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Small Satellite Rideshares on Commercial Resupply Missions to the International Space Station

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ABSTRACT

Gaining access to space is currently a major challenge facing small satellites. Developers must find reliable, affordable, and most importantly compatible rideshares to put their small satellites on orbit. Commercial Resupply Service (CRS) missions to the International Space Station (ISS) have the potential to provide a robust and repetitive platform for small satellite rideshares. There are currently nine planned missions of the Cygnus spacecraft to the ISS extending through 2016, with a strong potential for additional missions beyond 2016. Cygnus enables hosting and rideshare opportunities at a regular interval, thus filling the void left after the retirement of the space shuttle. The Cygnus spacecraft can potentially accommodate up to the equivalent of 18U of CubeSat volume. Cygnus rideshares would be capable of utilizing power generated from its solar arrays, TT&C capacity, and attitude control capability prior to deployment. The Antares launch vehicle which provides access to space for Cygnus also has the capability to support deployable rideshares at low altitudes. This paper details the opportunities for rideshares on CRS missions and the unique capabilities of the Cygnus rideshare platform to enable low cost, regularly scheduled rides for small satellites and small satellite technology. Current research on the mission concept of operations, rideshare accommodation interfaces and mechanisms, mission lifetime trades, integration and test flow, and ground architecture are investigated in the paper.

INTRODUCTION

Gaining access to space is currently a major issue facing small satellites. Rideshares provide an affordable means for getting small satellites on orbit, however, finding a compatible ride within a reasonable time frame can be challenging. Commercial Resupply Service (CRS) missions to the International Space Station (ISS) have the potential to provide a robust and repetitive platform for small satellite rideshares. Two CRS platforms include Orbital's Cygnus spacecraft and SpaceX's Dragon spacecraft. Additional ISS resupply vehicles include Russia's Progress spacecraft, ESA's Automated Transfer Vehicle, and JAXA's HTV. NASA has invested in commercial development of the CRS system under a Space Act Agreement, under which programs are not subject to normal Federal Acquisition Regulations[1]. As a result, commercial companies have augmented substantial investment in the CRS missions. This paper investigates how CRS missions such as Orbital's Cygnus spacecraft can not only benefit NASA's ISS program, but also open up rideshare opportunities for small satellites.

Both deployable and non deployable rideshares can be incorporated into a CRS vehicle without interrupting the primary resupply mission. Additionally, a CRS vehicle potentially provides a platform with an excess of power, thermal, and attitude control to rideshares; and for small satellite technology demonstration missions, the ground architecture used for CRS missions can be utilized for data and telemetry transmission. Cygnus launches are expected to be approximately every six months through 2016, with rideshare capability both on the spacecraft itself and the Antares launch vehicle. This offers great flexibility to small satellite providers and payloads looking for a ride in the near future.

The CRS contract is an indefinite delivery indefinite quantity (IDIQ) contract for flights to the ISS through 2016. The anticipated launch schedule is shown in Figure 1. Resupply missions are expected at regular intervals over the next several years and possibly further, making them ideal candidates for small satellite rideshares. If a small satellite or payload is late, then it is possible to catch the next resupply ride. The regularity of missions provides schedule relief in the event of payload schedule slips. There are nine planned missions of the Cygnus spacecraft to the ISS through 2016 with the strong potential for additional missions beyond 2016.

