# Commercial Heavy-lift Orbital Refueling Depot

# CHORD

Aerosp 483 Space Systems Design
Final Report

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**Abstract**

The Commercial Heavy-lift Orbital Refueling Depot (CHORD) is a private mission proposed by Reliable Refuels to provide economically feasible orbital refueling for deep space missions. By decoupling cargo/propellant from the dry bus, CHORD will enable much higher mass payloads such as those necessary to complete manned missions to Mars or deep space robotic landings. This report summarizes our mission motivation, proposed business model and space system design.

# Contents

# 1 Introduction and Motivation

Modern space mission architectures are limited by exponentially decreasing ratio of payload mass to total mass with increasing distance from Earth and duration of operations. For instance, about two-thirds of the mass of a Mars sample return mission would be propellant [2]. Conventional designs for missions expecting to land on the Moon or Mars call for multiple stages in series, landing rockets, and an even smaller final payload. This is colloquially known as the Russian Nested Doll architecture, with successively smaller stages inside/on top of the larger boosters [13]. Unfortunately, the risk of failure is compounded via this series insertion–one mishap on any stage dooms the entirety of the interplanetary mission with no chance of reuse.

Orbital refueling depots address this issue by allowing spacecraft to be launched "dry" without fuel. This allows a much larger spacecraft to be launched at once, or an equivalently smaller spacecraft on a smaller rocket. Depots have long been cited as a critical capability for manned missions beyond Low Earth Orbit (LEO). As early as Wernher von Braun, industry leaders have shown that pre-launched propellants would be required for any sustainable interplanetary highway of exploration [13]. Indeed, no single launch vehicle (even super heavy lift) is capable of hoisting all necessary propellant, water and oxygen for a manned Mars mission.

Before recent technological advancements, the subtle complexities in cryogenic propellant slosh, autonomous rendezvous, and passive thermal control made the implementation of such depots expensive and infeasible. However, the 2009 Augustine report calls "these technologies...ready for flight demonstration, according to both NASA and industry experts working in the field" [2].

By building on high-TRL technologies and existing launch vehicle opportunities, we propose commercializing the world's first on-orbit "gas station" by assembling multiple tanks (or cartridges) of fuel (or other payload such as water and oxygen) on a space dock we call CHORD–the Commercial Heavy-lift Orbital Refueling Depot. The propellant is to be launched to orbit in increments and stored for transfer to the customer after rendezvous. Our privately funded company, Reliable Refills, will first demo an integrated system and on-orbit rendezvous before guaranteeing interplanetary contracts with NASA, the ESA and others.

In this report, we show that our design architecture, through Reliable Refills, is technically feasible, economically preferred, and robustly designed.

# 2 Mission Objectives and Feasibility

Two of the flagship technical challenges for orbital depots in the past were long term thermal storage of volatile propellants and zero-g propellant transfer and settling. In general, the propellants are cooled continuously, but some of the gases "boil off" and are vented away, leading to large wastages of fuel into space. However, using current multi-layer insulation and cryogenic coolers, boil off rates of 0.1% per day have been demonstrated for liquid hydrogen, oxygen, and methane–which means only 10% of the total mass would be lost over a 3.5 month period. Moreover, zero-boil off is not a necessary requirement for lunar and asteroid missions [12].

Secondly, propellant transfer has already been flight demonstrated with storable propellants through Orbital Express and the Automated Transfer Vehicle (ATV) missions at the ISS. The Cryogenic Propellant Storage and Transfer Technology program at NASA is further expected to raise the operational TRL of cryogenic storage in orbit. These tech demo have been more proof of concept, with the program terminating shortly thereafter. Reliable Refills seeks to be the first long-term sustainable venture in this regard.

Economically, we can show that decoupling the fuel/cargo campaign from the main mission payload can be healthier for the space industry and the mission than super-heavy lift or in-situ propellant production (which has an extremely low TRL). Although multiple launches would be required, our calculations show that the use of smaller rockets will reduce the overall cost of the mission while also reducing risk. In depth economic analysis is given in Section 3.2.

Using established commercial launch vehicles (Falcon, Atlas, Delta, Proton) reduces development payload delivery cost compared to, for example, the Space Launch System. Multiple smaller launches every few months sustains the U.S. commercial launch fleet, which has many favorable economic outcomes. First, it reduces the cost per flight (and subsequently cost per kg to orbit) by spreading the fixed costs of facilities and operations over more flights and more customers. Second, it encourages increased efficiency in production and infrastructure (such as higher fairing packing efficiency) [26]. Finally, the higher frequency launches give more experience to the workforce, improving launch reliability.

Moreover, medium lift vehicles (rather than super heavy lift) allow for more competition in propellant/cargo delivery, which effectively drives down and sustains costs. Experimentation and innovation, such as a fully reusable rocket, is naturally rewarded. Finally, this approach will enforce strong partnerships between industry, the U.S., and (eventually) other nations, which can politically sustain the private space market over generations [3].

From a safety and reliability perspective, our approach of (relatively) small-quantity, high-frequency propellant deliveries to space will achieve guaranteed higher success rates. As a rule of thumb, "inherent reliability of a system takes tens of flights" [26]. For a new heavy lift rocket, averaging 1 launch per year, this could take more than 10 years. In contrast, the Delta, Atlas, and (soon) Falcon series are already industry reliable to within predictions [2]. This is very attractive to our customers, specifically because there would be a higher frequency of reliable, medium-sized launches that can still enable deep space missions to the edge of the solar system.

## 2.1 Mission Objectives

The CHORD mission proposed by Reliable Refills will address a number of necessary advancements in space infrastructure to allow for larger, more complex, and more frequent deep space missions. At the same time, CHORD is a commercial venture that we intend to be profitable by providing a valuable service to an expanding private space sector. The primary and secondary objectives of the CHORD mission are detailed below.

*Primary Objectives:*

1. Enable higher complexity deep space missions by establishing an economically sustainable orbital refueling service
2. Prove through demonstration the feasibility of short term cryogenic propellant storage and transfer
3. Create a profitable business in our increasingly privatized space market
4. Establish the necessary infrastructure to support Martian colonization

*Secondary objectives:*

1. Feed the private space industry by demanding more frequent launches
2. Provide a satellite backbone for temporary science missions in low Earth orbit
3. Increase the heritage of two-body rendezvous algorithms
4. Inspire a new generation with space missions that will extend the frontier of human knowledge

To meet these mission objectives, we have created a mission requirements matrix that contains the system level and subsystem level requirements. The full requirements matrix can be found in Table E.

## 2.2 Design Drivers

We have identified three major design drivers that have directed our design path. First, the CHORD mission design is primarily driven by economic concerns. The mission must be able to safely provide clients with refueling and reduce their mission cost while increasing their payload mass. At the same time Reliable Refills must be able to secure profits by the mission lifetime end. Hence this economic driver lead us to choose the optimal rocket, hub, and cartridge configuration for our application.

Second, to ensure reliability in both docking and cartridge transfer maneuvers, CHORD must have an extremely precise Guidance and Control System (GNC/ADCS). Not only does the hub have to retrieve the cartridges but it also has to dock with customers with the cartridge attached. This will require a robust attitude determination and control system that can adapt to changes in mass distribution. Placement of thrusters and various sensors are issues that will be explored.

Finally, the necessity to store cryogenic fuels for extended periods of time will be a primary design driver for much of the thermal and power systems. Minimizing the quantity of boil-off affects the customer's delivered product and affects both profit and economic sustainability.

# 3 Economic Analysis

The following subsections seek to prove that our business model is not only possible, but more importantly, profitable.

## 3.1 Customer Base

The first three years of project development for CHORD will focus on market research and contacting potential customers. Reliable Refills will be primarily targeting customers looking to take their missions to, or beyond, geosynchronous orbits - our audience may include, but is not limited to, NASA, the ESA, the Department of Defense, international groups, or universities like the University of Michigan. These extended missions are expected to include Lunar and GEO missions, but will certainly have a heavy focus on Mars and deep space missions. SAVIOR, a student group from the University of Michigan, has showed interest in our services as well for a planetary asteroid defense project.

When completing a deep space mission, a company will typically prefer to use a heavy-lift launch vehicle (HLLV) for their payload due to its larger carrying capacity to deeper space. Due to the current price of these vehicles (well over $100,000,000), customers are looking for a way to cut back on this expenditure without losing out on available mass for their payload. Reliable Refills offers not only a decrease in cost to the customer, but also an increase in payload capacity - a true win-win situation. Using a medium-lift launch vehicle (MLLV) and the ability to fuel-up at LEO, these customers can get a typical LEO-sized payload to a Geosynchronous Transfer Orbit (GTO) which in some cases is more than 4,000 kilograms greater than an HLLV's payload to GTO. Moreover, the customer saves on both cost and risk. HHLVs compound risks in series, while multiple fueling launches parallelizes the risk, reducing the chance of losing the expensive, dry payload. For these reasons, we expect high customer demand for Reliable Refills once CHORD is in orbit.

## 3.2 Economics of Development and Operations

Given a projected on-orbit lifespan of twenty years, CHORD is expected to have a total cost of over $550,000,000. This number includes labor costs, facility usage, components and materials, launch and operations, and overhead. An abbreviated cost budget can be seen in Section 3.3, which includes the details of each funding phase, and when we expect to incur different costs (the complete cost budget is broken down in Appendix A). Reliable Refills has worked out a twenty-year-plan based on projected numbers which leads to an expected profit of nearly $120,000,000.

To begin, we looked at a sample mission type for which we could compare the use of an HLLV with an MLLV, in an attempt to deliver a payload to GTO. The HLLV would carry the payload all the way to GTO, whereas the MLLV would need to fuel up from CHORD at LEO to continue its mission to GTO. For our study, we compared the following launch vehicles: Falcon 9 v1.1 and Falcon Heavy, Atlas V 400 and Atlas V HLV, and Delta IV Medium and Delta IV Heavy.

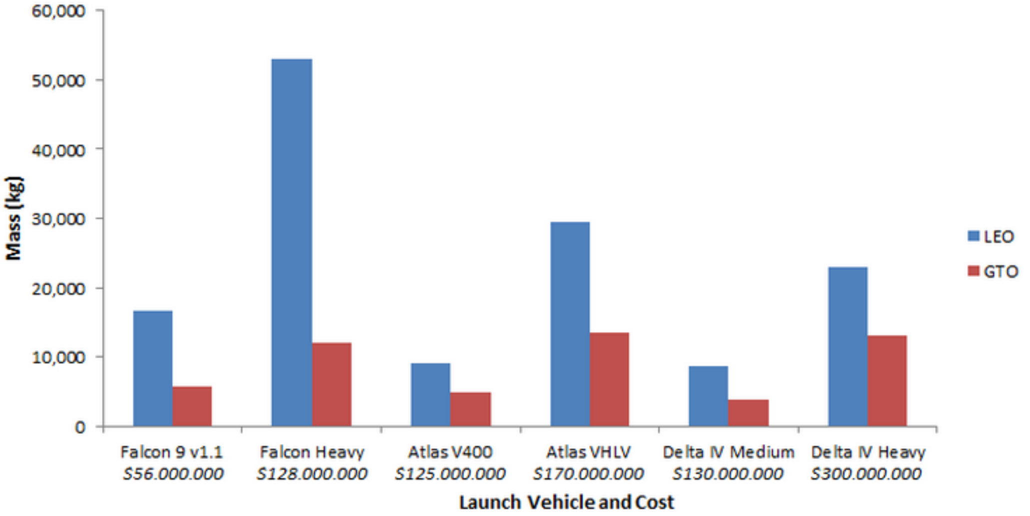

Figure 1: Possible launch vehicle comparison of cost and payload masses [24]

As shown in Figure 1, the Falcon Heavy carries the second largest payload to GTO (12,000 kg), yet it is by far the best HLLV option in terms of dollars per kilogram for GTO missions. For MLLV, the Falcon 9 v1.1 is the best option for missions to LEO in terms of dollars per kilogram, and it also carries the largest payload to LEO of the MLLV class (16,625 kg). For these reasons, we chose to compare the Falcon Heavy with the Falcon 9 v1.1 (including a refuel at LEO) for our sample mission to GTO. Table 1 breaks down the expected customer costs for each scenario in our sample mission.

Table 1: High level sample customer mission costs

| | **Falcon Heavy** | **Falcon 9 v1.1 w/ Refuels** |
|---|---|---|
| **Launch Vehicles** | $128,000,000 | (Mission) $56,000,000<br>(Refuel) $56,000,000 |
| **Additional Fuel** | $0 | $1,200,000 |
| **Cartridges** | $0 | $8,000,000 |
| **Reliable Refills Service Fees (50%)** | $0 | $4,600,000 |
| **TOTAL COST** | $128,000,000 | $125,800,000 |
| **TOTAL SAVINGS** | | **$2,200,000** |

The Falcon Heavy portion of the table is very straightforward, whereas the Falcon 9 v1.1 column includes many different costs based on our service model. First, the customer would pay for two launch vehicles; one for the fuel cartridges and the other for the mission payload. Second, the customer is responsible for the cost of the additional fuel and fuel cartridges. Finally, Reliable Refills charges a 50% service fee on the total cost of additional fuel and cartridges which covers handling services and also acts as an insurance policy. The Falcon 9 v1.1 mission shows an expected savings of over $2,000,000 against the Falcon Heavy mission. To calculate total revenue, we will use the above mission model as an average as it is nearly impossible to predict exact costs of future missions. Since this sample mission brings in $8,600,000 ($4,000,000 from cartridges and $4,600,000 from service fees) of revenue, an average of three or four missions every year over the course of twenty years yields a total projected revenue of $670,370,000. Subtracting the expected cost of CHORD ($553,815,000), Reliable Refills expects to make $116,555,000 in profit over 20 years. Figure 2 displays the path to a profitable business for Reliable Refills.

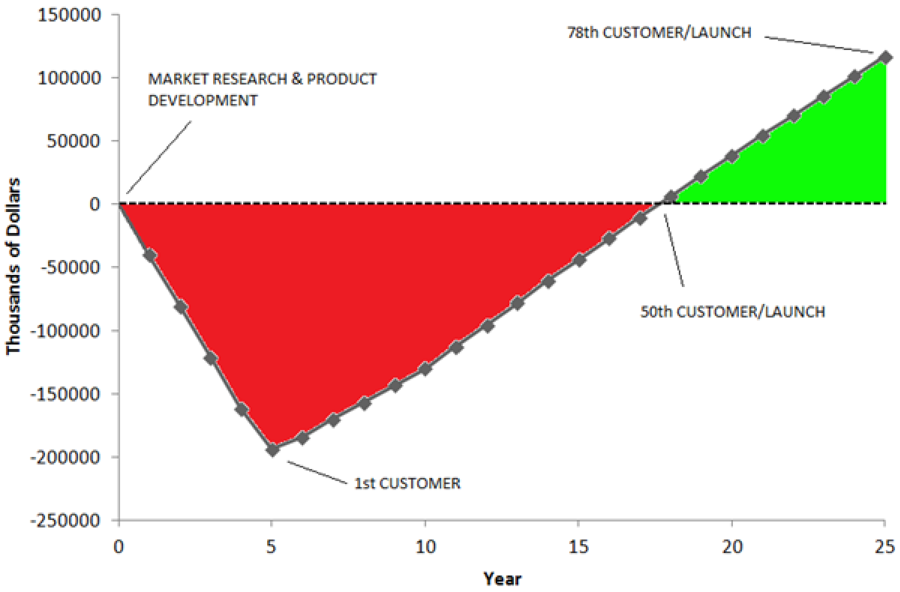

Figure 2: Projected financial outlook for Reliable Refills

In conclusion, for an average mission, a customer would save over $2,000,000 and Reliable Refills would profit about $8,600,000. Additionally, due to the increased carrying capacity of the Falcon 9 v1.1 to LEO compared to the Falcon Heavy's capacity to GTO, the customer could increase their mission payload by 4,000 kilograms or more. Also, this plan reduces the customer's risk by using well tested MLLV and carrying less fuel while launching to LEO, reducing the loss in the event of a single launch failure. These three selling points make for a mutually advantageous and profitable business.

## 3.3 Cost and Funding Phases

As a startup company in its early stages, Reliable Refills will be looking for investments from many different sources during the first years of CHORD's development and further into the operations phase.

