Commercial Heavy-lift Orbital Refueling Depots (CHORD)

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Aerospace 483 Final Presentation

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Motivation

- Modern deep space mission architecture relies on staging large rockets to launch small payloads
  - "Russian Nested Doll Architecture"
  - Risk of failure is compounded serially
- It is impractical to use this architecture for large, manned interplanetary missions
- >2/3 of deep space missions are propellant by mass
  - Can the bulk of cargo be handled by a service...?

Our Mission, Should We Choose To Accept…

- CHORD - Low Earth Orbit Refueling Depot
  - Modular fuel cartridges
  - Multiple fuel types
  - Safe and reliable refueling for deep space missions
- Reliable Refills – Commercial Venture
  - Develop the CHORD mission to expand private space sector
  - Create infrastructure for future large-scale missions
  - Profit

RELIABLE REFILLS

Objectives and Design Drivers

- Objectives
  - Enable more deep space missions with economically sustainable orbital refueling
  - Create a profitable business
  - Establish infrastructure to support Martian colonization
  - (Secondary science, national inspiration)
- Design drivers
  - Economic feasibility
  - Precision pointing and rendezvous maneuvers
  - Cryogenic fuel storage and transfer

Business Plan

- Customer Base
- Cost and Funding Brea[illegible]

SEGMENT	CO[illegible]
PHASE I – *Customer Research & Produc[illegible] Development (Year 1-4)*	[illegible]
PHASE II – *Technology Demo & [illegible] Outreach (Year 5-17)*	[illegible]
PHASE III – *Venture Capital & [illegible] (Year 18-25)*	[illegible]
TOTAL	**$553,815,000**

Economics of Dev. And Ops.