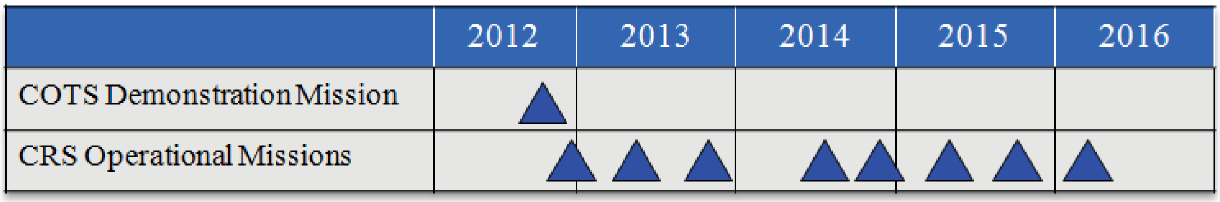

Figure 1: Anticipated launch schedule for Cygnus resupply mission

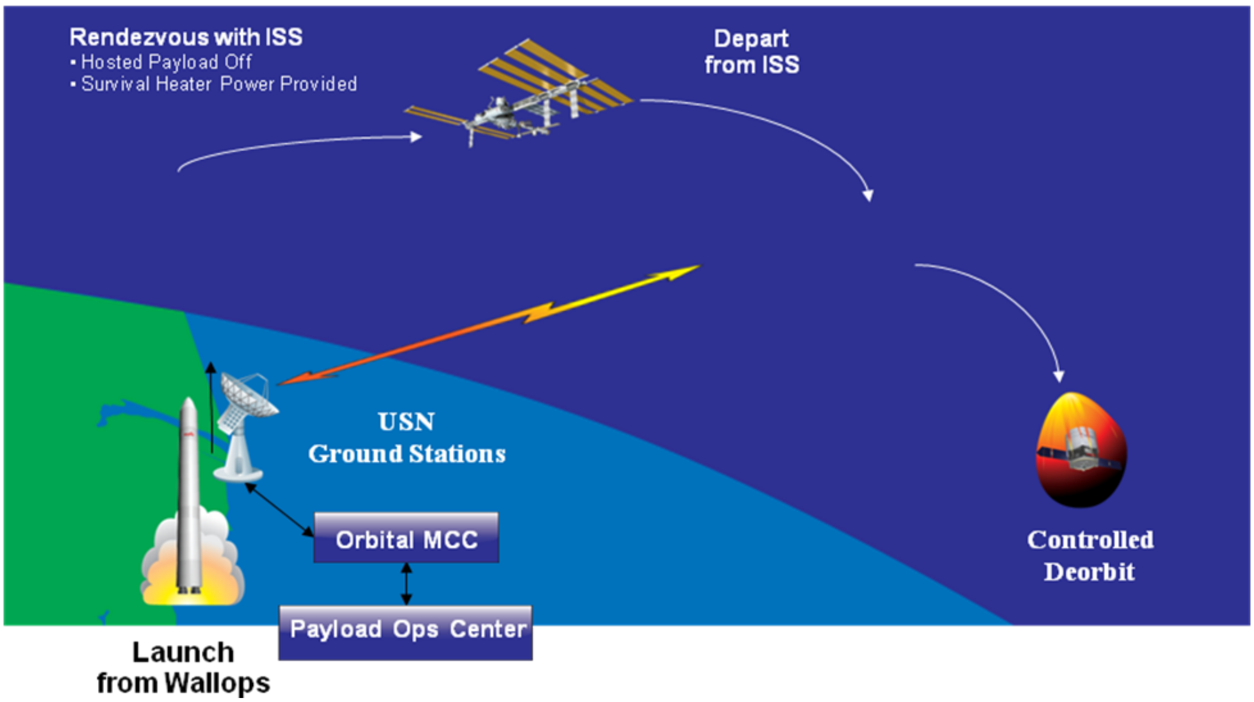

Figure 2: Notional CRS Concept of Operations

RIDESHARE CONCEPT OF OPERATIONS

The notional CRS concept of operations consists of five operational phases: Integrated Launch Operations (ILOPS), Phasing Operations (POPS), Joint Operations (JOPS), Berthing Operations (BOPS), and Departure and Reentry Operations (DROPS). The progression of these phases is shown in Figure 2. For deployable rideshares, there are two options for deployment: deploying prior to ISS berthing and deploying after ISS berthing. Deploying prior to ISS berthing offers the advantage of potentially avoiding ISS safety regulations for deployables. However, this option directly interferes with established flight plans for the primary resupply mission. Deployment would need to occur between POPS and JOPS such that a safe distance is ensured between the ISS and the small satellite. This is a feasible option, but the advantages may not be worth the intrusion of the CRS flight plans, since a failed deployment may put the primary mission at risk. Deploying after ISS berthing requires adherence to ISS safety regulations, but it is significantly less intrusive to the established flight plan. Deployment during DROPS (i.e. after resupply to the ISS is successfully completed) is simpler to incorporate, since the sole function of the vehicle during this phase is to depart station proximity and enter a controlled, destructive reentry.