Table 2: Expected funding phases for Reliable Refills

| SEGMENT | COST |
|---|---|
| PHASE I – Customer Research & Product Design (Year 1-4) | $162,019,000 |
| PHASE II – Technology Demo & Corporate Outreach (Year 5-17) | $243,845,000 |
| PHASE III – Venture Capital & Expansion (Year 18-25) | $147,950,000 |
| **TOTAL** | **$553,815,000** |

The first phase consists mainly of customer research and product design, which we expect to be solely funded by Reliable Refills and angel investors. Next, we plan to gain support from NASA with a technology demonstration and use their funding to finance the fabrication process and early years of operations. NASA has been recently looking for ways to jumpstart the burgeoning private space market (such as the through the COTS program), so it is reasonable to expect some opportunities. Once Reliable Refills becomes a profitable business (expected around year 18), we will seek out venture capitalists in order to further progress the fabrication and launch of multiple hubs into different locations through space. Private investors maybe hesitant to invest in us early as we don't expect to be profitable until over 15 years into the business. Once we successfully demonstrate our technology, we expect we will take on more investors to grow our business further.

## 3.4 Development and Operations Schedule

The first three years of CHORD will be devoted to market research and reaching out to potential customers. Development of the spacecraft and a small inventory of cartridges will also begin and be scheduled to conclude by the end of the fifth year. CHORD will launch after these first five years and will remain in orbit for a minimum of twenty years to service our customers. After demonstrating profitability with CHORD-1, we plan to invest in subsequent depots on a variety of orbit planes to enable a greater diversity in customers and set the foundations for Martian colonization. More details can be found in Section 8.

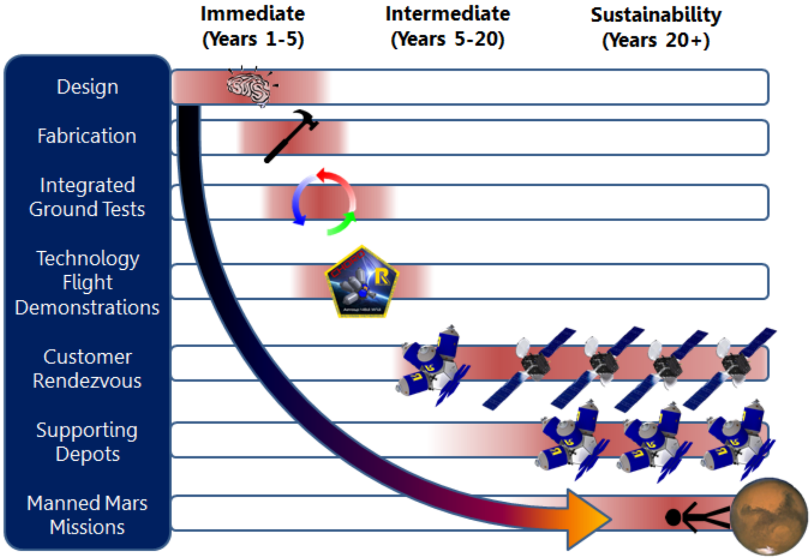

Figure 3: Reliable Refills's twenty year development and production schedule

# 4 Mission Architecture

The primary objective of the CHORD mission is to establish an economically sustainable space depot in order to increase access to deep space. To successfully achieve this goal, our integrated satellite must function as designed and meet all mission requirements. The first step will be a demonstration mission featuring an on-orbit rendezvous and propellant transfer between the hub (CHORD) and a single cartridge.

## 4.1 Mission Requirements

To accomplish the mission objectives, we have developed a number of specific mission requirements for each subsystem. Many of the requirements shown in Table 3 are set by our launch vehicle provider, currently baselined as SpaceX's Falcon 9 v1.1. The others are derived from the need to complete specific mission objectives.To accomplish the mission objectives, we have developed a number of specific mission requirements for each subsystem. Some of the requirements shown in Table 3 are set by our launch vehicle provider, currently baselined as SpaceXs Falcon 9 v1.1. Most are derived from the need to complete specific mission objectives.

Table 3: Consolidated requirements matrix

| | **System Requirements** |
|---|---|
| SYS-01 | CHORD shall rendevous with and store customer cartridges |
| SYS-02 | CHORD shall rendevous with customer satellites and deliver cartridges |
| SYS-03 | CHORD shall be able to store up to 5 cartridges |
| SYS-04 | CHORD shall be able to store 5 different fluids: methane, RP-1, liquid oxygen, Monomethylhydrazine and nitrogen tetroxide |
| SYS-05 | CHORD shall pioneer a universal docking configuration that is easily integratable into the customer's bus structure |
| SYS-06 | The CHORD bus design shall be scalable and universal for expansion into a variety of orbit locations |
| | **Structural Requirements** |
| STR-01 | CHORD dimensions shall fit within a Falcon 9v1.1 fairing |

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| | |
|---|---|
| STR-02 | CHORD structural elements shall have mass less than 13,000kg |
| STR-03 | All CHORD structural elements shall have a factor of safety of 2.0 for yield strength and 2.6 for ultimate strength |
| STR-04 | The CHORD bus structure shall rigidly enclose and protect internal components |
| STR-05 | CHORD shall not interefere with cartridge recipient in any way except for at cartridge attachment points |
| **Pressure and Thermal System Requirements** | |
| PTS-01 | PTS shall maintain the stored propellant at a stable temperature and pressure in a liquid state |
| PTS-02 | PTS shall safely release excess boil off from cartridges through pressure release valve |
| PTS-03 | PTS will prevent hypergolic propellants from traveling through the same lines during propellant cycling |
| **GNC Requirements** | |
| GNC-01 | CHORD orbital position shall be determined to an accuracy of 20 m and velocity to an accuracy of 5 m/s for rendezvous procedures |
| GNC-02 | GNC shalll be able to track incoming fuel cartridges for docking maneuvers |
| **ADCS Requirements** | |
| ADCS-01 | ADCS shall autonomously control attitude in all three axes to within an objective of 1 degree accuracy, (2 degree cone) and threshold of 2 degree accuracy (4 degree cone) during docking maneuvers. |
| ADCS-02 | ADCS shall provide 3-axis pointing knowledge within 0.2 |
| ADCS-03 | ADCS shall, on command, perform docking maneuvers with incoming fuel cartridges |
| **Communication Requirements** | |
| COM-01 | CHORD shall broadcast location and general health in a beacon signal during nominal operation |
| COM-02 | COM shall be able to receive commands during docking procedures |
| COM-03 | COM shall have the capability to cease transmission upon command |
| COM-04 | COM shall transmit telemetry at a rate no lesser than 1 Hz during docking procedures |
| **Ground Station Requirements** | |
| GS-01 | COM shall receive ground station data and commands. |
| GS-02 | CHORD shall execute commands and telemetry transmitted from the CHORD ground station. |
| GS-03 | COM shall transmit telemety to the ground station. |
| **Electrical Power System Requirements** | |
| EPS-01 | EPS shall provide a regulated and conditioned 5 V and 28 V DC, and raw battery voltage line at 3.6 V. |
| EPS-02 | EPS shall generate enough power to sustain attitude control and high-rate telemetry downlinking during docking operations |
| EPS-03 | EPS solar panels shall produce enough power to provide at least 1.9 kW for 20 years |
| EPS-04 | EPS solar panels shall not exceed a power degradation of 2.75% per year |
| **Command and Data Handling Requirements** | |
| CDH-01 | CDH shall provide power and data interfaces for all CHORD subsystems |
| CDH-02 | CDH shall perform fault and error correction from single event upsets |
| CDH-03 | CDH shall store all data for a minimum of 250 orbits. |
| CDH-04 | CDH shall schdeule rendevous operations at the commanded times |
| CDH-05 | CDH shall monitor the staus of attached cartridges |

## 4.2 Concept of Operations

Based on the mission requirements and design drivers, the mission's concept of operations has been developed and is outlined in Figure 4. There are two primary phases required to provide an operating orbital fuel depot. Initially, a hub module must be launched that will serve as the spacecraft's central bus. This module will contain the depot's power system, flight computer, ADCS, and communications system. The module also serves as the physical skeleton of the spacecraft, providing multiple docking ports for fuel and oxidizer cartridges. The hub will be launched into low-Earth orbit with a nominal altitude and inclination that allow the depot to be reached from nearly all major space launch facilities, including Kennedy Space Center, Vandenberg, and the Baikonur Cosmodrome (more orbit details in Section 5).

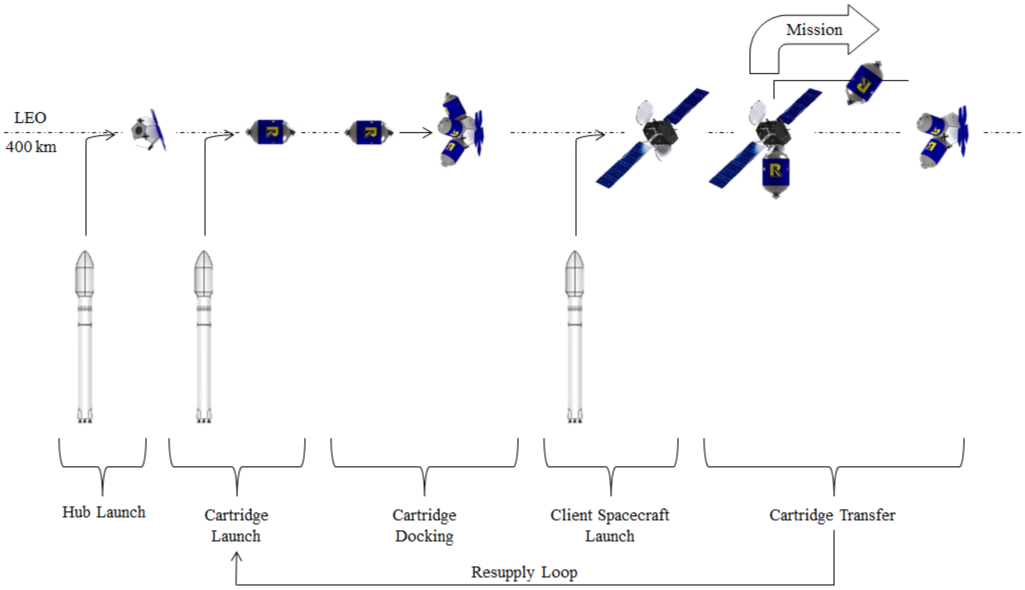

Figure 4: Diagrammed process flow for nominal mission operation

The second phase of the mission involves launching supply modules to populate the hub with the deployable resources. These supply modules (or cartridges) have a simple on-board control system, limited to magnetic stabilization of the cartridge while in orbit. After being injected into a suitable trajectory by the launch vehicle, the cartridges will stabilize and be approached by the hub module before it halts at a safe distance. The hub module will assume primary responsibility for the docking procedures during the rendezvous process, with the fuel module in a passive safe mode. This process is diagrammed in Figure 5. Modules will be flown to the depot on an as-needed basis, sufficiently in advance of the mission they will service (on the order of 3 months).

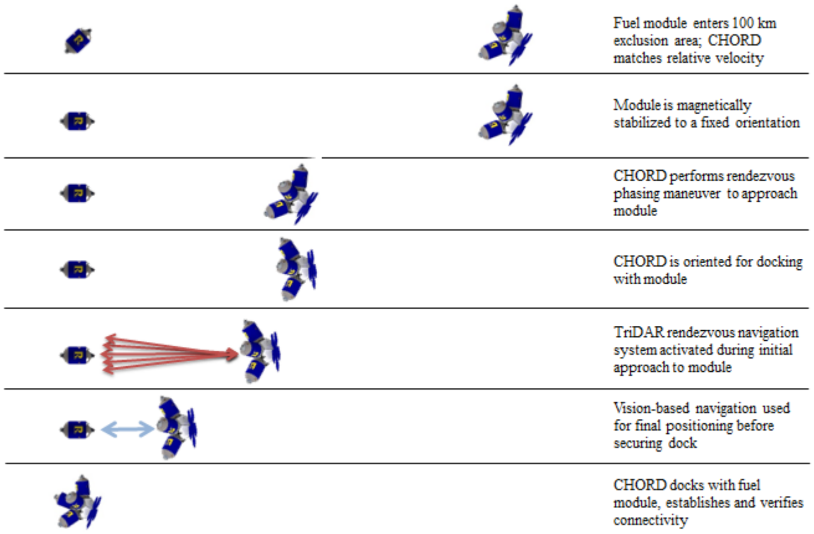

Figure 5: Chronology of nominal docking procedures

A client's spacecraft must be launched into a plane-matched orbit with the depot, much like the transfer orbit used to deliver new fuel modules. That spacecraft will be responsible for parking itself outside of a mandated keep-out-zone around the depot before the fuel module(s) can be transferred to it. The specific transfer procedures are flexible, and will depend on the design and capabilities of the receiving spacecraft. Due to the double-ended cartridge design, the client spacecraft could be docked directly with CHORD before the module is released from the hub. Alternatively, CHORD could release a module before moving to a safe separation distance, allowing to client to assume full responsibility for cartridge retrieval and docking. After the module transfer procedure is completed, the client spacecraft must use limited thrust until it has reached a safe distance from the depot, and it must never operate in an orientation that would expose CHORD to engine exhaust.

The proposed mission architecture allows for significant flexibility with regards to orbital parameters. The CHORD mission can be expanded to provide multiple stations at varying altitudes, inclinations, and phases. This extended capability would allow CHORD to service a wide variety of mission types, and potentially offer expanded access times.

# 5 Virtual Mission Simulations

The entirety of the CHORD mission consists of 5 phases: (1) the hub launch, (2) cartridge launches, (3) hub/cartridge rendezvous, (4) client spacecraft launch (5) cartridge transfer to the client. The launch vehicle selection was discussed in Section 3.2, and these simulations will assume CHORD is launched into our intended orbit. This section will analyze the rendezvous between CHORD and the client spacecraft, the atmospheric effects on CHORD in LEO, and the mission execution through simulation.

## 5.1 Orbital Analysis

The purpose of the CHORD mission is to enable deep-space missions; therefore, appropriate orbital parameters must be chosen to minimize client fuel launching requirements to enable docking with CHORD. We can expect that clients will launch eastward, as close to the equator as possible, and use this launching latitude to determine the appropriate orbital inclination. For American clients, this corresponds to launch sites at either Kennedy or Cape Canaveral, at approximately 28.5 degrees latitude. Operational altitude of CHORD will be the lowest altitude possible to minimize launching costs and take advantage of the Oberth effect. However, it will be high enough that corrections for atmospheric drag will not be necessary over the mission's lifespan.

To analyze atmospheric decay, we assume an exponential drag model. The drag force imposed on CHORD and the time for the orbit to decay to zero altitude is calculated by:

$$\rho = \rho_0 e^{\frac{a-R_E}{h}} \tag{1}$$

$$|F_D| = \frac{1}{2} v^2 C_D A * \rho \tag{2}$$

$$t_d - t_0 = \frac{h}{\sqrt{\mu R_E} B^{-1} \rho_0} (e^{\frac{H_0}{h}} - 1) \tag{3}$$

Here, $\rho_0$ and h are reference values for density and altitude. Thus, a minimum orbital altitude of 224 km must be chosen for a 20 year mission in order to avoid correctional maneuvers. Because an exponential model is not exact–it neglects temperature fluctuations which play a substantial role in air density–it is advantageous to assume a higher minimal altitude. We chose to use an orbital altitude based on the ISS.

