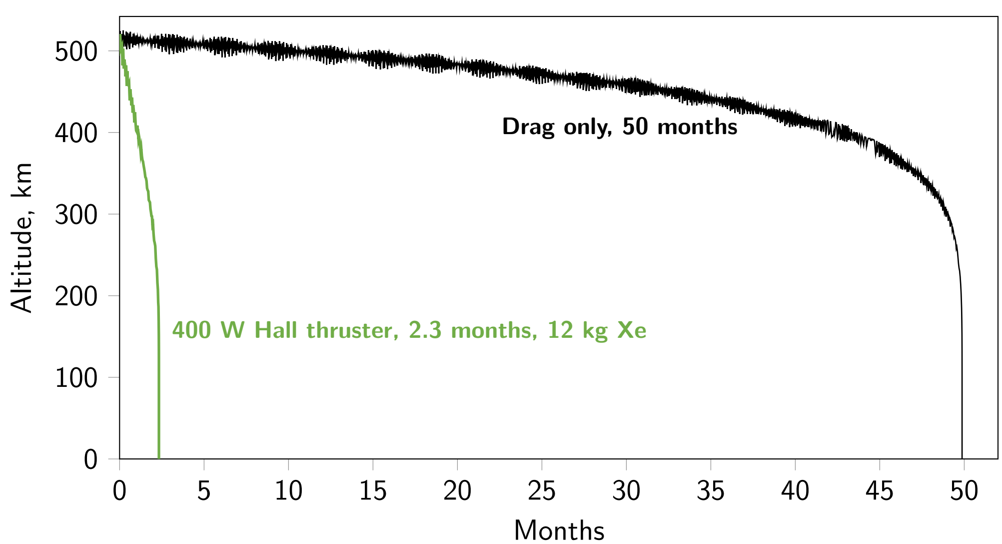

Figure 15: Deorbit time for a 1000 kg second stage from 500 km using a 400 W Hall thruster pair compared to relying on aerodynamic drag alone.

NASA guidelines stipulate that all spacecraft and rocket bodies deorbit within 25 years of end of mission. For missions with a perigee greater than 500 km, aerodynamic drag alone is typically insufficient to deorbit a craft in that time span. The SUV can deorbit satellites or rocket bodies. In Fig. 15, a comparison is made between an Alpha second stage deorbit using drag alone, and a similar deorbit assisted by the SUV. The SUV is shown to deorbit the second stage in 2.3 months at 400 W, compared to 50 months with drag alone. This mission requires only 12 kg of propellant.

6.4 Super Low Altitude Orbits

Super low altitude orbits below 400 km offer significant advantages for missions where detection of surface features is the primary objective, or where proximity to the Earth's surface is required. For example, the ESA GOCE gravity mapping mission required flying at 255 km. However, aerodynamic drag typically limits such missions to short durations. In order to overcome drag for an extended period, the GOCE mission employed electric propulsion. Similarly, at the 2 kW power level, the SUV can sustain a 250 km orbit for up to 150 days.

6.5 Lunar Orbit Insertion

The SUV is capable of delivering substantial payloads (>500 kg) from an Alpha launch to low lunar orbit or beyond. In Fig. 16, we show an example lunar mission powered by a 5 kW solar array, and beginning at 200 km LEO. The SUV gradually increases altitude, spiraling out to lunar orbit over a 5 month duration. Because the orbit is approximately circular, only a minimal lunar orbit insertion maneuver is necessary. Once captured by the Moon's gravity, the SUV can spiral down to near the lunar surface.

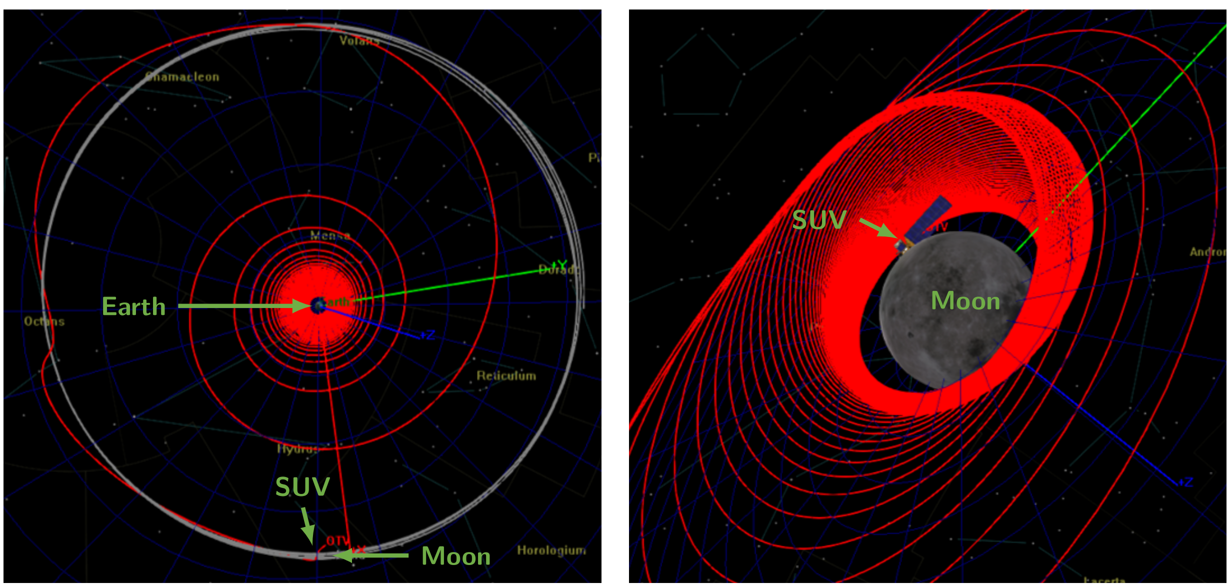

Figure 16: SUV lunar transfer trajectory (red, left) and descent to low lunar orbit (right) simulated using the General Mission Analysis Tool (GMAT).

High altitude missions, such as those to the Moon, typically require high power levels in order to deliver a significant payload mass in a reasonable time frame. For this reason, the SUV is especially suited to missions that require high power at the destination orbit. For example, if a communications relay satellite is needed at the Moon, the solar array can power the propulsion system during transit to the Moon. Once the destination orbit is reached and the propulsion system is powered down, the solar array can be used to power the communications system.

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