Two flight operations phases have been proposed for rideshare accommodation on Cygnus. The Deployable Operations Phase (DOPS) covers operation of the Cygnus vehicle after ISS berthing for deployable small satellite rideshares. DOPS consists of three segments in which the vehicle departs station (departure), descends to the rideshare's desired orbit (descent), and deploys the rideshare (deployment). The second segment requires a descent to deployment altitude, rather than allowing any ascent for ISS safety reasons. Ascending would require Cygnus to cross ISS altitude twice for ascent and descent, thereby presenting a potential collision hazard with station. Deployment of a small satellite above (and near) ISS altitude may also present a hazard to station through the satellite's natural orbit decay. The entire DOPS duration adds approximately 24-36 hours to a notional CRS mission, depending on the desired orbit. During this time, TT&C links are maintained through visible USN ground stations, subject to availability. NASA's TDRSS is also used during other flight operations for CRS missions, but is likely not available for DOPS.

The second proposed operations phase, which is called the Hosting Operations Phase (HOPS), covers operation of the Cygnus vehicle after ISS berthing for non-deployable small satellite technology demonstrations. HOPS is similar to DOPS, however, the deployment segment is replaced by a pre-hosting and a hosting segment. Pre-hosting covers the steps in transitioning from a nominal descent, such as powering down non-essential components and charging the batteries to full capacity. The hosting segment is when the small satellite technology performs its intended functions while its performance is monitored. The hosting segment can potentially last one to two years, depending on the fuel margin available following the CRS mission, and communication is maintained via available USN stations. Figure 3 illustrates the flow of a flight operation plan (FOP) for a notional CRS mission and for a mission with a deployable small satellite rideshare. The FOP shown can also be applied to non-deployables by replacing the deployment segment with pre-hosting and hosting segments.

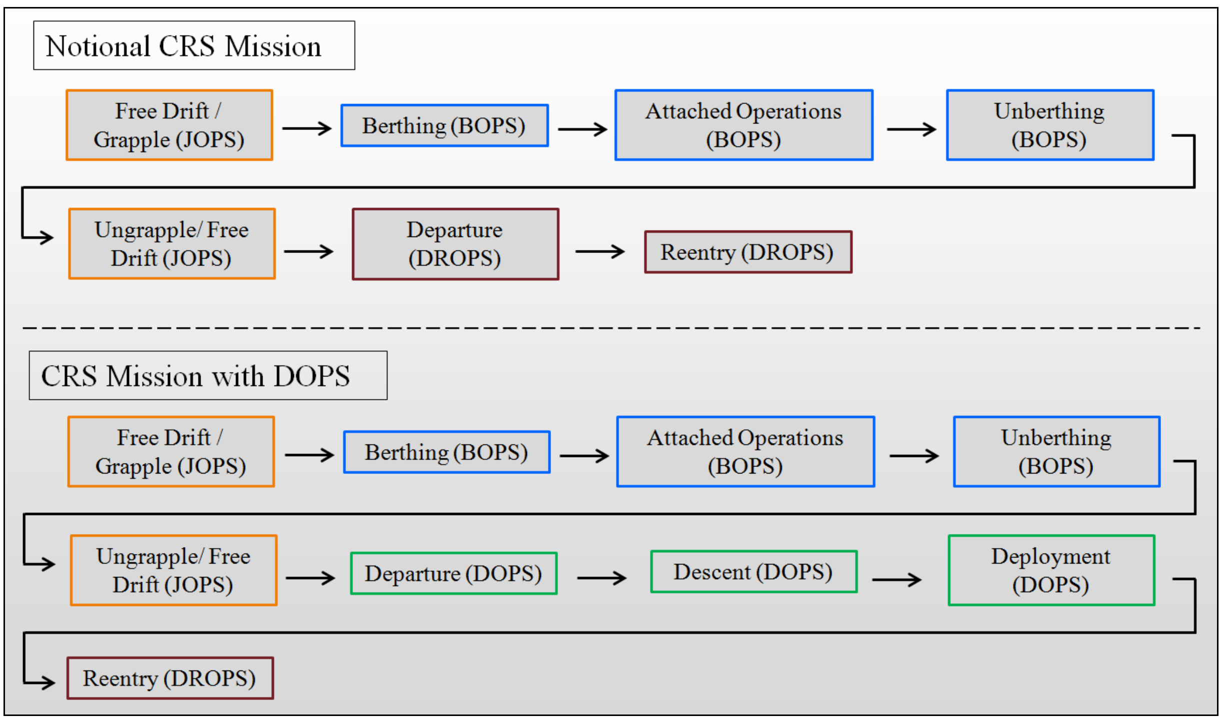

Figure 3: Flight Operation Plan for notional CRS mission and for mission with deployable small satellites rideshare

In addition to the proposed operations for rideshares on the Cygnus spacecraft, the Antares launch vehicle, shown in Figure 4, is also capable of providing a rideshare platform. Antares is a two stage vehicle designed to provide the needed repeatable and reliable access to space for CRS missions. Antares provides an ideal platform for smaller, lost cost rideshares, such as CubeSats due to their low complexity and ease of integration. Rideshares on Antares would be deployed after separation of the first stage, meaning that orbit altitudes would be significantly lower than on Cygnus, thus resulting in decreased mission lifetime. However, this platform is ideal for short duration technology demonstrations or low cost deployable spacecraft without requirements for extended mission durations.