Table 4: Orbital parameters

| **Item** | **Symbol** | **Value** |
|---:|---:|---:|
| Altitude | a | 413 km |
| Repeat Cycle | - | ≅ 3 days |
| Inclination Angle | i | 28.5° |
| Velocity | $\lvert v \rvert$ | 7.66 km/s |

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| | | |
|---|---|---|
| Rendezvous Delta-v Expenditure | $\lvert \Delta v\_total \rvert$ | $\cong$ 0.02 km/s |
| Period | $T\_cir$ | 92.8 min |
| Revolutions per Sidereal Day | f_cir | 15.5 rev/day |

## 5.2 Systems Tool Kit (STK)

The fuel cartridges and client spacecraft will be expected to launch into a planar orbit with CHORD, keeping approximately 100 km between themselves and CHORD. The rendezvous will be performed by maneuvering the hub into an elliptical orbit, then phasing the difference in orbital periods in order to dock with the cartridge/client. As derived in Appendix G, the delta-v required for the maneuver is dependent only on the difference in the argument of longitude between CHORD and the client, $\Delta\omega$:

$$|\Delta v_{total}| = 2\left(\sqrt{\frac{2\mu}{r_{cir}} - \frac{\mu}{r_{cir}(1+\frac{\Delta\omega}{2\pi})^{\frac{2}{3}}}} - \sqrt{\frac{\mu}{r_{cir}}}\right) \tag{4}$$

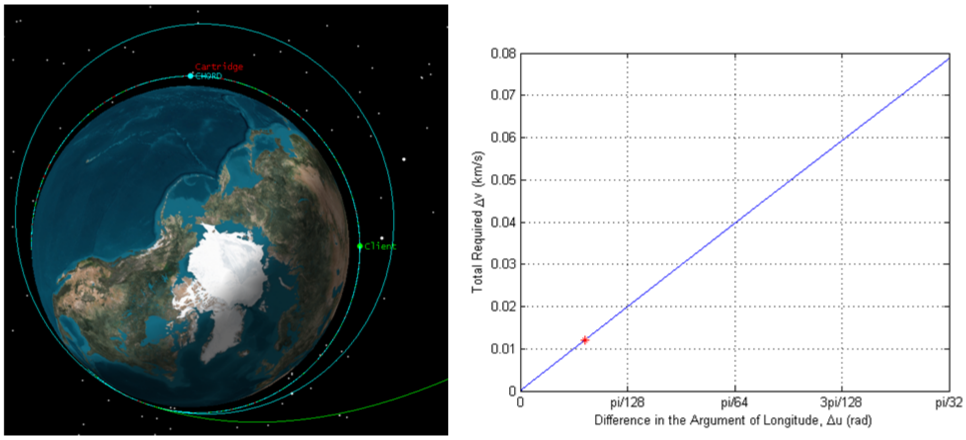


Figure 6: Rendevous simulation and required $\Delta v$

The shown STK simulation exhibits an exaggerated view of the distance between the client spacecraft and CHORD. A 100 km separation between the client and CHORD corresponds to a 0.84° difference in argument of longitude. When run, the simulation shows CHORD following the elliptical trajectory, as described above, to dock within close proximity of the client spacecraft, followed by the client following its own escape trajectory. Simplified CAD models were imported into the simulation, showing the actual transfer of the cartridge. From Figure 6, we see that each CHORD/client rendezvous maneuver will require a 0.012 km/s delta-v expenditure. Appendix F contains additional STK figures.

# 6 Subsystem Specifications

CHORD can be broken down into the following six main subsystems: (1) cartridges, (2) structure and thermal, (3) electrical power, (4) guidance, navigation, attitude determination, and control, (5) command and data handling, and (6) communications. The components of these subsystems and their relations to each other are shown in Figure 8.

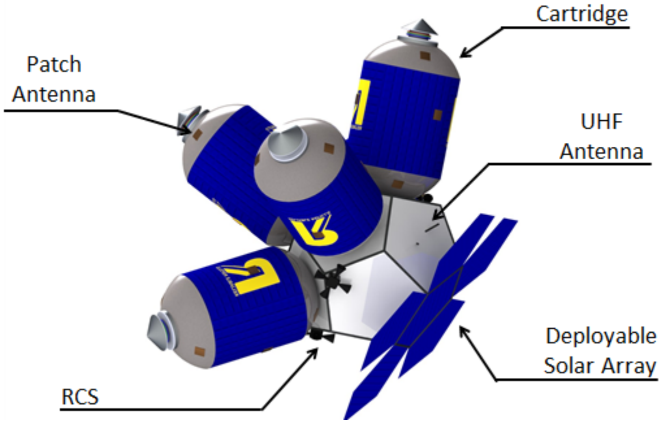


Figure 7: CHORD as depicted with fully populated cartridges

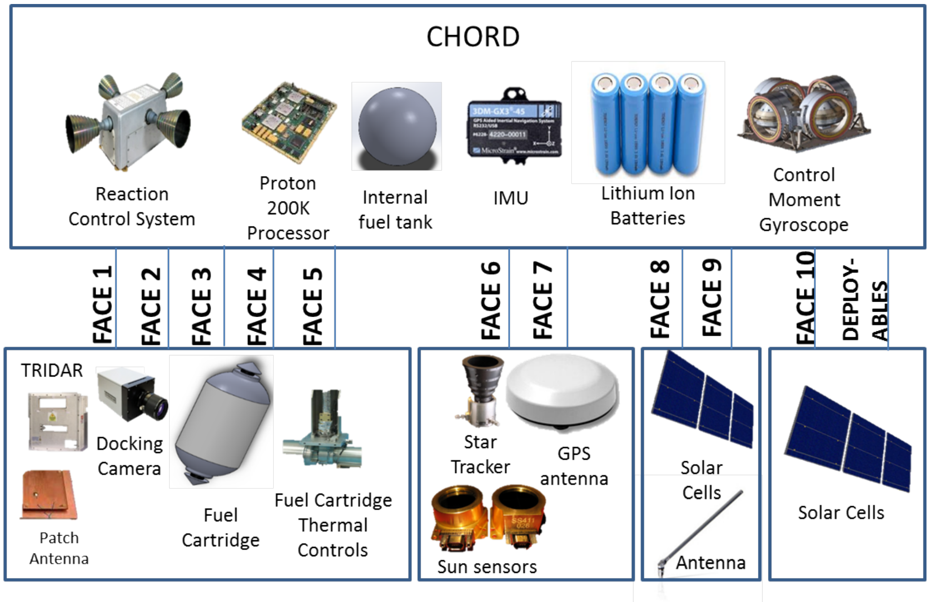


Figure 8: The Satellite Architecture Diagram shows the relations between all subsystem components.

## 6.1 Cartridge Configuration

Cartridges are the disposable fuel or alternative storage cells stored on CHORD and later transferred to clients. Each cartridge will be an aluminum ore, fiber reinforced polymer (FRP) cylinder with two custom valves and a male docking component at each end. The custom valves will have an adapter fitting that will connect to a propellant regulator in the fuel hub and the client spacecraft. The purpose of having two valves is to maintain thermal control while allowing continuous circulation of the fuel through an inlet and outlet. Electromagnets will be installed at both ends of the cartridges and in the female docking port of the fuel hub. When the cartridges are close in proximity to the hub, the electromagnets will be turned on with opposite polarity to attract each other and successfully dock. The female docking component on the cartridges has a conical pyramid shape to ease guidance. Cartridges will be secured through a latching mechanism in the hub, which will also transfer power and data between the cartridge and hub. The seal is vacuum tight for propellant transfer. The connection ports for power and data are rings around the male docking component that precisely match with slots in the latch. The design of the docking mechanism only requires that the female and male components are concentric to each other to successfully dock. See Figure 9 for a docking schematic.

Figure 9: Berthing mechanism for hub/cartridge mating

Reliable Refills will provide clients with the option of storing five different fuels: Liquid Oxygen (LOX), Liquid Methane (LCH4), RP-1, Monomethyl Hydrazine (MMH), and Nitrogen Tetroxide (NTO). Each cartridge is capable of storing up to 10,000 kg of any fuel for 3 months. The quantity of fuel is constrained by the total mass that a Falcon 9 can take to LEO. Additionally, clients are free to design compatible cartridge that better fit their needs.

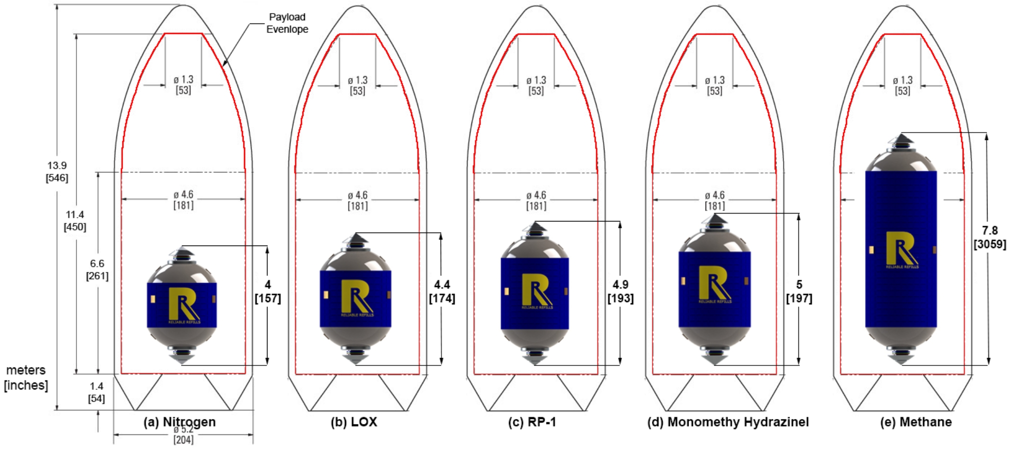


Figure 10: All fuel specific tanks fit within the Falcon 9v1.1 fairing envelope.

The cartridges will have a passive ADCS composed of electromagnets [20] installed on all three axes to prevent uncontrolled tumbling upon their release into LEO. This method has been proven to work in the past for small satellites and will be scaled to size for the cartridges. Cartridges will also be equipped with seven patch antennas, three spread 120 degrees around the cylindrical section and two on each opposite end for communication with the hub. Propellants are volatile and need to be protected from launch conditions and the space environment. To prevent the propellants from boiling off or reacting, cartridges will be equipped with passive thermal and pressure control systems (see Section 6.3 for further description). To supply enough power for all electrical components in both the cartirdge and hub, cartridges will be covered with solar cells. Figure 11 shows a detailed cross-section of a cartridge with all of its internal components.

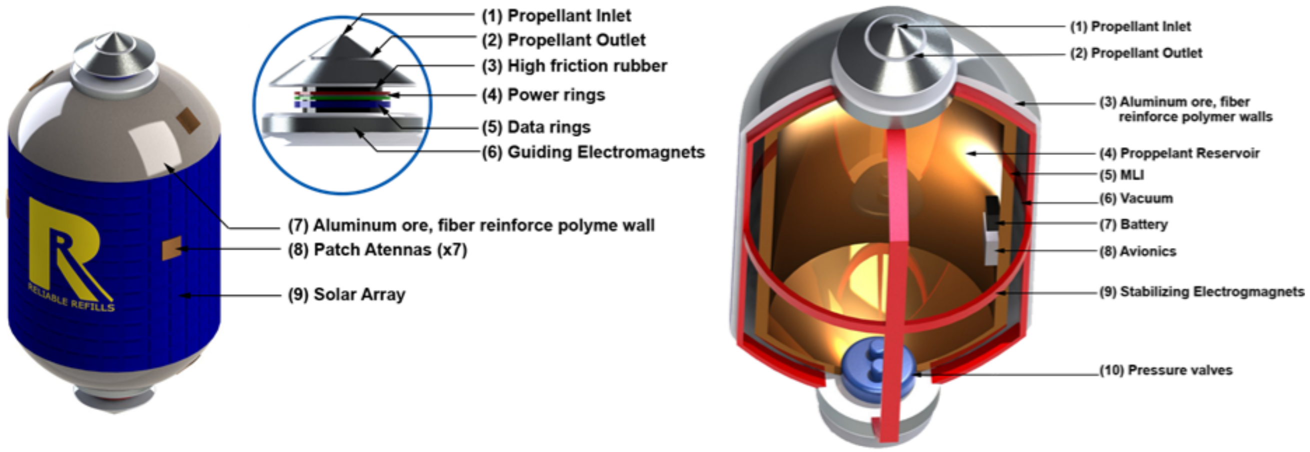


Figure 11: Isometric and cross sectional views of cartridge with detailed docking interface

## 6.2 Structures (STR)

The structural configuration of our central hub models a dodecahedron. The availability of twelve useable sides, each in the shape of an equilateral pentagon, allows us to place several cartridges of an adequate size on the hub while leaving space for other essential hardware, such as solar panels, communication antennas, and sensors. The internal frame will be constructed out of an aluminum truss system, reducing the mass and allowing for wiring from the central avionics system to each face. The avionics system will be located near the center of mass of the hub, encased in its own housing and separated structurally from the rest of the spacecraft to protect it from structural failure of another part of the spacecraft. Also located in the interior of the spacecraft will be the RCS propellant tanks and piping. Each outer surface will be made of aluminum sheets. The surfaces allow for simple mounting of components. A breakdown of the components on each face is listed in the system architecture section.

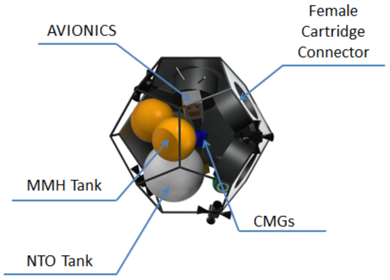


Figure 12: CHORD isometric bus structure and components

As seen in the mass budget, Table 7, both the hub and cartridge reach the 13,500 kg limit for launch when factoring in margin. A large portion of the hub's structural mass is the connectors for the cartridges. The solid part of the structure can be hollowed to reduce mass. The internal propellant has been sized for hub operation for at least twenty five years and is a limiting factor in total system mass. The cartridge system design focuses on reducing the mass of structural components to increase the amount of fuel that can be carried. The cartridge thermal and pressure system masses are based on existing systems. The connection point on the cartridge is significantly massive and can be hollowed out if needed.

Table 5: Systems level mass budget

| **Subsystem** | **Mass Budget (kg)** | **Percent of Total Mass** |
|---|---:|---:|
| *Structures* | 5000 | 47.4% |
| *Avionics* | 100 | 0.9% |
| *Power* | 200 | 7.6% |
| *RCS* | 250 | 2.4% |

*Continued on next page*

*Continued from previous page*

| | | |
|---|---|---|
| *Stored propellant mass* | 5000 | 47.4% |
| **Subtotal** | **10550** | **100.0%** |
| Margin | 2638 | 25.0% |
| **Total** | **13188** | |
| **For individual cartridge** | | |
| *Structure* | 700 | 6.5% |
| *Stored propellant* | 10000 | 92.7% |
| *Thermal Control* | 45 | 0.4% |
| *Pressure Control* | 45 | 0.4% |
| **Subtotal** | **10790** | **100.0%** |
| Margin | 2698 | 25.0% |
| **Total** | **13488** | |

## 6.3 Thermal and Pressure Control System (TPC)

The cartridges will require a system of thermal and pressure control that is able to maintain the fuels in a liquid state and minimize losses in mass due to boil-off. Most of the fuels offered to be transported can be kept at approximately $0°C$ while others such as LOX and Methane must be kept at cryogenic temperatures to prevent boil-off. The passive thermal control we are using is to contain the propellant in a dewar flask, which separates the volume of stored fuel from the external wall of the storage tank by a vacuum "wall" between the two. By placing multi-layer insulation (MLI) on the outside of this we can further reduce the amount of heating due to radiation. Additional peltier thermoelectric coolers will be placed around the neck on either end of the cartridge to assist in the cooling process. These small devices have an operating temperature down to $-40\,°\mathrm{C}$ and are less costly to run than a cryocooler non-stop [23]. In cases where the cooling is excessive, the current through the peltier devices can be reversed to gradually heat up the cartridges instead. This will likely not be needed for the cryogens, but may be necessary for the fuels maintained at higher temperatures, e.g. NTO which has a stable temperature range of $-11\,°\mathrm{C}$ to $20\,°\mathrm{C}$ at standard pressure.

Any built-up pressure due to boil-off inside the cartridges will be sent through a pressure release valve. This will effectively return the cartridge back to optimal pressure but at a loss of a small percentage of fuel. Increased pressures allow for the propellant to remain a liquid at higher temperatures, which in turn will conserve power towards cooling and fuel-loss due to boil-off. To ensure the cartridges are able to withstand the higher pressures desired, a hoop stress analysis was done (and confirmed) to verify the structural integrity of the cartridges storing the propellants.