- Sample Mission

	Falcon Heavy	Falcon 9 v1.1 w/Refuels
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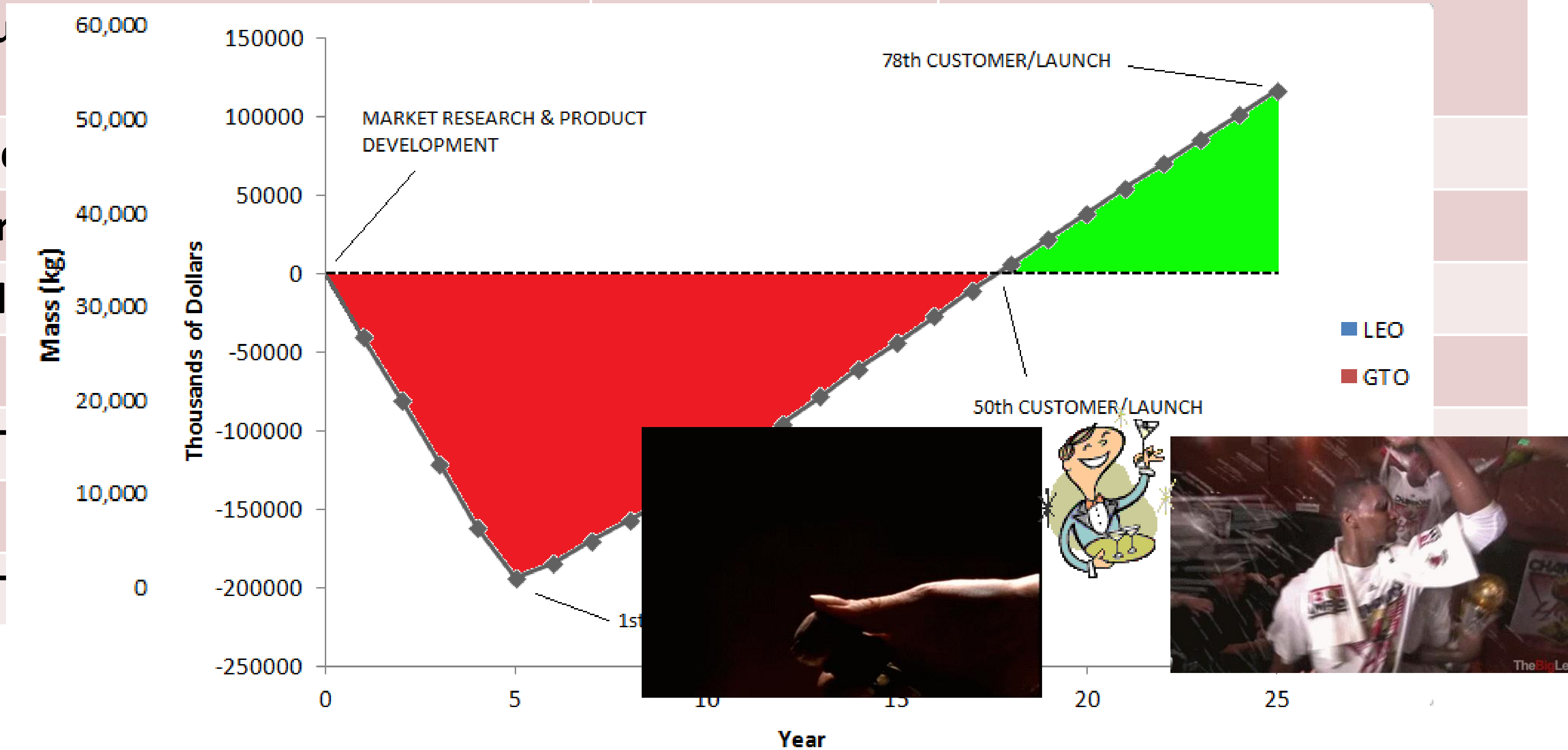
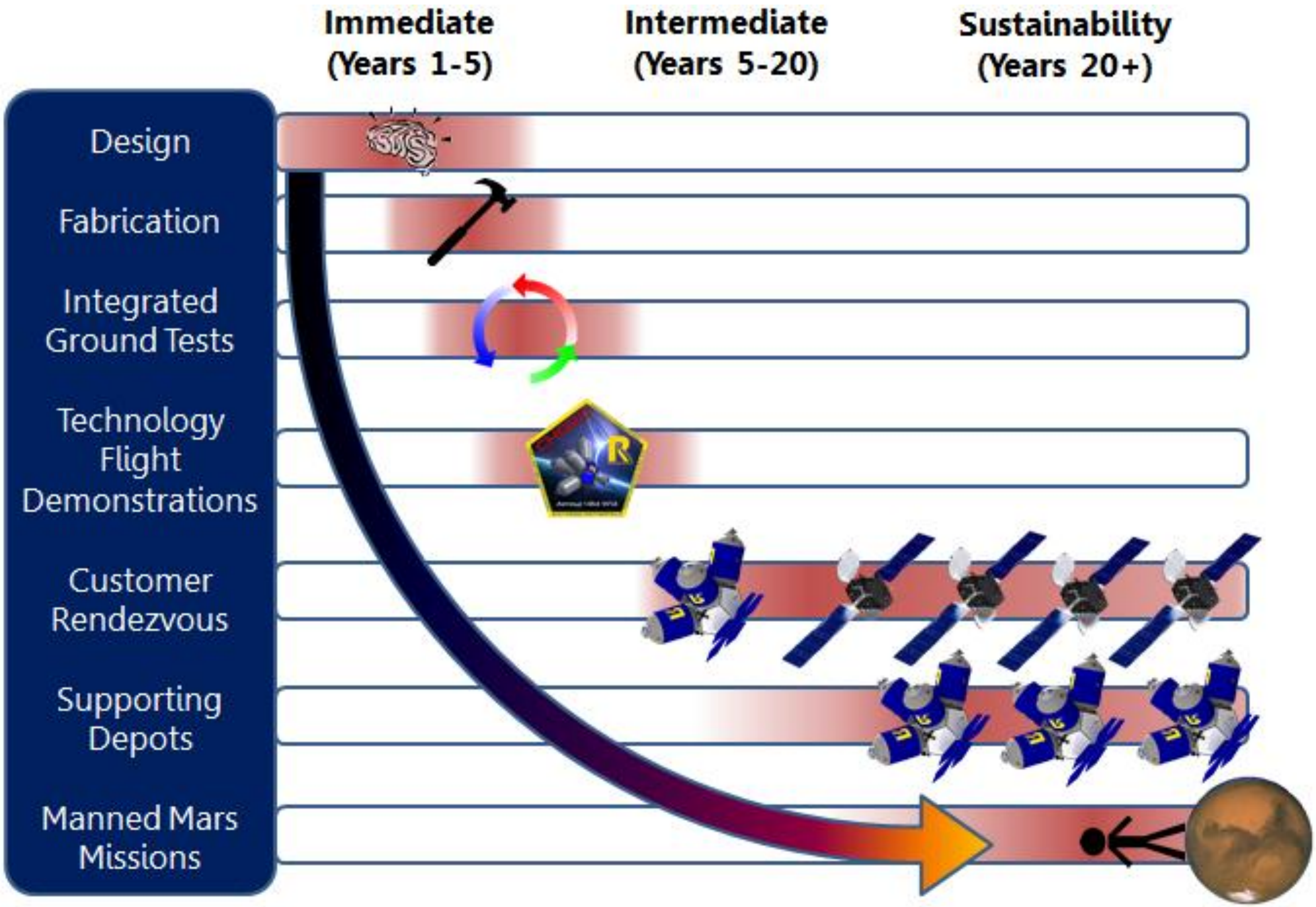
Ad		
Car		
Rel		
TOT		
TOT		