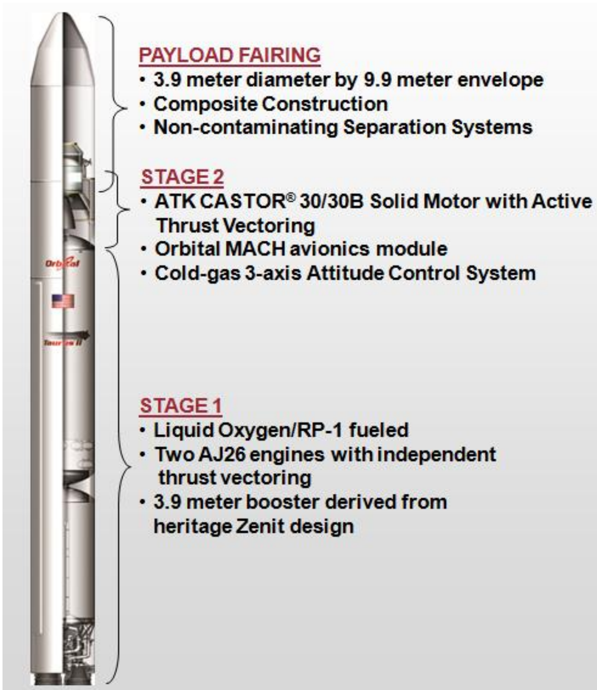

Figure 4: Antares Launch Vehicle

VEHICLE INTERFACES, ALLOCATIONS, AND CAPABILITY

ISS visiting vehicles are a versatile platform for both deploying small satellite rideshares and demonstrating small satellite technology. The Cygnus spacecraft consists of two main parts, the Pressurized Cargo Module (PCM) and the Service Module (SM). The PCM is built by Thales Alenia Space and contains the ISS cargo[2]. It has heritage from the Multi-Purpose Logistics Module. Berthing at the ISS occurs at Node 2 via the Common Berthing Mechanism. The Service Module is built by Orbital and has heritage from the Dawn spacecraft and the GEOStar platform used for geosynchronous communications satellites. Two Cygnus service modules are shown in Figure 7, along with a scale picture of the complete spacecraft in a poster hanging above the hardware. Cygnus is compatible with the Antares rocket.

Volume for a small satellite rideshares is allocated on the outside of the Cygnus service module. External mounting on the service module provides good fields of view and minimal interference from communications antennas, GPS antennas, and thruster plumes. Figure 5 highlights a particular area of interest on the +Z face of the external service module. The +Z face of the service module (on the external perimeter) avoids obstructions such as thruster plumes and fits within the Antares volume constraints.

Available space for a rideshare is potentially as high as the volume of approximately 18 PPODs, which can be used for either deployable or a non-deployable technology demonstration.

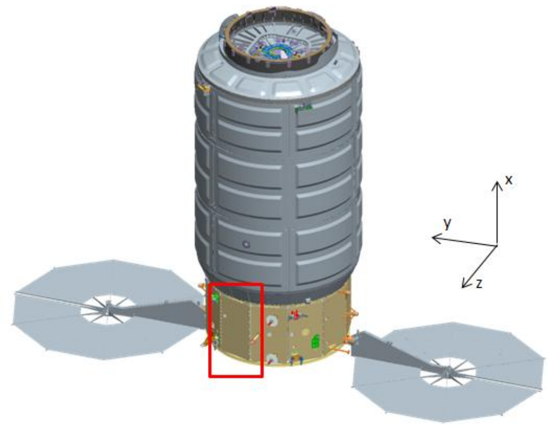

Figure 5: Potential rideshare mounting location on external service module

The nominal attitude is with the –X direction to the Sun. Long excursions to other altitudes are feasible and supported by the large battery capacity of Cygnus. However, slewing capability to other attitudes is driven by the propellant margin and directly correlates to mission lifetime. Thus, frequent attitude changes are not conducive to extended mission durations. Moderate thermal accommodation can also be provided for rideshares mounted externally to the service module. Additional locations for rideshare mounting include the –X face of the service module, and inside the service module. Figure 6illustrates potential volume allocations for rideshares on both the +Z and –X faces of the Cygnus service module.