Once docked, each cartridge will be assisted by the hub with a more robust thermal and pressure control. Four cartridge ports will be connected with the hub's pressure and temperature control system. While the fifth cartridge, containing Monomethylhydrazine, a hypergolic propellant, will be isolated from the rest of the fuel to prevent catastrophic failure with other hypergols, such as Nitrogen Tetroxide. The stored propellant from each of these four cartridges will be sent through the pressurized lines inside the hub and through a heat exchanger cooled via a cryocooler, as shown below in Figure 13.

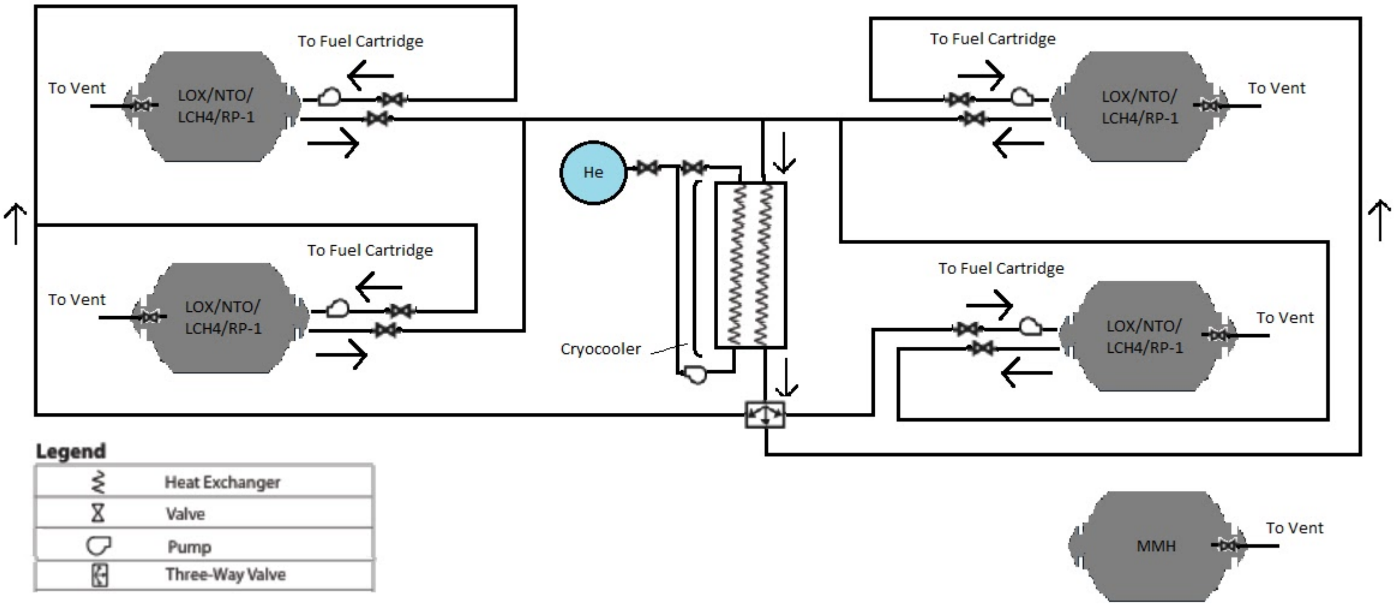


Figure 13: Pressure flow diagram for payload thermal control

The cryocooler is a fairly compact method of cooling the propellants to cryogenic temperatures and so contributes little mass to the space mission. Cryocoolers generally are inefficient and costly in terms of the amount electrical power needed to dissipate excess heat, ∼ 10% Carnot efficiency. However they are very effective in reaching temperatures below 100 K [7]. The energy flow for CHORD was estimated and can be found below in Figure 14 and sample calculations can be found in Appendix H. Values shown shown are for maximum heat flow for each device.

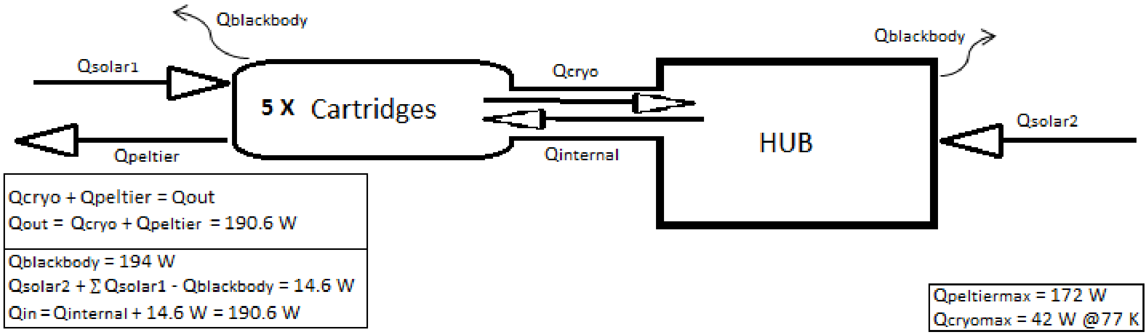


Figure 14: Thermal flow diagram for CHORD

### 6.4 Guidance, Navigation, Attitude Determination, and Control System

The CHORD control system will have four different modes of operation that will allow it to complete its mission: (1) stabilization and sun tracking, (2) cartridge rendezvous and docking, (3) mass, center of mass, and moment of inertia determination, and (4) client rendezvous and cartridge transfer. During the interim between rendezvous operations, ADCS will simply orient itself for maximum power generation or communications capabilities. During cartridge rendezvous operations, CHORD must maintain very accurate attitude and positional control. It will track the cartridge using a TriDAR laser triangulator and computer vision, using its thrusters to maneuver and dock with it. Immediately after receiving a cartridge, CHORD will perform a number of small diagnostic maneuvers to determine its exact mass characteristics. This will allow it to transfer the cartridge to the client with the required precision.

CHORD will make use of a wide array of sensors for precise location and attitude determination. The depot will have an accurate inertial measurement unit (IMU) containing a 3-axis gyroscope, accelerometer, and magnetometer.

For more accurate attitude determination, it will use sun sensors and star trackers. Orbital location and velocity will be determined using GPS. Sensor selection and trades are shown in Appendix I.

CHORD will make use of both control moment gyroscopes (CMG) and a reaction control system (RCS) for attitude control and rendezvous maneuvering. It will have four CMG units for complete 3-axis rotation control as well as redundancy. The CMG units were scaled from an Astrium off the shelf model and will provide a total of 344 Nm, which will be adequate for slow, precise maneuvers. The RCS thrusters will be similar to the SpaceX Draco MMH-NTO thrusters which can provide 400 N each. They will be arrayed in banks of four to allow for both translational and rotational control. Actuator selection and trades are shown in Appendix **??**. 5000 kg of propellant has been dedicated in the hub mass budget to allow for approximately 2000 m/s $\Delta v$ without additional cartridges. This has been sized to allow more than 50 missions to be completed without refueling the hub given our anticipated required $\Delta v$ per rendezvous.

## 6.5 Communications System, Ground Station and Operations (COM and GroundOps)

This section details the communications architecture between CHORD, the cartridges, the relay satellites and ground stations for all phases of the mission.

### 6.5.1 Description of COM between hub and cartridge

Communication between the hub and cartridges will be established using Mobile Satellite S-bands. This band was chosen for its smaller antennae footprints, radio-location capabilities, and facilitation of communication links with relay satellites. Patch antennas provide an outward gain pattern and will be placed on each docking face of CHORD. Similar patch antennas will also be placed on the cartridges in strategic locations based on shape. Cylindrical cartridges will have patch antennas located at 180 deg offsets on the sides and one on each of the opposite faces. This will ensure connectivity despite the orientation of the cartridge with respect to the hub. The cartridge will give out periodic pings that CHORD will use to detect and monitor the status of the cartridge prior to docking. Table 22 outlines the ping details and link budget.

### 6.5.2 Nominal Operation and Docking Operation

The Ground communications system for CHORD will primarily be divided into two modes of operation: Nominal and Docking. Each mode has its own communication and ground station scheme. Docking mode occurs when special mission specific actions are taking place such as retrieval and docking of the cartridges, as well as docking with Customer payloads to deliver the Cartridges. Nominal mode refers to the inactive standby operation of the CHORD satellite.

Docking maneuvers are highly complex and will require constant monitoring of satellite operation throughout the procedure to ensure proper functionality. Communications during docking operations which typically last on the order of hours will not be sustainable through one ground station only as the access time for satellites in LEO is on the order of 10 minutes. To achieve long duration high rate communications during docking, CHORD will rely on relay satellites located in GEO orbits to send information to the ground. Highly detailed subsystem data, telemetry and rendezvous parameters detailed in Table 23 will be relayed at a rate of 510 bytes per second.

Reliable Refills will use the data relay capabilities of the TDRS satellites provided by NASA to communicate with the hub during docking procedures. The TDRS constellation was chosen because of its multiple relay satellites, ability to receive on the S-Band from low gain antenna and heritage with prior docking missions such as SpaceX's Dragon capsule. The S-Band patch antennas used for cartridge communication will also serve to transmit high-rate data to the TDRS satellites. As each docking face has an antenna, the antenna pointing requirements during docking are reduced thereby reducing the load on the ADCS system. The data received by the TDRS satellites is relayed to the TDRS managing facility then relayed over the internet to the Reliable Refills managing facility. Commands for maneuver correction can also be issued through the same route in the reverse direction. Table 17 outlines the link budget for communications to the TDRS satellites.

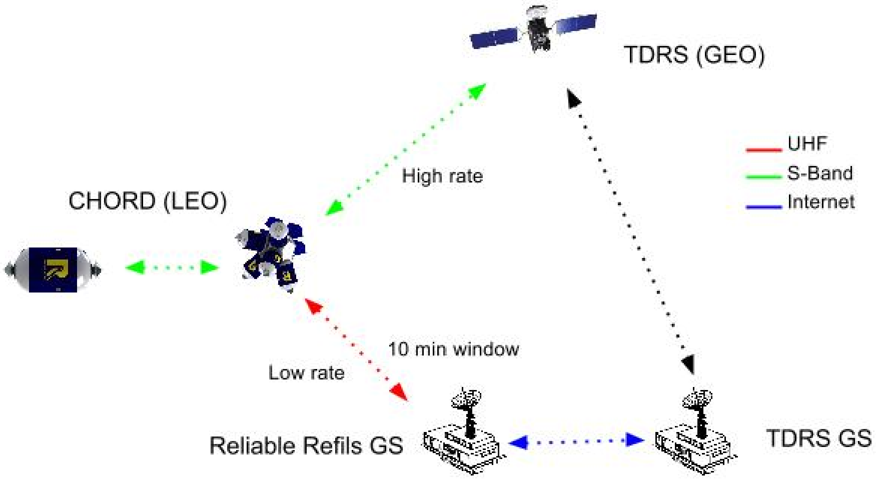


Figure 15: Communications Overview

In Nominal mode, the satellite is not involved with high risk cartridge retrieval and docking procedures. Therefore high rate, detailed telemetry data is not required and instead a low rate status beacon at 10s intervals will suffice to relay the health of the satellite to the ground. Extensive ADCS parameters, power consumption, and temperature profiles can be excluded to minimize beacon size. Communication between the hub and the Reliable Refills management facility will be established using Mobile Satellite UHF bands. A ground station will be built at the management facility to receive beacons and uplink commands during Nominal operations. The management facility will analyze the beacons during each overhead pass to ensure nominal functionality. Any issue on board will be highlighted in the beacon, and the operators will be able to request error specific information for download. Table 21 outlines the beacon parameters and size.

Crossed UHF monopole antennas on opposite faces of CHORD will provide an omni-directional radiation pattern to transmit the beacons. This system was chosen because of its simplicity, low risk deployment and no need for attitude control. This will ease the requirements on the ADCS system during nominal operation thereby reducing risk and power consumption. A detailed link budget is highlighted in Table 15.

## 6.6 Electrical Power System (EPS)

The electrical power system for the orbital depot will be solar powered with batteries to store charge. The solar power array will be 51 $m^2$, which will provide the power necessary for the orbital depot under nominal operating conditions which is a monitored non-docking orbit as shown in Table 6. The solar array will consist of triple junction gallium arsenide solar cells because of their high power output per given area ( 253 $W/m^2$) that will reduce overall cell area and mass compared to traditional silicon cells. The solar array provides slightly more power than the average power draw which will compensate for the degradation of the effectiveness of the solar array over time and allow for an operational lifetime of approximately 20 years. The batteries must be capable of storing 10.9 MJ, enough energy to power the depot for 2 successive docking orbits at peak power draw (for detailed energy budget see Appendix L). For this purpose our batteries will be Quallion QL075KA lithium-ion batteries due to their high specific energy density, greater than 110 $W * hr/kg$, and large battery capacity (to see full battery capabilities and comparison see Appendix L). There will be two redundant batteries for powering the pressure and temperature regulation of the cartridges. There will be an additional redundant battery for the control and communications systems to allow for emergency maneuvering and if necessary deorbit. A smaller isolated battery will power the purge system that will eject all cartridges from the hub in case of emergency deorbit or individual cartridges for normal docking operations or cartridge failure. A summary of batteries and backups is shown in Appendix L).

Table 6: Power Budget Summary

| | Unit Power Draw | Peak Power Draw (W) | Nominal Power Draw (W) | |
|---|---|---|---|---|
| **ADCS** | | | | |
| Control Moment Gyros | 252 W/CMG | 1008 | 705.6 | (scaling based on Astrium CMG 15-45S) |
| Basic Sensors (magnetometer, accelerometer, gyroscope) | 1 W/sensor | 9 | 9 | (based on specs from cubesatshop) |
| Control Board | 5 W/Board | 5 | 5 | (based on Proton 200k) |
| Laser Range Finder | 0.5 W/LRF | 5 | 2 | (based on specs from cubesatshop) |
| Camera | 0.66 W/Cam | 6.6 | 2 | (based on specs from cubesatshop) |
| **COM** | | | | |
| Transmitter Power | 6 W/system | 6 | 1 | (based on AstroDev) |
| **EPS** | | | | |
| Power Board | 5 W/board | 5 | 5 | (based on Proton 200k) |
| **Cartridges (5 Max)** | | | | |
| P/T Controls | 400 W/car | 2000 | 1000 | (Based on Cryocooler) |
| TRIDAR Docking Systems | 10 W active/0.5 W passive | 12 | 2.5 | (Based on TRIDAR) |
| **CDH** | | | | |
| Boards | 5 W/board | 30 | 30 | (based on Proton 200k) |
| **Miscellaneous** | | | | |
| Purge Systems | 10 W/system | 10 | 0 | |
| **Subtotal** | | **3096.6** | **1762.1** | |
| Line Losses | 0.1 | 309.66 | 176.21 | |
| **Total** | | **3406.26** | **1938.31** | |

## 6.7 Command and Data Handling (CDH)

The command and data handling system for an orbital depot must be able to quickly deal with a wide variety of data, both as a part of normal operations and in case of emergencies. This system must collect and process all pressure and temperature data of the propellant cartridges to ensure that the propellant will stay in a stable, usable state. In addition, this system must also monitor and calculate orbital position data so as to maintain a stable orbit for docking procedures. Related to the docking procedures, the system must be able to react to sensor data about inertial changes from the unloading of propellant during docking, as well as send data to the ADCS to ensure stability of the depot and spacecraft during refueling. The data handling system must also keep an accurate time stamp of the depot and distribute this time across various systems to ensure that time-dependent operations are carried out successfully (e.g. orbital maneuvers and docking). Devoted to these processes will be a Proton 200k DSP processor board. This board can operate with a floating point processor speed of 300 MHz and requires 5 Watts to operate. The board also contains 128 Mbyte of SDRAM and up to 512 Mbyte of RH Flash. Additionally, this board is radiation hardened with a TID of 100 krad with built in systems to mitigate single event upsets and functional interruptions. This level of radiation hardening is necessary since the depot will be in orbit for a planned operational life of 20 years. The Proton 200k boards will form the backbone of the standard operational mode as detailed in Figure 17. The secondary mode of operation is when the cartridge is in the process of docking with the hub and focuses mainly on preserving operational temperature and pressures for the fuels Figure **??**.