Dev. and Ops. Schedule



System and Mission Requirements

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

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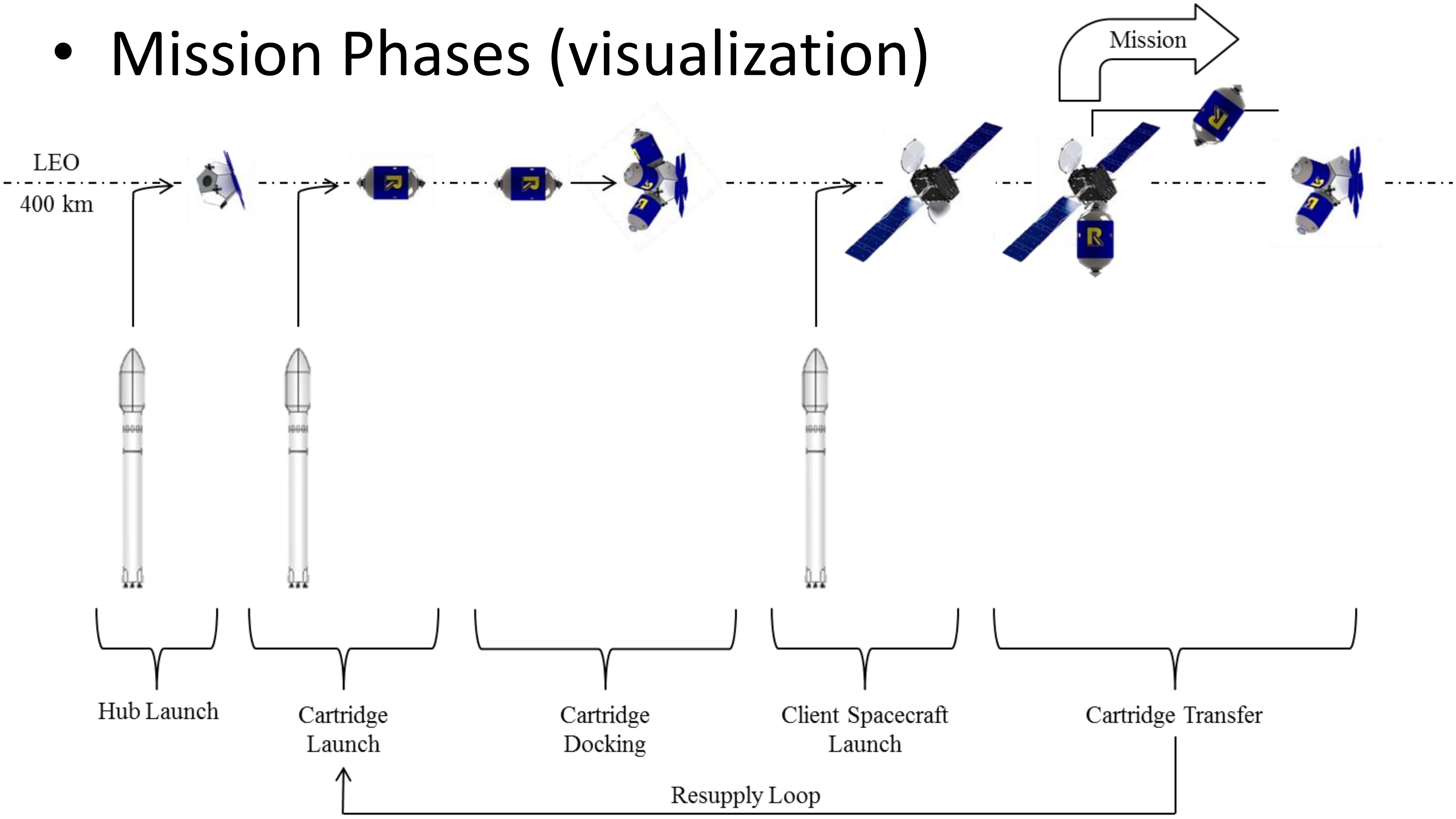
SYS-22