Mass margin is available on the Orb-4 mission (fourth Orbital CRS mission) and beyond as unused margin is currently present. Cargo mass to the ISS can be traded for rideshare mass and may vary mission by mission. In some cases the cargo mass may be lower on a particular CRS mission than predicted due to volume constraints, rather than actual mass constraints. Having a low cargo density opens up additional mass margin for rideshares. The current outlook is for greater than 100 kg and potentially up to 250 kg available for a rideshare. This includes additional structural mass and propellant, but it is subject to the details of a particular CRS mission and its cargo.

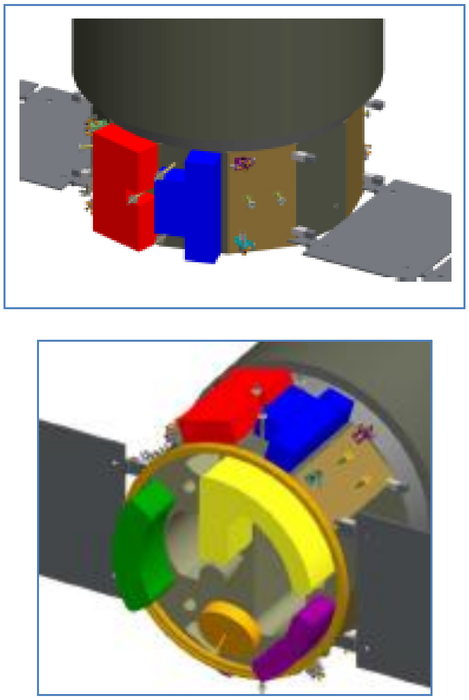

Figure 6: Example rideshare volume allocations on +Z (top) and -X (bottom) faces of Cygnus service module

CRS missions have abundant power for a rideshare mission after delivery of cargo since the primary mission demands are greater than the small satellite payload. Excess power is due to large solar arrays and redundant systems. In its nominal sun pointing mode, Cygnus can provide approximately 1 kW or more orbit average to a rideshare while maintaining a 10% operational margin. The battery capacity allows for up to 36 hours without solar array generation following ISS berthing. In these cases it is assumed that the PCM is not active, that redundant systems have been switched off, and Cygnus is in a 350 km orbit with 30% depth of discharge. As an alternative to the sun pointing mode (and as a means to increase mission lifetime) a gravity gradient pointing mode can be used. In this mode power available to rideshares is reduced, but still sufficient for most payloads, particularly those on a nanosatellite scale. Additionally, power generation can be increased using a moderate degree of sun tracking while still maintaining a stable gravity gradient orientation. The trade between pointing, power generation, and mission lifetime is subject the specific needs of a rideshare. In general, power generation is less of a challenge than optimizing for mission life.

Figure 7: Two Cygnus service modules in the manufacturing facility

MISSION LIFETIME

Mission lifetime for Cygnus is determined by the propellant availability after ISS berthing, the mission orientation, and pointing accuracy. Two cases were analyzed, a sun pointing mode and a gravity gradient mode. STK was used to obtain the attitude data which was used to determine the angular impulse commands used by the propulsion system. A Matlab propellant estimation tool for used for each commanded thrust. The frequency of angular impulse commands determines the pointing accuracy. As the command frequency increases, the pointing accuracy asymptotically reaches its limit. For example, very frequent commands provide for a very good pointing accuracy, but the propellant usage and thruster cycling are very high. The analysis determined the propellant usage in kilograms per day for each scenario. Additional cases were run for situations where the CRS mission had to abort an initial berthing, which reduced the initial propellant for a rideshare mission by over one half.