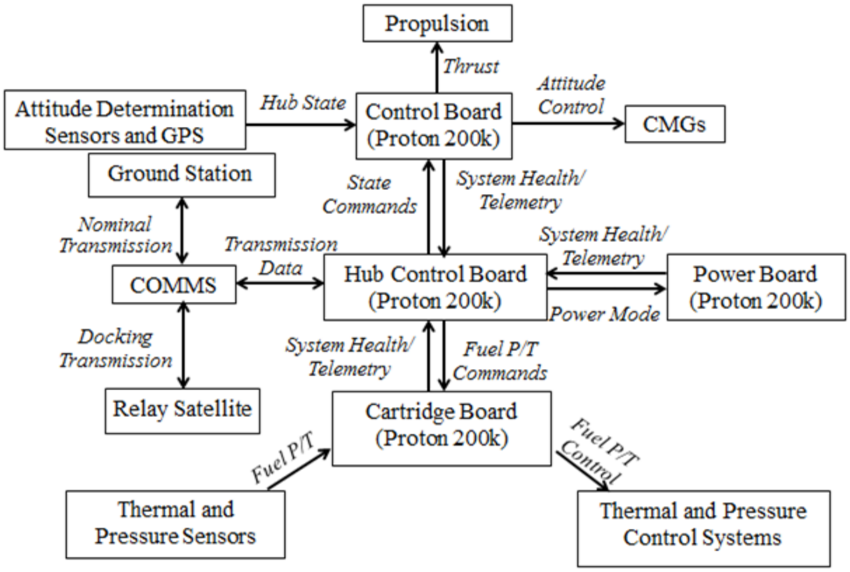


Figure 16: Data handling block diagram of the hub (CHORD)

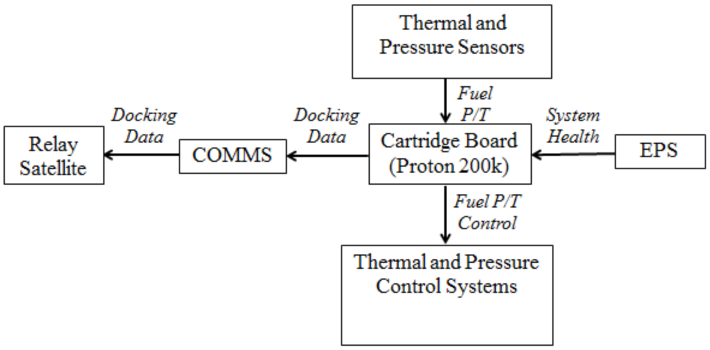


Figure 17: Data handling block diagram of the cartridge

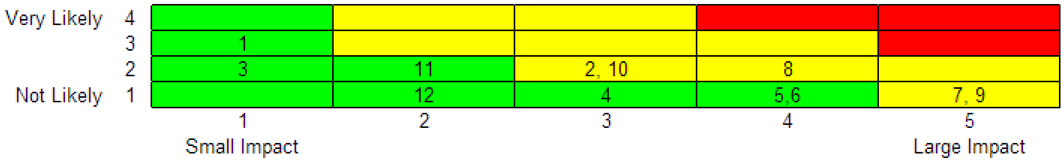
# 7 Risk Analysis

Because a prime benefit that Reliable Refills provides to our customers will be reliability, it is very important that all the risks associated with the system are identified and mitigated. The primary risks we have considered are highlighted in Table ??:

Table 7: Systems level risk analysis

| Callout | Risk | Callout | Risk |
|---|---|---|---|
| 1 | Communications loss during idle | 7 | Damaging collision during rendezvous |
| 2 | Communications loss during rendezvous | 8 | Loss of stability during docking |
| 3 | Pointing error during idle | 9 | Pressure breach during on-board thermal management |
| 4 | Pointing error during rendezvous | 10 | High boil-off losses |
| 5 | Thermal control system failure | 11 | Spacecraft charging |
| 6 | Improper orbit injection of cartridge or client | 12 | Micrometeorite and debris damage or puncture |

Once risks are identified, they are weighted on both their likelihood to occur and the impact they would have on the mission. A risk matrix combines these weights to determine if the given risks are considered low risk (green) or high risk (red). As shown in Figure 18, the majority of the risks in the CHORD mission are designated low or medium risk, and there are additional methods in place to further reduce these risks.



| | | | | | | |
|---|---|---|---|---|---|---|
| Very Likely | 4 | 🟩 | 🟨 | 🟨 | 🟥 | 🟥 |
| | 3 | 🟩 1 | 🟨 | 🟨 | 🟨 | 🟥 |
| | 2 | 🟩 3 | 🟩 11 | 🟨 2, 10 | 🟨 8 | 🟨 |
| Not Likely | 1 | 🟩 | 🟩 12 | 🟩 4 | 🟩 5,6 | 🟨 7, 9 |
| | | 1<br>Small Impact | 2 | 3 | 4 | 5<br>Large Impact |

Figure 18: Graphical risk matrix of the CHORD mission

Our risk mitigation methods are focused on the items deemed as medium risk (yellow). In the event of communications loss during docking, the control system will be capable of performing the docking maneuvers autonomously. During the autonomous docking, the navigation and control system will monitor its control accuracy and cease the approach maneuver if it detects instability. If control can not be regained, the system will abort the approach, ensuring no collision is possible, and wait for instructions from the ground control station. To reduce the risk of boil off and pressure breach, the hub will supplement the cartridge thermal control system with its own active thermal and pressure control systems. This will add redundancy and extra capability in the case of emergency.

# 8 Planned Ventures

Reliable Refills recognizes the extended future possibilities available for such a depot configuration. For one, secondary science missions can utilize the storage space usually reserved for fuel. Similar cartridges could be manufactured which act as an individual satellite would, but rely on the fuel and maneuverability of our spacecraft. Also, CHORD could service pre-existing satellites (similar to F9 or the Phoenix project) which would benefit from additional fuel, lengthening their lifespan. The resulting configuration would be composed of a central hub that includes lines to different fuel cartridges, much like the fuel pump at a gas station.

Looking further ahead, Reliable Refills has the potential to expand this business to more depots in more locations. Some possible locations for additional depots include an Aldrin cycler, a Martian orbit, a geosynchronous orbit, or at L2. Our main purpose is to propose scalable storage depots which can be stationed at a number of locations in space. These particular depot options have a long operating timeline and would be ideal for small, low mass secondary scientific missions.

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# Appendices

## A Detailed Cost Analysis

| Year 1 costs | | Year 2 costs | | Year 3 costs | | Year 4 costs | | Year 5 costs | |
|---|---|---|---|---|---|---|---|---|---|
| | $k | | $k | | $k | | $k | | $k |
| Engineers | 2000 | Engineers | 2046 | Engineers | 2093.058 | Engineers | 2141.2 | Engineers | 2190.4459 |
| Senior Engineers | 2000 | Senior Engineers | 2046 | Senior Engineer | 2093.058 | Senior Engineers | 2141.2 | Senior Engineers | 2190.4459 |
| Technicians | 1500 | Technicians | 1534.5 | Technicians | 1569.7935 | Technicians | 1605.9 | Technicians | 1642.83442 |
| Dev Lab & Production Facilities | 100 | DL & PF | 100 | DL & PF | 100 | DL & PF | 100 | DL & PF | 100 |
| Cartridge | 1000 | Cartridge | 1000 | Cartridge | 1000 | Cartridge | 1000 | | |
| Components | 1312 | Components | 1312 | Components | 1312 | Components | 1312 | Components | 1312 |
| Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 |
| LV | 22400 | LV | 22400 | LV | 22400 | LV | 22400 | LV | 22400 |
| | | | | | | | | | |
| | | | | | | | | Initial Demo Customer Launch | 8170 |
| | | | | | | | | | |
| | | | | | | | | | |
| Total | -40312 | | -40438.5 | | -40567.9095 | | -40700 | | -31665.7262 |
| GRAND TOTAL | -40312 | | -80750.5 | | -121318.4095 | | -162019 | | -193684.431 |

| Year 6 costs | | Year 7 costs | | Year 8 costs | | Year 9 costs | | Year 10 costs | |
|---|---|---|---|---|---|---|---|---|---|
| | $k | | $k | | $k | | $k | | $k |
| Engineers | 2240.826151 | Engineers | 2292.365153 | Engineers | 2345.089551 | Engineers | 2399.027 | Engineers | 2454.204223 |
| Senior Engineers | 2240.826151 | Senior Engineers | 2292.365153 | Senior Engineers | 2345.089551 | Senior Engineers | 2399.027 | Senior Engineers | 2454.204223 |
| Technicians | 1680.619613 | Technicians | 1719.273865 | Technicians | 1758.817163 | Technicians | 1799.27 | Technicians | 1840.653167 |
| Dev Lab & Production Facilities | 100 | DL & PF | 100 | DL & PF | 100 | DL & PF | 100 | DL & PF | 100 |
| | | | | | | | | | |
| | | | | | | | | | |
| Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 |
| | | | | | | | | | |
| Increased Customer Launches | 25800 | ICL | 30100 | ICL | 30100 | ICL | 30100 | ICL | 30100 |
| | | | | | | | | | |
| | | | | | | | | | |
| Total | 9537.728084 | | 13695.99583 | | 13551.00373 | | 13402.68 | | 13250.93839 |
| GRAND TOTAL | -184146.703 | | -170450.7072 | | -156899.7035 | | -143497 | | -130246.0883 |

| Year 11 costs | | Year 12 costs | | Year 13 costs | | Year 14 costs | | Year 15 costs | |
|---|---|---|---|---|---|---|---|---|---|
| | $k | | $k | | $k | | $k | | $k |
| Engineers | 2503.288307 | Engineers | 2553.354074 | Engineers | 2604.421155 | Engineers | 2656.51 | Engineers | 2709.63977 |
| Senior Engineers | 2503.288307 | Senior Engineers | 2553.354074 | Senior Engineers | 2604.421155 | Senior Engineers | 2656.51 | Senior Engineers | 2709.63977 |
| Technicians | 1877.466231 | Technicians | 1915.015555 | Technicians | 1953.315866 | Technicians | 1992.38 | Technicians | 2032.22983 |
| Dev Lab & Production Facilities | 10 | DL & PF | 10 | DL & PF | 10 | DL & PF | 10 | DL & PF | 10 |
| | | | | | | | | | |
| | | | | | | | | | |
| Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 |
| | | | | | | | | | |
| Increased Customer Launches | 34400 | ICL | 34400 | ICL | 34400 | ICL | 34400 | ICL | 34400 |
| | | | | | | | | | |
| | | | | | | | | | |
| Total | 17505.95715 | | 17368.2763 | | 17227.84182 | | 17084.6 | | 16938.4906 |
| GRAND TOTAL | -112740.131 | | -95371.8548 | | -78144.013 | | -61059 | | -44120.924 |

| Year 16 costs | | Year 17 costs | | Year 18 costs | | Year 19 costs | | Year 20 costs | |
|---|---|---|---|---|---|---|---|---|---|
| | $k | | $k | | $k | | $k | | $k |
| Engineers | 2763.832565 | Engineers | 2819.109216 | Engineers | 2875.491401 | Engineers | 2933 | Engineers | 2991.66125 |
| Senior Engineers | 2763.832565 | Senior Engineers | 2819.109216 | Senior Engineers | 2875.491401 | Senior Engineers | 2933 | Senior Engineers | 2991.66125 |
| Technicians | 2072.874424 | Technicians | 2114.331912 | Technicians | 2156.618551 | Technicians | 2199.75 | Technicians | 2243.74594 |
| Dev Lab & Production Facilities | 10 | DL & PF | 10 | DL & PF | 10 | DL & PF | 10 | DL & PF | 10 |
| | | | | | | | | | |
| | | | | | | | | | |
| Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 |
| | | | | | | | | | |
| Increased Customer Launches | 34400 | ICL | 34400 | ICL | 34400 | ICL | 34400 | ICL | 34400 |
| | | | | | | | | | |
| | | | | | | | | | |
| Total | 16789.46045 | | 16637.44965 | | 16482.39865 | | 16324.2 | | 16162.9316 |
| GRAND TOTAL | -27331.4633 | | -10694.0136 | | 5788.38504 | | 22112.6 | | 38275.5632 |

| Year 21 costs | | Year 22 costs | | Year 23 costs | | Year 24 costs | | Year 25 costs | |
|---|---|---|---|---|---|---|---|---|---|
| | $k | | $k | | $k | | $k | | $k |
| Engineers | 3051.494478 | Engineers | 3112.524368 | Engineers | 3174.774855 | Engineers | 3238.27 | Engineers | 3303.03576 |
| Senior Engineers | 3051.494478 | Senior Engineers | 3112.524368 | Senior Engineers | 3174.774855 | Senior Engineers | 3238.27 | Senior Engineers | 3303.03576 |
| Technicians | 2288.620859 | Technicians | 2334.393276 | Technicians | 2381.081142 | Technicians | 2428.7 | Technicians | 2477.27682 |
| Dev Lab & Production Facilities | 10 | DL & PF | 10 | DL & PF | 10 | DL & PF | 10 | DL & PF | 10 |
| | | | | | | | | | |
| | | | | | | | | | |
| Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 | Operations | 10000 |
| | | | | | | | | | |
| Increased Customer Launches | 34400 | ICL | 34400 | ICL | 34400 | ICL | 34400 | ICL | 34400 |
| | | | | | | | | | |
| | | | | | | | | | |
| Total | 15998.39018 | | 15830.55799 | | 15659.36915 | | 15484.8 | | 15306.6517 |
| GRAND TOTAL | 54273.9534 | | 70104.51139 | | 85763.88053 | | 101249 | | 116555.289 |

# B Expanded Business Plan

## B.1 Scheduling and Logistics

A customer should approach Reliable Refills at least 1 year before their payload launch date to reserve fuel docking space. Any requests for space with less than 1 year preparation time are subject to additional fees, the amount of which will be determined by Reliable Refills. Dates of availability will be listed on Reliable Refill's website calendar, with structured pricing outlined on each date. Favorable pricing directly correlates to the amount of preparation time available. Any requests for cancellation of a docking reservation less than 6 months before launch are subject to no refund. They would be charged a reservation fee (similar to a security deposit in case contract termination). The customer assumes all risk relating to inclement weather delay or uncontrollable events. Launches delayed by these events will be initiated at the earliest time possible.

While the primary mission statement of Reliable Refills is to provide a cost-effective source of fuel storage, alternative options are available. In the event that a fuel docking station is left unreserved, proposals for alternative dockings will be accepted. Alternative docking proposals (scientific) will be launched at the earliest possible time, and may remain docked for 2 months or until a fuel docking proposal is submitted (whichever is longer).

## B.2 Security

Reliable Refills recognizes the possible risk such a depot in space presents. In order to prevent fuel hijacking from a foreign source, docking access codes will be sent to the customer after payment is received in full. These codes are used to allow a cartridge access to dock to the main hub, and also allow for the release of the cartridges from the docking station. Neither of these actions will be completed until the access codes are received. Also, in the event of a significant, uncorrectable orbit change (i.e. malicious intent to destroy the fuel depot or use as an Earth-bound weapon), Reliable Refills will initiate an emergency release command to disperse the on-board cartridges in a safe manner. Customer charges will be refunded at the conclusion of an incident report and causal investigation.

# C Work Breakdown

Reliable Refills is a very horizontal company as there is only one manager and everyone, including the manager, is technically skilled. This allows our company to focus on the design and development process without overly much interference. This in turn allows for a shorter time span to complete important milestones in our design.