Concept of Operations

- Mission Phases
  1. Hub Launch
  2. Cartridge Launch(es)
  3. Cartridge Docking
  4. Client Launch
  5. Cartridge Transfer
- Long-term Options for Multiplicity
  - Phasing
  - Alternative orbits

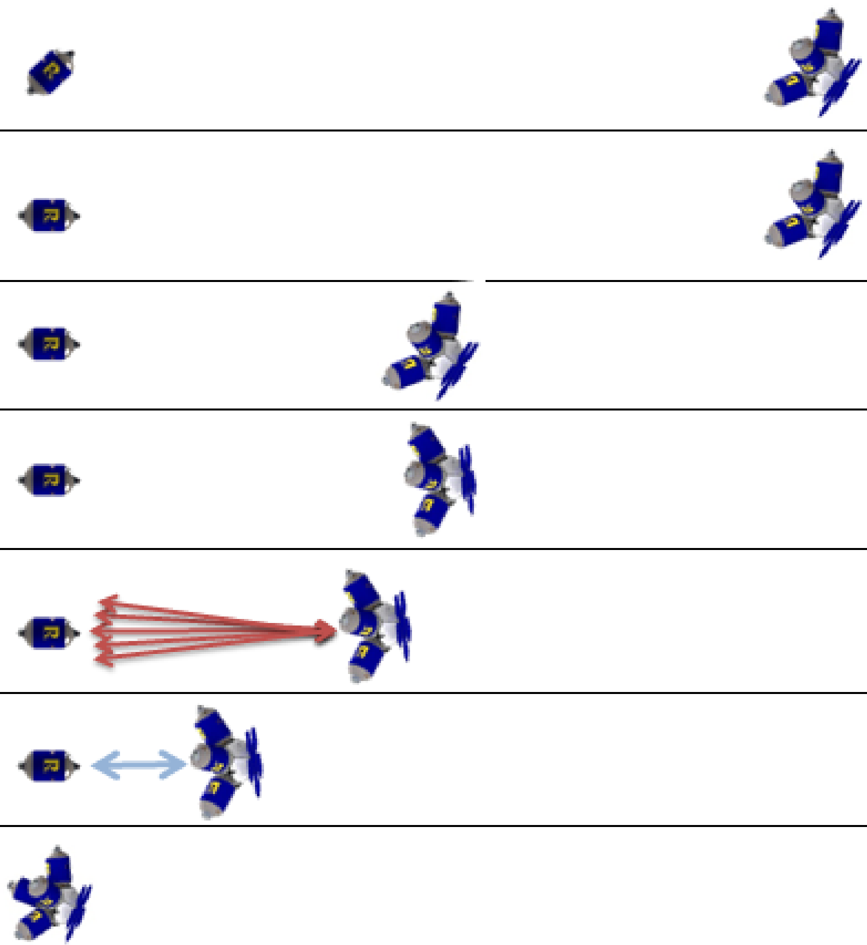
Concept of Operations

- Mission Phases (visualization)