In the sun pointing scenario, daily propellant usage was used for attitude maintenance. These scenarios had a shorter lifetime, but full power capability. In the gravity gradient drift scenario, the solar array points away from the Earth and the Cygnus spacecraft stabilizes into a gravity gradient drift. The stable attitude in this scenario is between 5° and 29° from zenith depending on the altitude of the orbit and its drag conditions. The gravity gradient scenarios led to longer lifetimes and minimal slewing was used to balance the energy budget. However, for certain sun angles the energy budget did not close with payloads requiring a large allocation of power. As a solution, some level of active pointing is required by mission planning to balance the energy budget. Both the sun point and gravity gradient scenarios used an altitude of 350 km with a 51.6° inclination. The rideshare mission has a lower altitude than the ISS to avoid safety concerns with the ISS.

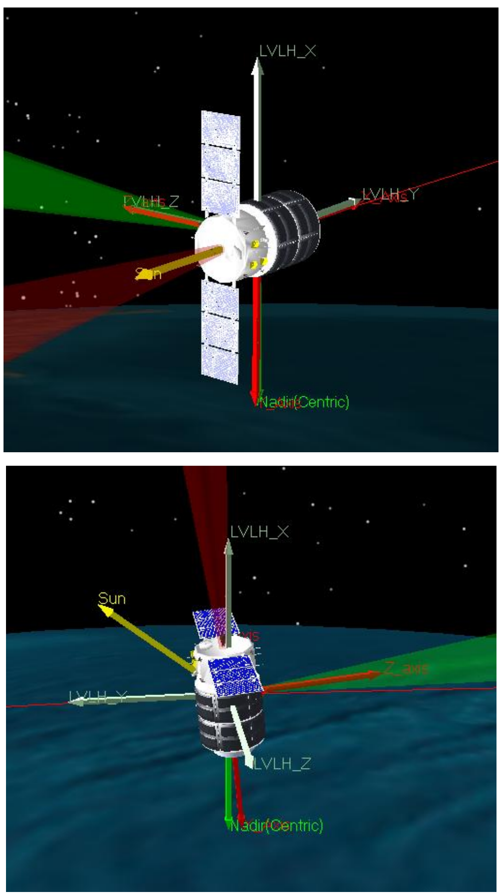

Figure 8: Cygnus spacecraft in a sun pointing mode (top) and gravity gradient mode (bottom)

A spacecraft lifetime of greater than one year is feasible especially in the gravity gradient cases and approaching three years given the level of maintenance.

Given the same amount of pointing accuracy, the gravity gradient lifetimes were approximately double the sun pointing lifetimes. Constant pointing control requirements have a strong effect on limiting mission lifetime. Regardless of pointing mode, lifetime depends on propellant availability after the CRS mission. Current analysis predicts propellant use for the CRS mission within 3 sigma bounds. Knowledge of this propellant use will be better understood following an actual flight demonstration, which will allow better predicting of rideshare lifetime.

The mission trades also determined that the thruster cycles, in number of firings per day, was not a hard limit on the potential mission lifetime, unless it is assumed that more propellant than is currently allocated will be available for rideshare use. Even in this case, this also assumes that thrusters fail immediately at their qualification limit for cycles. While numerous thruster failures can be tolerated due to redundancy, the number of firings was used as a constraint if the total cycles were greater than the qualified lifetime.

INTEGRATION AND TEST FLOW

Rideshare delivery should occur approximately 18 months prior to the launch of a CRS mission for both Cygnus and Antares rideshares. For very simple rideshare missions, this could be as close as 12 months before launch (This assumes that rideshares are delivered fully qualified prior to their integration). Delivery by at least 12 months prior to launch is critical to ensure compliance to interface control documents and enable rapid integration. Open panel integration and functional testing comes after rideshare delivery, followed by spacecraft assembly and harness installation. The main integration and test activities of the small satellite occur during this time and include installing internal and external components, initial alignments, and preparations for environment testing. The repetitive nature of CRS launches also provides the potential for rideshares to “off ramp” onto later flights if a late delivery occurs. Integration and interface impacts are minimal from an off ramp since the Cygnus vehicles are identical. The integration deadline for small satellites is before the CRS vehicle’s thermal vacuum test. If this deadline is not met, due to late delivery or other delays, an off ramp should be considered to minimally impact the primary CRS vehicles schedule. Once the small satellite is integrated, the next phases of I&T are conducted jointly with the CRS vehicle. These include any additional compatibility testing, final environmental testing, and the final integrated system test.