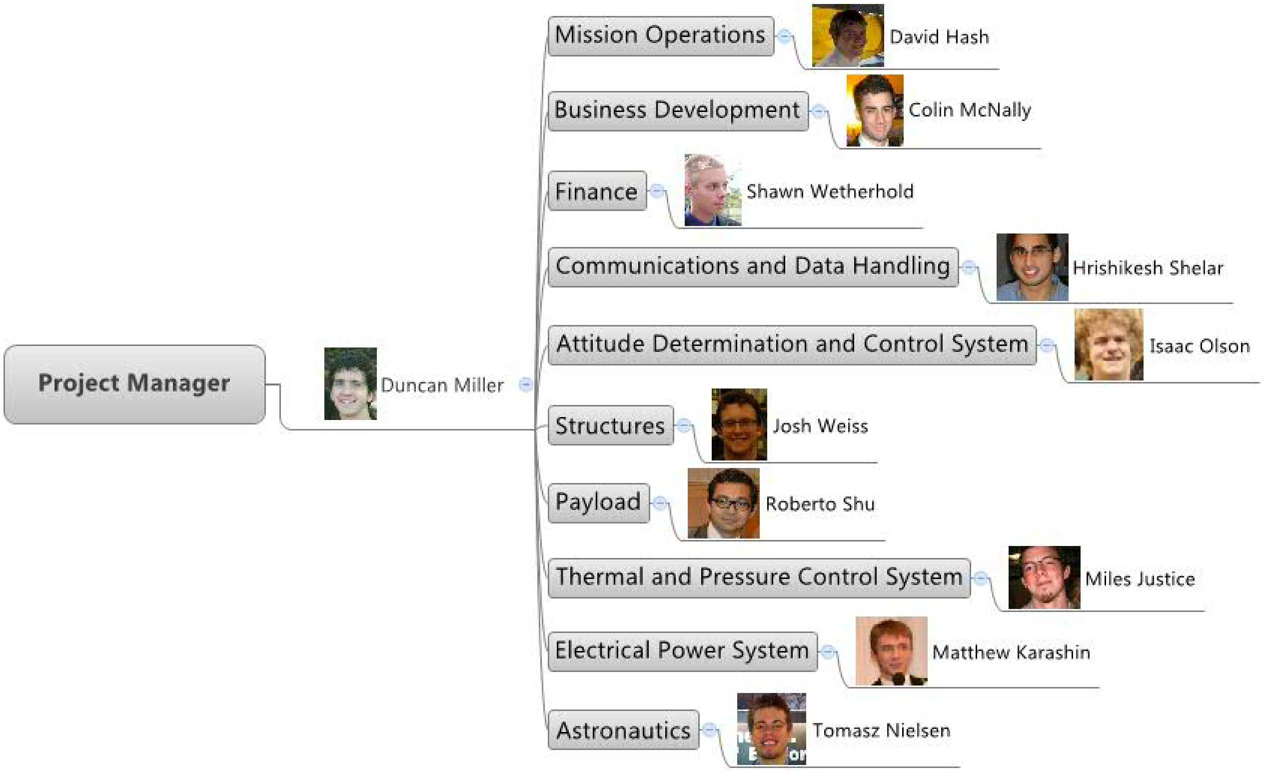

Figure 19: Personnel organization within the CHORD project

# D Marketing

In order to grow and develop Reliable Refills, we have created the website http://www.reliablerefills-inc.com/ which contains our publications, contact information, and information about the company. This will allow us to reach potential customers that we were unaware of and to allow for easy access to information on any progress that we have made to our current customers. The website also allows our customers to get in contact with us in order to answer any questions that they might have.

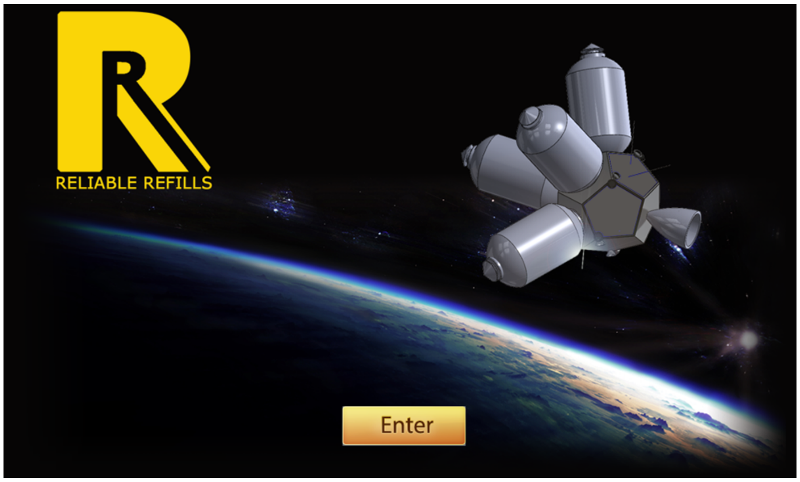

Figure 20: Splash page of our company's website

Reliable Refill is proposing a private mission named the Commercial Heavy-lift Orbital Refueling Depot (CHORD) to provide economically feasible orbital refueling for deep space missions. By decoupling cargo/propellant from the dry bus, CHORD will enable much higher mass payloads such as those necessary to complete manned missions to Mars or robotic landings on Titan. Additionally, refueling in orbit allows other missions to make use of more economic and frequent medium sized rocket launches as opposed to expensive and less reliable heavy-lift rockets.

Figure 21: Homepage of Reliable Refills

# E Detailed System Requirements

Table 8: Primary Requirements Matrix

| | **System Requirements** |
|---|---|
| SYS-01 | CHORD shall rendevous with and store customer cartridges |
| SYS-02 | CHORD shall rendevous with customer satellites and deliver cartridges |
| SYS-03 | CHORD shall be able to store up to 5 cartridges |
| SYS-04 | CHORD shall be able to store 5 different fluids: methane, RP-1, liquid oxygen, Monomethylhydrazine and nitrogen tetroxide |
| SYS-05 | CHORD shall pioneer a universal docking configuration that is easily integratable into the customer's bus structure |
| SYS-06 | The CHORD bus design shall be scalable and universal for expansion into a variety of orbit locations |
| SYS-07 | The cartridges shall detumble and align with Earth's magnetic field in a minium of 3 days |
| SYS-08 | The cartridges shall not lose more than 5% propellant mass (from boil-off) prior to rendezvousing with the customer |
| SYS-09 | CHORD shall be capable of phasing 100 km per customer for at least 50 missions |
| SYS-10 | CHORD shall maintain thermal and pressure conditions within the operational limit the thermal and pressure control units |
| SYS-11 | CHORD orbital decay lifetime shall be greater than 25 years after launch for operations |
| SYS-12 | CHORD shall be capable of transfering propellant between docked cartridges |
| SYS-13 | The cartridge design shall be able to be mass produced |
| SYS-14 | CHORD shall be deployed into the a low inclination orbit for customer accessibility |
| SYS-15 | The cartridge design shall be capable of carying non-propellant payloads (water, supplies, electronics) |
| SYS-16 | All technologies used on CHORD shall be of TRL greater than 7 |
| SYS-17 | CHORD shall utilize as many Commercial Off The Shelf parts as possible |
| SYS-18 | CHORD shall be designed for electronmagnetic compatability (EMC) and for mitigation of electromagnetic interference (EMI), specifically susceptibility to launch vehicle and range environments |
| SYS-19 | CHORD shall not exceed the maximum fairing 13000 kg mass |
| SYS-20 | CHORD shall meet all sine sweep, burst, shock, and vibration test levels per launch requirements |
| SYS-21 | CHORD shall successfully demonstrate cryogenic storage, transfer and rendezvous before securing customers |
| SYS-22 | CHORD shall not exceed more than $560M of required capital investment |
| | **Structural Requirements** |
| STR-01 | CHORD dimensions shall fit within a Falcon 9v1.1 fairing |
| STR-02 | CHORD structural elements shall have mass less than 13,000kg |
| STR-03 | All CHORD structural elements shall have a factor of safety of 2.0 for yield strength and 2.6 for ultimate strength |
| STR-04 | The CHORD bus structure shall rigidly enclose and protect internal components |
| STR-05 | CHORD shall not interefere with cartridge recipient in any way except for at cartridge attachment points |
| STR-06 | CHORD structural components shall remain attached during launch, ejection, and operation. |
| STR-07 | CHORD spacecraft shall have a fundamental frequency to meet launch requirements |
| STR-08 | CHORD non-metallic materials shall have a maximum collected volatile condensable material (CVCM) content ¡0.1% and a total mass loss (TML) of ¡1.0%. |
| STR-09 | CHORD and the cartridges shall be able to withstand launch loads |
| STR-10 | CHORD materials shall not interfere with cartridge mounting electromagnet system |
| STR-11 | CHORD components shall remain attached during launch, ejection, and operation |
| STR-12 | The CHORD deployable solar arrays shall maximize solar collection area |
| | **Pressure and Thermal System Requirements** |

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| | |
|---|---|
| PTS-01 | PTS shall maintain the stored propellant at a stable temperature and pressure in a liquid state |
| PTS-02 | PTS shall safely release excess boil off from cartridges through pressure release valve |
| PTS-03 | PTS will prevent hypergolic propellants from traveling through the same lines during propellant cycling |
| PTS-04 | Cartridges with cryogenic propellants shall be kept between -250 and -190 degrees Celsius |
| PTS-05 | PTS pumps and cryocoolers shall have flight heritage prior to our first customer |
| PTS-06 | PTS shall cycle cryogenic propellants to both cool neighboring cartridges and limit boil-off. |
| PTS-07 | PTS shall utilize both active and passive (vacuum) insulation to maintain payload pressure and temperature |
| PTS-08 | CHORD shall thermally insulate cartridges from neighboring tanks. |
| **GNC Requirements** | |
| GNC-01 | CHORD orbital position shall be determined to an accuracy of 20 m and velocity to an accuracy of 5 m/s for rendezvous procedures |
| GNC-02 | GNC shalll be able to track incoming fuel cartridges for docking maneuvers |
| GNC-03 | GNC shall be able to control the relative velocity to a cartridge to within 0.1 m/s for docking procedures |
| GNC-04 | GNC shall, on command, perform docking maneuvers with incoming fuel cartridges |
| GNC-05 | GNC shall, on command, perform docking maneuvers with a client for cartridge exchange |
| **ADCS Requirements** | |
| ADCS-01 | ADCS shall autonomously control attitude in all three axes to within an objective of 1 degree accuracy, (2 degree cone) and threshold of 2 degree accuracy (4 degree cone) during docking maneuvers. |
| ADCS-02 | ADCS shall provide 3-axis pointing knowledge within 0.2 |
| ADCS-03 | ADCS shall, on command, perform docking maneuvers with incoming fuel cartridges |
| ADCS-04 | ADCS shall, on command, perform docking maneuvers with client for cartridge exchange |
| ADCS-05 | ADCS shall, on command, perform attitude change maneuvers to re-orient cartridges and/or solar panels |
| ADCS-06 | ADCS shall be able to re-orient CHORD for optimal communication data transfer |
| ADCS-07 | ADCS shall be able to de-saturate the Control Moment Gyroscopes using the Reaction Control System |
| ADCS-08 | ADCS shall run on-board algorithms for optimal maneuvering and system characterization. |
| ADCS-09 | ADCS shall consume less than 1.25 kW of power during nominal operations. |
| **Communication Requirements** | |
| COM-01 | CHORD shall broadcast location and general health in a beacon signal during nominal operation |
| COM-02 | COM shall be able to receive commands during docking procedures |
| COM-03 | COM shall have the capability to cease transmission upon command |
| COM-04 | COM shall transmit telemetry at a rate no lesser than 1 Hz during docking procedures |
| COM-05 | COM electronics shall be deactivated during launch |
| COM-06 | COM shall begin beaconing no sooner than 30 minutes after ejection from the fairing |
| COM-07 | COM shall send periodic beacons with telemetry at a rate of 0.1 Hz during nominal operations |
| COM-08 | COM shall produce EMI no greater than -115dB |
| **Ground Station Requirements** | |
| GS-01 | COM shall receive ground station data and commands. |
| GS-02 | CHORD shall execute commands and telemetry transmitted from the CHORD ground station. |
| GS-03 | COM shall transmit telemety to the ground station. |
| GS-04 | The client shall have the ability to view the cartridge status at all times |

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| | |
|---|---|
| **Electrical Power System Requirements** | |
| EPS-01 | EPS shall provide a regulated and conditioned 5 V and 28 V DC, and raw battery voltage line at 3.6 V. |
| EPS-02 | EPS shall generate enough power to sustain attitude control and high-rate telemetry downlinking during docking operations |
| EPS-03 | EPS solar panels shall produce enough power to provide at least 1.9 kW for 20 years |
| EPS-04 | EPS solar panels shall not exceed a power degradation of 2.75% per year |
| EPS-05 | CHORD shall be fully deactivated during launch. |
| EPS-06 | EPS shall provide enough power for two successive docking orbits at max power draw |
| EPS-07 | EPS shall not exceed a 20% battery depth of discharge after 2 successive docking orbits. |
| EPS-08 | EPS shall signal CDH when batteries near 50% battery depth of discharge |
| EPS-09 | EPS shall produce EMI no greater than -115dB |
| EPS-10 | EPS shall be capable of distributing power to all subsystems with a maximum of 10% line power loss |
| **Command and Data Handling Requirements** | |
| CDH-01 | CDH shall provide power and data interfaces for all CHORD subsystems |
| CDH-02 | CDH shall perform fault and error correction from single event upsets |
| CDH-03 | CDH shall store all data for a minimum of 250 orbits. |
| CDH-04 | CDH shall schdeule rendevous operations at the commanded times |
| CDH-05 | CDH shall monitor the staus of attached cartridges |
| CDH-06 | CDH shall process ground station data and commands |
| CDH-07 | CDH shall provide ADCS with information required to perform rendovous and docking procedures |
| CDH-08 | CDH shall synchronize data collection from the magnetometers, gyroscopes, sun sensors, laser range finders, and cameras |
| CDH-09 | CDH shall collect housekeeping data for telemetry at a rate of at least 1 Hz |
| CDH-10 | CDH shall interface with EPS to command attitude change maneuvers for power point tracking |
| CDH-11 | CDH flight boards shall remain running at all times except for power cycles. |
| CDH-12 | CDH shall produce EMI no greater than -115dB |

# F Additional STK Figures

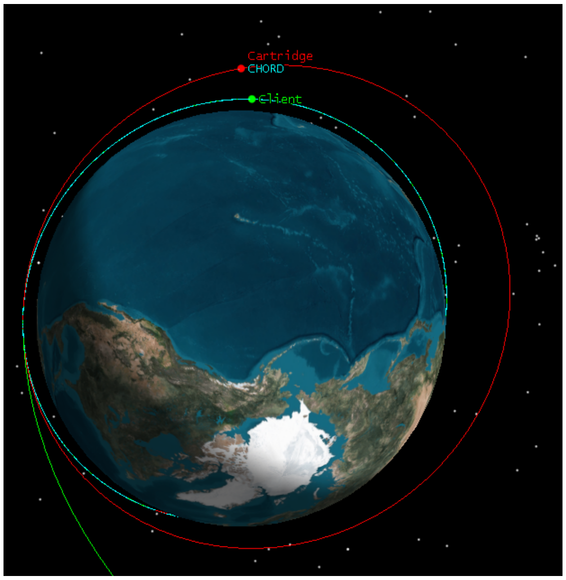

Figure 22: Orbit transferral

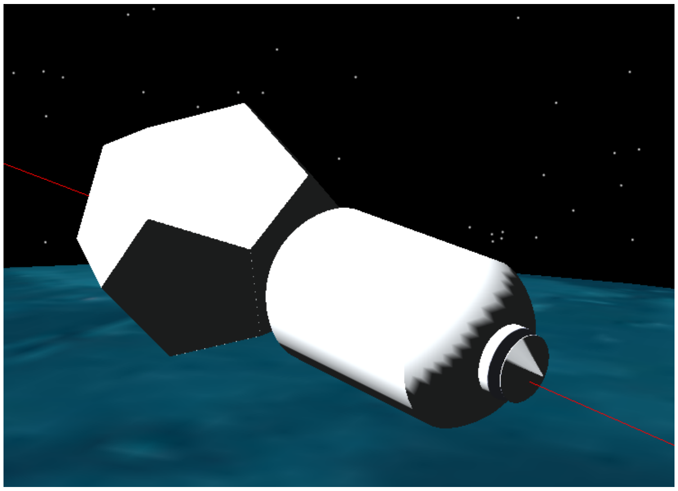

Figure 23: CHORD hub and a single cartridge

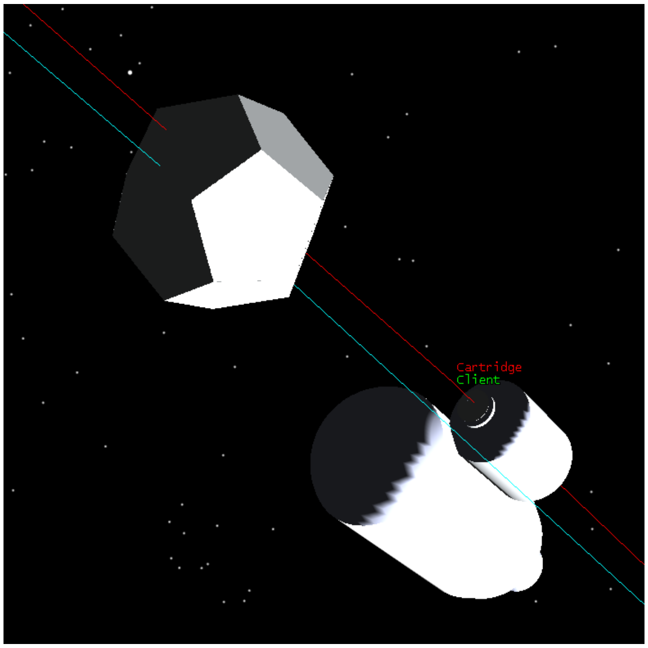

Figure 24: CHORD about its transfer orbit

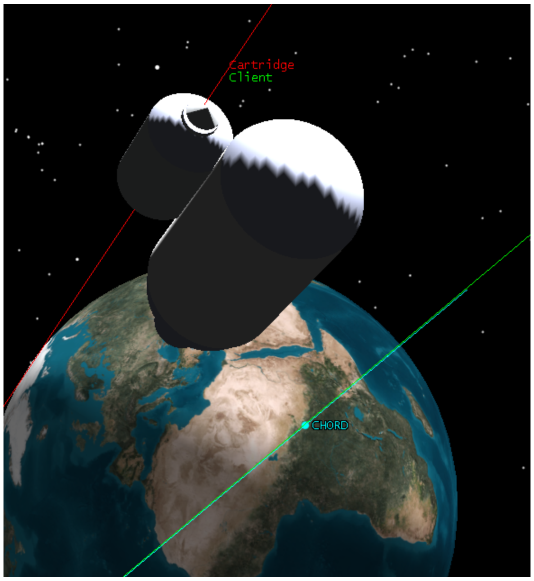

Figure 25: CHORD about its transfer orbit

# G Orbital Parameter Calculations

Derivation of the CHORD/Client RdV equation:

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{5}$$

$$\Delta\omega(rad) = \frac{2\pi(T_{el} - T_{cir})}{T_{cir}} \tag{6}$$

$$a_{el} = ((\frac{T_{el}}{2\pi})^2\mu)^{\frac{1}{3}} \tag{7}$$

$$\Delta v_1 = \sqrt{(\frac{2\mu}{r_{cir}} - \frac{\mu}{a_{el}})} - \sqrt{\frac{\mu}{r_{cir}}} \tag{8}$$

$$\rightarrow \Delta v_1 = \sqrt{\frac{2\mu}{r_{cir}} - \frac{\mu}{r_{cir}(1+\frac{\Delta\omega}{2\pi})^{\frac{2}{3}}}} - \sqrt{\frac{\mu}{r_{cir}}} \tag{9}$$

$$\Delta v_2 = -\Delta v_1 \text{ by symmetry} \tag{10}$$

$$|\Delta v_{total}| = 2|\Delta v_1| \tag{11}$$

$$|\Delta v_{total}| = 2\left(\sqrt{\frac{2\mu}{r_{cir}} - \frac{\mu}{r_{cir}(1+\frac{\Delta\omega}{2\pi})^{\frac{2}{3}}}} - \sqrt{\frac{\mu}{r_{cir}}}\right) \tag{12}$$

T: orbital period
$\Delta\omega$ = difference in the argument of the longitude
$a_{el}$ = semi-major axis of the elliptical transfer orbit
$\mu$ = Earth gravitational constant
$r_{cir}$ = Radius of the Operational Orbit

Drag Assumptions:

$$\rho_0 = 1.2041\frac{kg}{m^3} = \text{reference density} \tag{13}$$

$$h = 6 - 8 \text{ km} = \text{atmospheric scale constant} \tag{14}$$

$$B = \frac{m}{c_D A} = \text{Ballistic Coefficient} \tag{15}$$

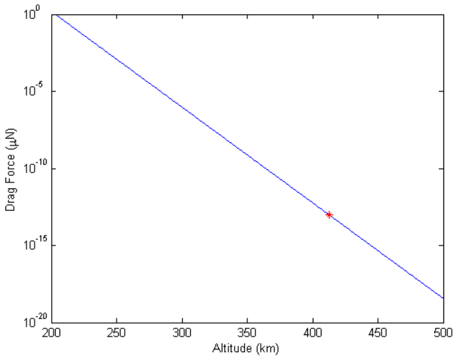

Figure 26: Drag force acting on CHORD at potential altitudes

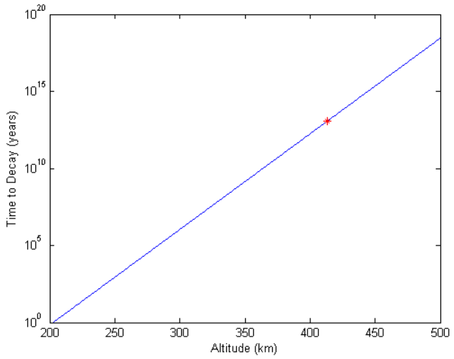

Figure 27: Time for CHORD to enter a terminal orbit

The asterisks in Figures DragForce.png and TimetoDecay.png correpond to CHORD's operational altitude.

# H Propellant Phase States and Thermal Energy Flow Calculations

Table 9: Maximum stable fuel temperatures for storage

| Fuel | Max Safe Temperature (K) | Pressure (kPa) | Source |
|---|---|---|---|
| "RP-1" | 316 | 101.325 | (Encyclopedia Astronautica) |
| Methane | 160 | 2300 | (Pressure Scaled to SF 1.5 for 3 inches of Aluminum) |
| Oxygen | 130 | 2300 | (Pressure Scaled to SF 1.5 for 3 inches of Aluminum) |
| Nitrogen Tetroxide | 295 | 101.325 | (Boiling Point) |
| Monomethylhydrazine | 364 | 101.325 | (Flash Point) |

$$Q_{in} = Q_{out} \tag{16}$$

$$Q_{ext} + Q_{int} = Q_{rad} \tag{17}$$

$$Q_{internal} + q_{ext} * A_{eff} = Q_{cryo} + Q_{peltier} \tag{18}$$

$$Q_{internal} \approx \text{Line Loss Power} = 176W \tag{19}$$

$$A_{eff} = 50.7m^2 \tag{20}$$

$$Q_{solar} = q_{ext} * A_{eff} \tag{21}$$

$$Q_{solar} * 93\% = P_{BOL} = 194W \tag{22}$$

$$Q_{solar} = 208.6W \tag{23}$$

$$Q_{in} = 176W + 208.6W = 384.6W \tag{24}$$

$$\tag{25}$$

$$Q_{cryo} = 42W@77K \tag{26}$$

$$Q_{peltiermax} = 172W \tag{27}$$

$$Q_{outmax} = 5 * Q_{peltiermax} + Q_{cryo} \tag{28}$$

$$Q_{outmax} \approx 806W \tag{29}$$

$$\tag{30}$$

# I Guidance, Navigation, Attitude Determination, and Control Component Tables and Trades

Table 10: Attitude actuator architecture trade study

| **Type** | **Pros** | **Cons** | **Selection** |
|---|---|---|---|
| Magnetorquers | No moving parts low volume and mass | High power draw for low torque can't actuate along Earth's field lines | |
| Reaction Wheels | High torque Easy control laws | High mass Complicated redundancy Require desaturation | |
| Control Moment Gyros | High torque Simple redundancy | Complex control laws Complecated mechanics | Primary |
| Reaction Control Thrusters | High torque Simple redundancy Simple control laws | Requires propellant | Secondary |

Table 11: Propulsion architecture trade study

| **Type** | **Pros** | **Cons** | **Selection** |
|---|---|---|---|
| Electric Propulsion | High $I_sp$ Easy reignition | Low thrust Low density propellant | |
| Keroscene + LOX | High thrust Moderate $I_sp$ | Hard reignition More propellant necessary Cryogenic storage required | |
| Hypergolics (MMH + NTO) | Moderate thrust Moderate $I_sp$ Storable propellants | Low density propellant Toxic propellants | Primary |

Table 12: Sensor selection trade table

| **Type** | **Sensitivity** | **Update Rate** | **Possible Option** | **Links** |
|---|---|---|---|---|
| IMU (gyro, accel, mag) | 0.35 deg RMS pitch/roll 1.0 deg RMS heading | 100 Hz | Microstrain 3DM-GX3-45 | Microstrain |
| Star trackers | 0.003 deg +/- deg | 30 Hz | Sodern Hydra Star Tracker | Sodern |
| Sun sensors | 0.1 +/- deg over 70 +/- deg view (2 axis) | 5 Hz | Sinclair SS-411 Two-Axis Digital Sun Sensors | Sinclair |
| GPS | 2.5 m +/- | 4 Hz | Microstrain 3DM-GX3-45 | Microstrain |
| Docking Sensor | position from 2000 to 0.5 m | unspec | Neptec TriDAR | Neptec |

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| | | | | |
|---|---|---|---|---|
| Camera (computer vis.) | position for near approach | 10 Hz | Malin Space Science Systems ECAM Imaging System | Malin |

Table 13: Actuator selection trade table

| **Type** | **Strength** | **Number** | **Possible Option** |
|---|---|---|---|
| Control Moment Gyro | 86 Nm | 4 arranged in a square for control redundancy | Scaled from Astrium CMG 15-45S |
| Reaction Control Rockets | 400 N | 5 banks of 4 thrusters for both attitude and position control | SpaceX Draco Rocket Engine |

# J Communications Tables

Table 14: Trade study of possible communication architectures

| Sub-System | Options | Pros | Cons |
|---|---|---|---|
| Docking Communications | No Communications | Cheapest option. | No control over satellite until next groundstation pass |
| | Network of Groundstations | Reduced latency | Complicated architecture of switching through groundstations. |
| | | Dual use of S-Band antennae | |
| | Relay Satellites | High-data rate | Expensive |
| | | Constellation of Relay satellites | |
| | | Per need basis | |
| | | Simplified Architecture | |
| Cartridge Communications | No Communications | Cheapest option | High-risk operation |
| | S-Band Link | Dual use of S-Band antenna | Increased power consumption in cartridge |
| | | Can augment Tridar system | |
| | | Small antennae Footprint | |
| Ground Communications | VHF/UHF | Commercially available radios | Low Data rate (exceeds our requirements though) |
| | | Cheap GroundStation | |
| | S-Band | High Data rate | More power consumption |

Table 15: Operational link budget over UHF antennas

| Item | Symbol | Value | Source |
|---|---|---|---|
| Transmitter Output | TO | <6W | COTS Specs |
| Transmit Power | P | <7.78 dB | COTS Specs |
| Transmit Frequency | f | 450 MHz/ 144 MHz | UHF Band/VHF Band Full-Duplex Operation |
| Transmitter to Antennae Line Loss | Ll | -0.5 dB | Typical Value (Ref SMAD) |
| Transmit Antennae Gain | Gt | 1.7 dB | Typical of Dipole Antennae |
| Space Loss | Ls | -138 dB | Computed (Ref Appendix) |
| Atmospheric Path Loss (at Horizon) | La | -33 dB | Computed Worst Case Scenario (Ref Appendix K) |

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| | | | |
|---|---|---|---|
| Receive Antenna Gain | Gr | 18.9 dB | Ground Station Hardware used at Michigan |
| Received Power | C | -111 dB | Computed (Ref. Appendix K) |
| Receiver Sensitivity | | -120 dB | Ground Station Hardware used at Michigan |
| Link Margin | M | 9 dB | Computed |
| Data Rate | R | 9600 baud | Amateur Radio Specifications |
| Data Modulation | | GMSK | Amateur Radio Specifications |
| System Noise | Ts | 614 K | Typical Value (Ref SMAD) |
| **Received Energy-per-bit to Noise-density** | **Eb/R** | **17 dB** | **Computed (Ref. Appendix K). Assuming Worst Case Scenario** |

Table 16: Operational link budget with cartridges over S-Band

| **Item** | **Symbol** | **Value** | **Source** |
|---|---|---|---|
| Transmitter Output | TO | <10 W | COTS Transmitter Specs |
| Transmit Power | P | <10 dB | COTS Transmitter Specs |
| Transmit Frequency | f | 2250 MHz+/- 50 MHz | Based on TDRS Antenna Specifications |
| Transmitter to Antennae Line Loss | Ll | -0.5 dB | Typical Value (ref. SMAD) |
| Transmit Antennae Gain | Gt | 10 dB | COTS Patch Antenna |
| Space Loss | Ls | -124 dB | Computed at 10 km (Ref Appendix K) |
| Atmospheric Path Loss (at Horizon) | La | 0 db | No atmosphere |
| Receive Antenna Gain | Gr | 10 dB | COTS Patch Antenna |
| Received Power | C | -94 dB | Computed (Ref. Appendix K) |
| Receiver Sensitivity | | -115 dB | COTS Reciever Specs |
| Link Margin | M | 21 dB | Computed |
| Data Rate | R | 1200 BPS | Based on TDRS Specifications |
| Data Modulation | | BPSK | Based on TDRS Specifications |
| System Noise | Ts | 614 K | Typical Value (ref. SMAD) |
| **Received Energy-per-bit to Noise-density** | **Eb/R** | **87 dB** | **Computed (Ref. Appendix K)** |

Table 17: Operational link budget with relay satellites over S-Band

| **Item** | **Symbol** | **Value** | **Source** |
|---|---|---|---|
| Transmitter Output | TO | <10W | COTS Transmitter Specs |
| Transmit Power | P | <10 dB | COTS Transmitter Specs |
| Transmit Frequency | f | 2250 MHz+/- 50 MHz | TDRS Antenna Specifications |
| Transmitter to Antennae Line Loss | Ll | -0.5 dB | Typical Value (ref. SMAD) |
| Transmit Antennae Gain | Gt | 10 dB | COTS Patch Antenna |
| Space Loss | Ls | -180 dB | Computed (Ref Appendix K) |
| Atmospheric Path Loss (at Horizon) | La | 0 db | No atmosphere |

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| | | | |
|---|---|---|---|
| Receive Antenna Gain | Gr | 36.8 dB | TDRS Antenna Specifications |
| Received Power | C | -123.7 dB | Computed (Ref. Appendix K) |
| Receiver Sensitivity | | -131 dB | TDRS Specifications |
| Link Margin | M | 8 dB | Computed |
| Data Rate | R | 100 BPS to 100 kBPS | TDRS Specifications |
| Data Modulation | | BPSK | TDRS Specifications |
| System Noise | Ts | 614 K | Typical Value (ref. SMAD) |
| **Received Energy-per-bit to Noise-density** | **Eb/R** | **37 dB** | **Computed (Ref. Appendix K) Assuming 1.2 kBPS** |

# K Link Equations

$$P = 20\log_{10}(6\ W) \tag{31}$$

$$T_s = T_a + \frac{T_0(1 - L_r)}{L_r} + \frac{T_r}{L_r} \tag{32}$$

$$T_s = 150\ K + 36\ K + 33\ K = 219\ K \tag{33}$$

$$L_s = (\frac{c}{4\pi S f})^2 \tag{34}$$

$$S = 2\pi(r_e + h) \tag{35}$$

$$L_a = 20\log_{10}(4\pi\frac{H}{f}) = atmospheric\ path\ loss \tag{36}$$

$$H = \sqrt{r_e^2 + (r_e + h)^2 - 2r_e(r_e + h)\cos(a)} = slant\ range \tag{37}$$

$$\alpha = \frac{\pi}{2} - \theta - \arcsin(r_e\frac{\cos(\theta)}{r_e + h}) = relative\ observed\ angle \tag{38}$$

$$\theta = \arccos(-\frac{\rho\sqrt{\mu}}{\frac{3}{2}J_2}a^{\frac{7}{2}}) = required\ inclination\ for\ Sun\ Synchronous\ Orbit \tag{39}$$

$$\frac{E_b}{N_0}[dB] = P + L_l + G_t + L_s + L_a + G_r - k - T_s - R\ [all\ dB] \tag{40}$$