Concept of Operations

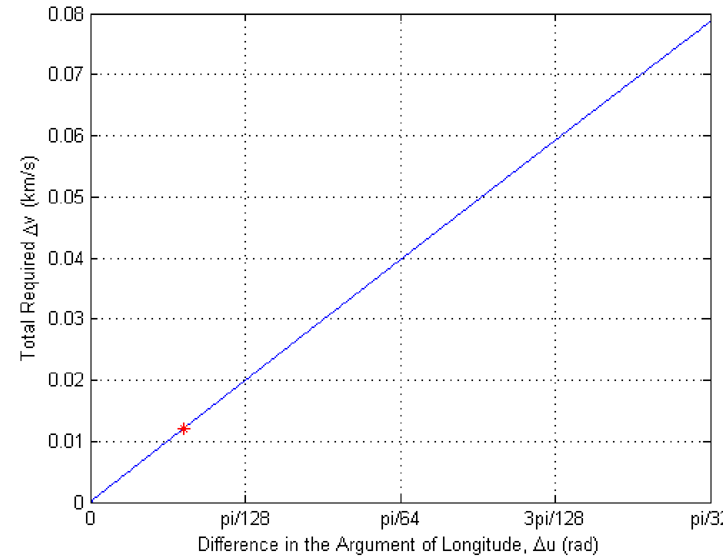
- Docking Process Flow

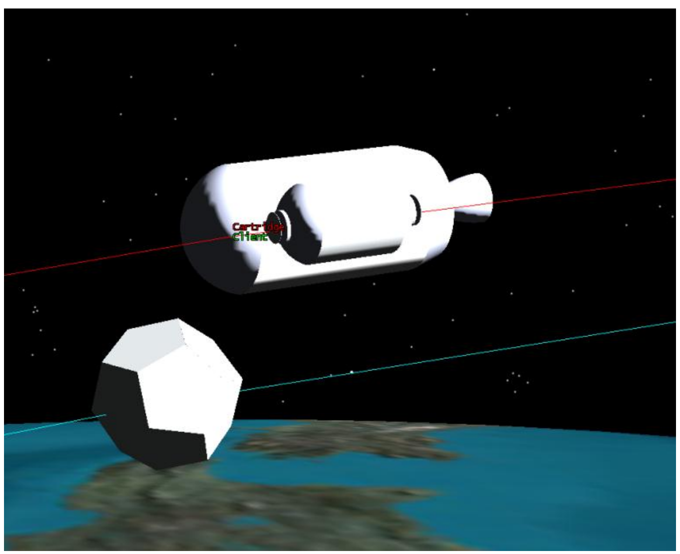


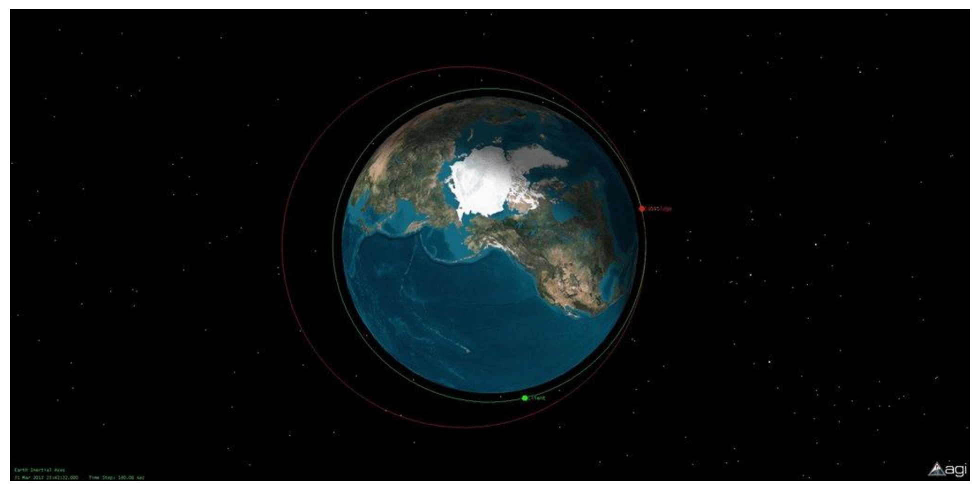
1. Fuel module enters 100 km exclusion area; CHORD matches relative velocity
2. Module is magnetically stabilized to a fixed orientation
3. CHORD performs rendezvous phasing maneuver to approach module
4. CHORD is oriented for docking with module
5. TriDAR rendezvous navigation system activated during initial approach to module
6. Vision-based navigation used for final positioning before securing dock
7. CHORD docks with fuel module, establishes and verifies connectivity