Table 1: Mission Opportunities

Opportunity	Timing	Price	Decision Date
1-2 Opportunities a year to fly rideshares	2013 and later	Dependent on desired service	L-12 to 18 months, dependent on desired service

While delivery of small satellites can occur as late as 12 months prior to launch, accommodation discussions should begin at or before authorization to proceed (ATP) for the particular Cygnus vehicle that is will be used. This allows the planning activities and development or tailoring of specific rideshare interfaces to occur in parallel with the established vehicle schedule. In terms of planning time, this means that small satellite providers should be prepared to begin planning rideshare arrangements approximately 3 years before launch, and plan on delivering the small satellite within 2 years after arrangements are made.

GROUND ARCHITECTURE

Space-to-ground communications between the CRS spacecraft and ground networks for TT&C use S-band. Uplink data rates are approximately 2 kbps (PCM/PSK/PM) and downlink is 3 Mbps using QPSK modulation. Cygnus utilizes the Universal Space Network (USN) which is networked with the Mission Control Center in Dulles, Virginia, shown in Figure 9. The MCC-D coordinates with the NASA Mission Operations center and with JSC and Mission Control Houston during a nominal CRS mission[3], but during rideshare operations the architecture would likely become exclusively USN and MCC-D. MCC-D provides a dedicated operations center capable of managing the deployment of a rideshare or supporting the operation of a hosted technology demonstration on Cygnus.

Figure 9: Mission Control Center - Dulles (MCC-D)

Cygnus has 2 Gigabytes of memory for on-orbit storage. Data throughput to the ground to one USN station can average 0.6 GB per day, with margin available for rideshare data in addition to Cygnus's telemetry generation. The actual margin available is dependent on which, if any, of the redundant systems are kept active during rideshare operations. For the case of a deployable rideshare, there is ample margin available for deployment telemetry if needed.

Several trades were conducted with varying number of ground stations, as shown in Figure 10. As expected, latency and throughput are improved with the use of additional USN stations. However, cost is a potential tradeoff for a rideshare mission. If latency of more than 12 hours can be tolerated (the time when the spacecraft ground track is on the opposite side of the Earth from the ground station) than the current single ground station architecture should be sufficient. While deployable rideshares are assumed to have their own communications, this capability is available for non-deployable rideshares, such as small satellite technology demonstrations.

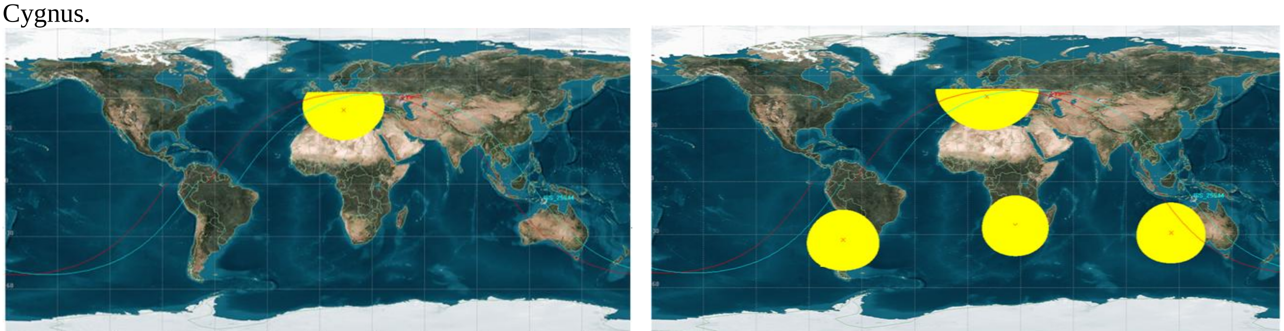

Figure 10: Trades with single vs. multiple ground stations

CONCLUSION

CRS missions such as the Cygnus spacecraft and Antares launch vehicle provide the potential for a robust and repetitive platform for small satellite rideshares. The rideshare capability can accommodate numerous small satellite configurations and mass upwards to 250 kg. Rideshares with a CRS mission have excess power, especially for missions occurring after visiting the ISS. Several variables determine the spacecraft lifetime, including the pointing control accuracy, vehicle orientation during the mission, and the CRS mission operations and cargo. In general, missions up to two years are feasible. Planning for rideshares should begin approximately 3 years prior to launch, and delivery of the rideshare should occur approximately 12-18 months prior to launch. However, given the regularity of missions, it is possible for late deliveries to catch a ride on later missions. The Universal Space Network and Orbital mission control center in Dulles provide an established ground architecture simplifying TT&C and mission data for small satellite missions. CRS missions are an ideal platform for small satellite rideshares and small satellite technology demonstrations.

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