# L Power Budgets

Table 18: Energy Budget Summary

| | **Nominal Orbit** | | **Emergency Ops** | | **Peak Power Orbit** | |
|---|---|---|---|---|---|---|
| **System** | **Seconds** | **Duty Cycle** | **Seconds** | **Duty Cycle** | **Seconds** | **Duty Cycle** |
| **Cartridge (5 max)** | | | | | | |
| Pressure/Temperature Control | 5544 | 1 | 5544 | 1 | 5544 | 1 |
| Docking System | 1109 | 0.2 | 5544 | 1 | 5544 | 1 |
| **ADCS** | | | | | | |
| Control Moment Gyros | 3881 | 0.7 | 111 | 0.02 | 5544 | 1 |
| Control Board | 5544 | 1 | 5544 | 1 | 5544 | 1 |
| Basic Sensors (magnetometer, accelerometer, gyroscope) | 5544 | 1 | 111 | 0.02 | 5544 | 1 |
| Laser Range Finder | 0 | 0 | 0 | 0 | 5544 | 1 |
| Camera | 0 | 0 | 0 | 0 | 5544 | 1 |
| **CDH** | | | | | | |
| Boards | 5544 | 1 | 5544 | 1 | 5544 | 1 |
| **EPS** | | | | | | |
| Power Board | 5544 | 1 | 5544 | 1 | 5544 | 1 |
| **COM** | | | | | | |
| Transmitter Power | 222 | 0.04 | 0 | 0 | 444 | 0.08 |
| **MISC** | | | | | | |
| Purge System | 0 | 0 | 277 | 0.05 | 0 | 0 |
| **Line Losses** | | | | | | |
| **0.1** | 5544 | 1 | 5544 | 1 | 5544 | 1 |
| **Energy Consumption** | **Nominal Orbit Energy** | | **Emergency Ops Energy** | | **Peak Power Orbit Energy** | |
| **Cartridge (5 max)** | | | | | | |
| Pressure/Temperature Control | 5544000 | Joules | 2217600 | Joules | 11088000 | Joules |
| Docking System | 13860 | Joules | 277200 | Joules | 66528 | Joules |
| **ADCS** | | | | | | |
| Control Moment Gyros | 3911846.4 | Joules | 111767.04 | Joules | 5588352 | Joules |
| Control Board | 27720 | Joules | 27720 | Joules | 27720 | Joules |
| Basic Sensors (magnetometer, accelerometer, gyroscope) | 49896 | Joules | 997.92 | Joules | 49896 | Joules |
| Laser Range Finder | 0 | Joules | 0 | Joules | 27720 | Joules |
| Camera | 0 | Joules | 0 | Joules | 36590.4 | Joules |
| **CDH** | | | | | | |
| Boards | 166320 | Joules | 166320 | Joules | 166320 | Joules |
| **EPS** | | | | | | |
| Power Board | 27720 | Joules | 27720 | Joules | 27720 | Joules |
| **COM** | | | | | | |
| Transmitter Power | 1330.56 | Joules | 0 | Joules | 2661.12 | Joules |
| **MISC** | | | | | | |
| Purge System | 0 | Joules | 2772 | Joules | 0 | Joules |
| **Line Losses** | | | | | | |
| **0.1** | 974269 | Joules | 283210 | Joules | 1708151 | Joules |
| Orbit energy consumed | 10716962 J | | 3115307 J | | 18789658 J | |
| Orbit energy generated | 15514884 J | | 15514884 J | | 15514884 J | |
| Net energy | 4797922 J | | 12399577 J | | -3274774 J | |

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| | | | |
|---|---|---|---|
| **Net battery capacity (daylight)** | **0.811** | **1.219** | **0.379** |
| **Discharge Max** | **0.383** | **0.111** | **0.671** |
| **Net battery capacity (per orbit)** | **0.428** | **1.107** | **-0.292** |

Table 19: Battery Budget Summary

| | **Unit Energy Supplied (J)** | **Units** | **Energy Supplied (J)** | **Volume ($m^3$)** | **Mass (kg)** | |
|---|---|---|---|---|---|---|
| **Nominal** | 933120 | 12 | 11197440 | 0.00948 | 21.84 | (based on Quallion Matrix QL075KA) |
| **P/T Backup** | 933120 | 2 | 1866240 | 0.00158 | 3.64 | (based on Quallion Matrix QL075KA) |
| **Purge** | 194400 | 1 | 194400 | 0.000182 | 0.36 | (based on Quallion Matrix QL015KA) |
| **ADCS/ COMM Backup** | 933120 | 1 | 933120 | 0.00079 | 1.82 | (based on Quallion Matrix QL075KA) |

Table 20: Battery trade study

| **Brand** | **Type** | **Capacity (A*hr)** | **Voltage (V)** | **Volume (cm$\hat{3}$)** | **Energy Density (W*hr/kg)** | **Mass (kg)** |
|---|---|---|---|---|---|---|
| **Quallion** | **QL015KA** | 15 | 3.6 | 182 | 150 | 0.36 |
| | **QL075KA** | 72 | 3.6 | 790 | 142 | 1.82 |
| **Saft** | **VES 100** | 27 | 3.6 | 408 | 118 | 0.81 |
| | **VES 140** | 39 | 3.6 | 552 | 126 | 1.13 |
| | **VES 180** | 50 | 3.6 | 552 | 175 | 1.11 |

The primary criteria for choosing a battery for our mission is high battery capacity since CHORD draws a large amount of energy during a highly active docking orbit. In addition, the battery should have a high energy density above 130 $W*hr/kg$ so that a relatively small battery mass can provide for the large energy requirements of CHORD. The Quallion QL075KA has the highest capacity and meets the set energy density requirements. The Saft VES 180 is the next best with the second highest capacity and the highest energy density.

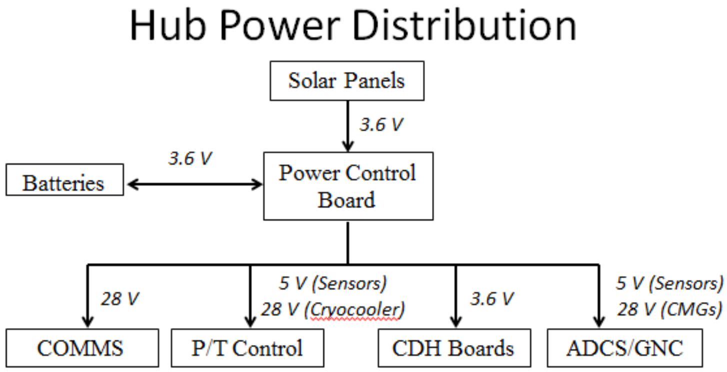

Figure 28: Hub power distribution

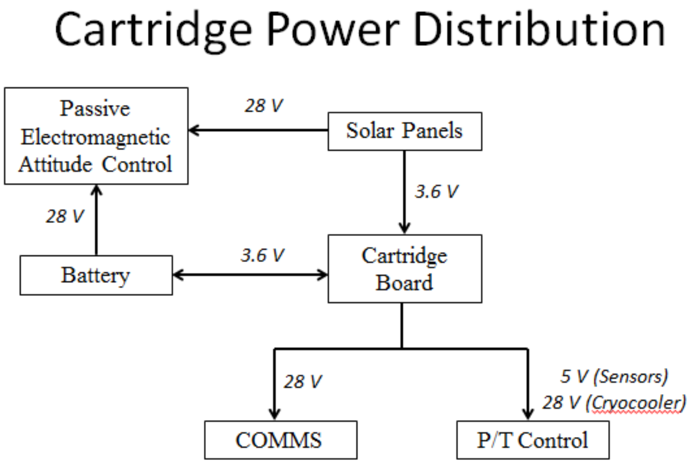

Figure 29: Cartridge power distribution

# M Solar Array Calculation Formulae

$$P_{sa} = P_d * \frac{T_d}{X_d} + \frac{P_e * \frac{T_e}{X_e}}{T_d} \tag{41}$$

$$P_{BOL} = I_d * P_{sa} \tag{42}$$

$$L_d = (1 - degradation/yr)^{satellitelife} \tag{43}$$

$$P_{EOL} = P_{BOL} * L_d \tag{44}$$

$$A_{sa} = \frac{P_s a}{P_{EOL}} \tag{45}$$

$$\tag{46}$$

$P_{sa}$ (power provided by solar array in daylight)
$X_d = 0.8$ (path efficiency of peak-power tracking in daylight)
$X_e = 0.6$ (path efficiency of peak-power tracking in eclipse)
$T_d$ (time of orbit spent in daylight)
$T_e$ (time of orbit spent in eclipse)
$I_d = 0.77$ (solar array incidence efficiency)
$P_{BOL}$ (beginning of life power)
$P_{EOL}$ (end of life power)
$A_{sa}$ (solar array area)

# N Data Budgets

Table 21: Operational data budget over UHF antennas

| **Sub-System** | **Sub-Sub Component** | **Units** | **Storage size (bits/unit)** | **Recording Frequency (Hz)** | **Data Rate (bytes/s)** | **Total Size (Bytes)** |
|---|---|---|---|---|---|---|
| *EPS* | Total Available Power | 1 | 8 | 0.1 | 0.1 | 1 |
| | Total Generated Solar Panel Power | 1 | 8 | 0.1 | 0.1 | 1 |
| | Power Consumption | 2 | 16 | 0.1 | 0.4 | 4 |
| | Battery Temperatures | 2 | 16 | 0.1 | 0.4 | 4 |
| | | | | | | 0 |
| *FCPU* | Time | 1 | 32 | 0.1 | 0.4 | 4 |
| | No. of Resets | 1 | 8 | 0.1 | 0.1 | 1 |
| | No. of Upsets | 1 | 8 | 0.1 | 0.1 | 1 |
| | Free Memory | 1 | 32 | 0.1 | 0.4 | 4 |
| | Memory in Use | 1 | 32 | 0.1 | 0.4 | 4 |
| | Total no of Tasks | 1 | 16 | 0.1 | 0.2 | 2 |
| | Uptime | 1 | 32 | 0.1 | 0.4 | 4 |
| | | | | | 0 | 0 |
| *Payload* | Nominal | 6 | 1 | 0.1 | 0.075 | 0.75 |
| | Content | 6 | 4 | 0.1 | 0.3 | 3 |
| | Powered | 6 | 1 | 0.1 | 0.075 | 0.75 |
| | | | | | | 0 |
| *Structures* | Temperature | 2 | 16 | 0.1 | 0.4 | 4 |
| | Measured MOI | 1 | 16 | 0.1 | 0.2 | 2 |
| | | | | | | 0 |
| *ADCS* | Operational 'Mode' | 1 | 4 | 0.1 | 0.05 | 0.5 |
| | Pointing Angle | 3 | 8 | 0.1 | 0.3 | 3 |
| | Gyrating Rate | 3 | 8 | 0.1 | 0.3 | 3 |
| | Coordinates | 3 | 8 | 0.1 | 0.3 | 3 |
| | Magnetometers | 1 | 16 | 0.1 | 0.2 | 2 |
| | Wheel Status | 4 | 16 | 0.1 | 0.8 | 8 |
| | Thrusters | 24 | 8 | 0.1 | 2.4 | 24 |
| | | | | | | 0 |
| *C&DH* | Last Command Index Received | 1 | 32 | 0.1 | 0.4 | 4 |
| | Point of Interest / Health Checks | 1 | 16 | 0.1 | 0.2 | 2 |
| | Subsystems on/off | 1 | 8 | 0.1 | 0.1 | 1 |
| | Operational 'Mode' | 1 | 1 | 0.1 | 0.0125 | 0.125 |
| | Payload data | 6 | 8 | 0.1 | 0.6 | 6 |
| | | | | | | 0 |
| *COM* | UHF Total Rx | 1 | 32 | 0.1 | 0.4 | 4 |
| | UHF Total Tx | 1 | 32 | 0.1 | 0.4 | 4 |
| | S-Band Total Rx | 5 | 32 | 0.1 | 2 | 20 |
| | S-Band Total Tx | 5 | 32 | 0.1 | 2 | 20 |
| | RSSI | 2 | 8 | 0.1 | 0.2 | 2 |
| | Amplifier Temperature | 2 | 16 | 0.1 | 0.4 | 4 |
| ***Total*** | | | | | 15.1125 | 151.125 |

Table 22: Operational data budget with cartridges over S-Band

| **Sub-System** | **Sub-Sub Component** | **Units** | **Storage size (bits/unit)** | **Recording Frequency (Hz)** | **Data Rate (bytes/s)** | **Total Size (bytes)** |
|---|---|---|---|---|---|---|
| *Cartridge* | Ping ID | 1 | 16 | 0.5 | 1 | 2 |
| | Cartridge Status | 1 | 8 | 0.5 | 0.5 | 1 |
| | Power Status | 1 | 8 | 0.5 | 0.5 | 1 |
| | Fuel Status | 1 | 8 | 0.5 | 0.5 | 1 |
| | Magnetorquer Status | 1 | 8 | 0.5 | 0.5 | 1 |
| | Valve State | 1 | 8 | 0.5 | 0.5 | 1 |
| ***Total*** | | | | | **3.5** | **7** |

Table 23: Operational data budget with relay satellites over S-Band

| **Sub-System** | **Sub-Sub Component** | **Units** | **Storage size (bits/unit)** | **Recording Frequency (Hz)** | **Data Rate (bytes/s)** |
|---|---|---|---|---|---|
| *EPS* | Total Available Power | 1 | 8 | 1 | 1 |
| | Total Generated Solar Panel Power | 1 | 8 | 1 | 1 |
| | Power Consumption | 25 | 16 | 1 | 50 |
| | Battery Temperatures | 25 | 16 | 1 | 50 |
| *FCPU* | Time | 1 | 32 | 1 | 4 |
| | No. of Resets | 1 | 8 | 1 | 1 |
| | No. of Upsets | 1 | 8 | 1 | 1 |
| | Free Memory | 1 | 32 | 1 | 4 |
| | Memory in Use | 1 | 32 | 1 | 4 |
| | Total no of Tasks | 1 | 16 | 1 | 2 |
| | Uptime | 1 | 32 | 1 | 4 |
| | | | | 1 | 0 |
| *Payload* | Nominal | 6 | 1 | 1 | 0.75 |
| | Content | 6 | 4 | 1 | 3 |
| | Powered | 6 | 1 | 1 | 0.75 |
| | Ping Count | 2 | 16 | 1 | 4 |
| | TriDar Status | 5 | 32 | 1 | 20 |
| | | | | 1 | 0 |
| *Structures* | Temperature | 25 | 16 | 1 | 50 |
| | Docking | 0 | 0 | 1 | 0 |
| | Measured MOI | 1 | 16 | 1 | 2 |
| *ADCS* | Operational 'Mode' | 1 | 4 | 1 | 0.5 |
| | Pointing Angle | 3 | 16 | 1 | 6 |
| | Gyrating Rate | 3 | 16 | 1 | 6 |
| | Coordinates | 3 | 16 | 1 | 6 |
| | Magnetometers | 1 | 16 | 1 | 2 |

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| | | | | | |
|---|---|---|---|---|---|
| | Wheel Status | 4 | 16 | 1 | 8 |
| | Thrusters | 24 | 64 | 1 | 192 |
| *C&DH* | Last Command Index Received | 1 | 32 | 1 | 4 |
| | Point of Interest / Health Checks | 1 | 16 | 1 | 2 |
| | Subsystems on/off | 1 | 8 | 1 | 1 |
| | Operational 'Mode' | 1 | 1 | 1 | 0.125 |
| | Payload data | 6 | 8 | 1 | 6 |
| *COM* | UHF Total Rx | 1 | 32 | 1 | 4 |
| | UHF Total Tx | 1 | 32 | 1 | 4 |
| | S-Band Total Rx | 5 | 32 | 1 | 20 |
| | S-Band Total Tx | 5 | 32 | 1 | 20 |
| | RSSI | 2 | 8 | 1 | 2 |
| | Amplifier Temperature | 2 | 16 | 1 | 4 |
| *Docking* | Distance | 3 | 16 | 1 | 6 |
| | Target Lock | 1 | 128 | 1 | 16 |
| | Status | 1 | 4 | 1 | 0.5 |
| ***Total*** | | | | | 512.625 |