Orbit

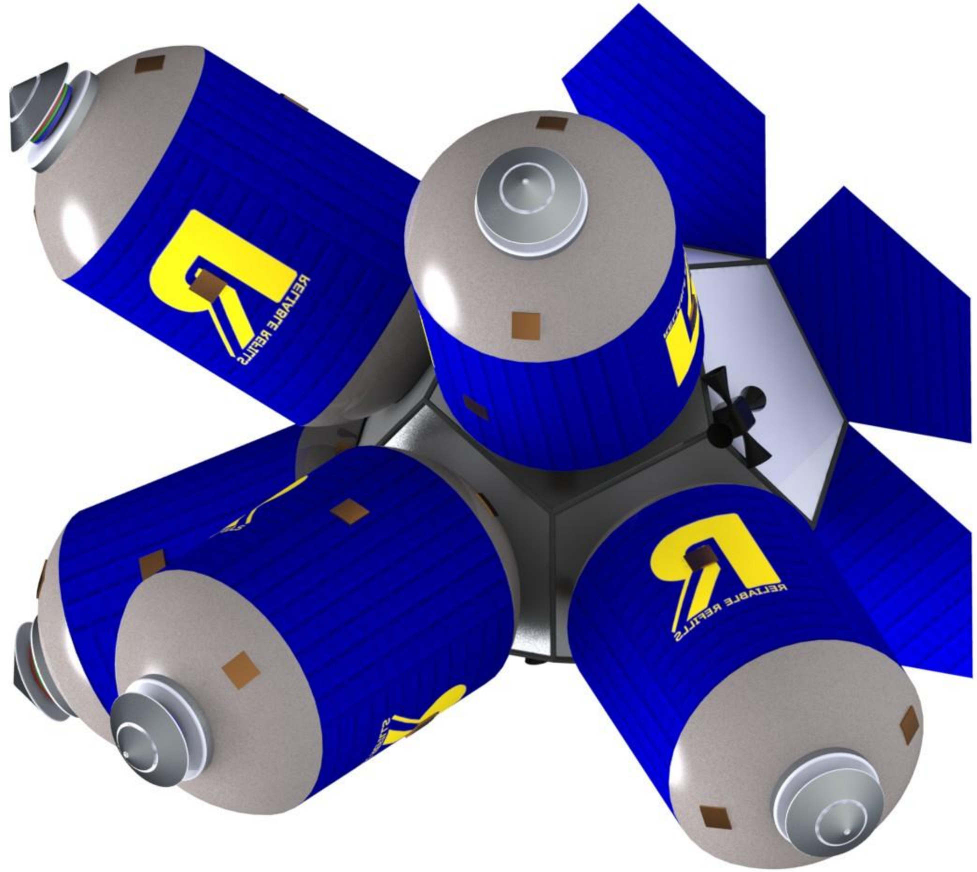
Item	Symbol	Value
Altitude	a	413 km
Repeat Cycle	-	≅ 3 days
Inclination Angle	i	28.5 deg
Velocity	$\|v\|$	7.66 km/s
Rendezvous Delta-v Expenditure	$\|\Delta v_{total}\|$	≅ 0.02 km/s
Period	T_{cir}	92.8 min
Revolutions per Sidereal Day	f_{cir}	15.5



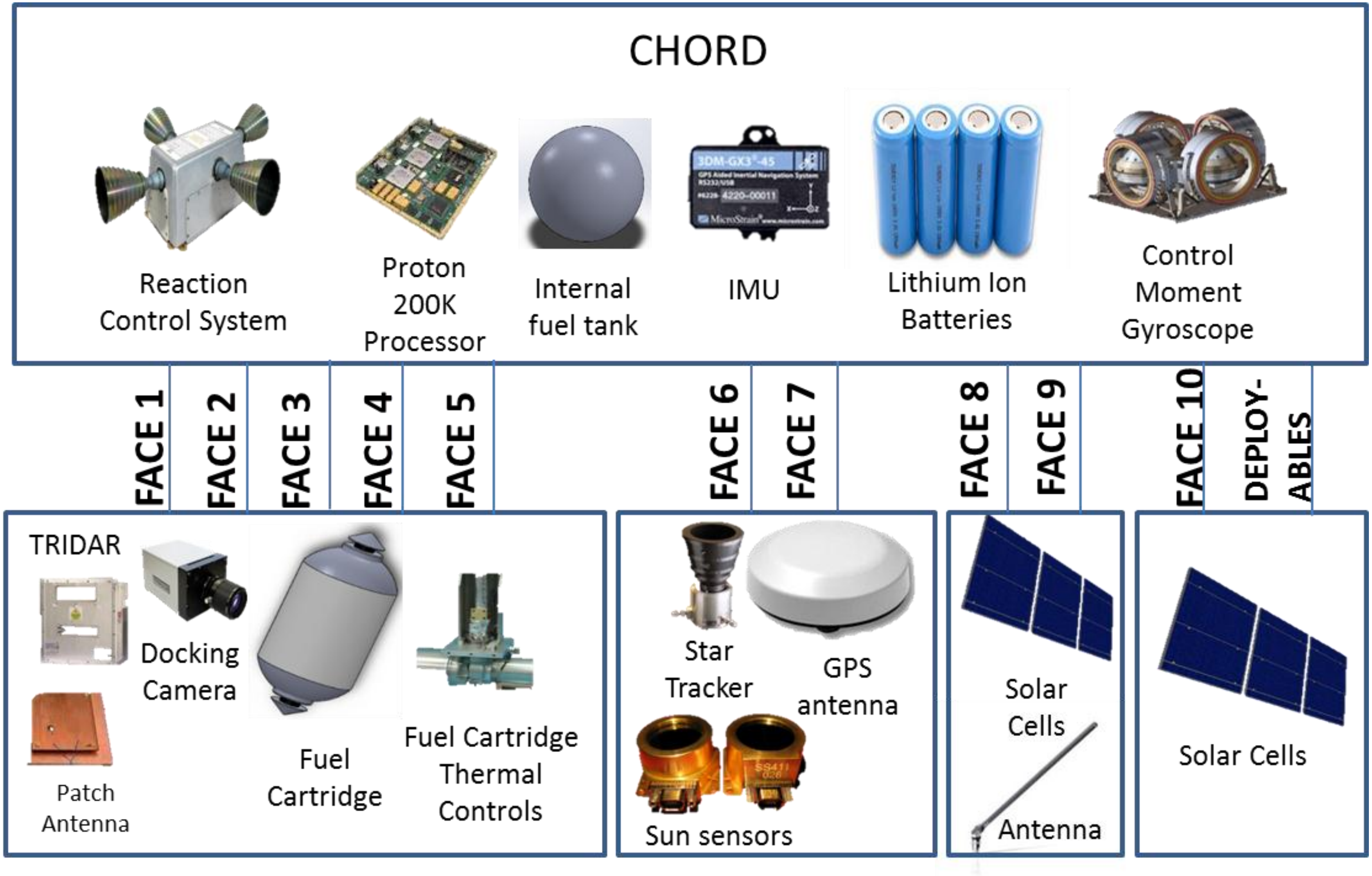




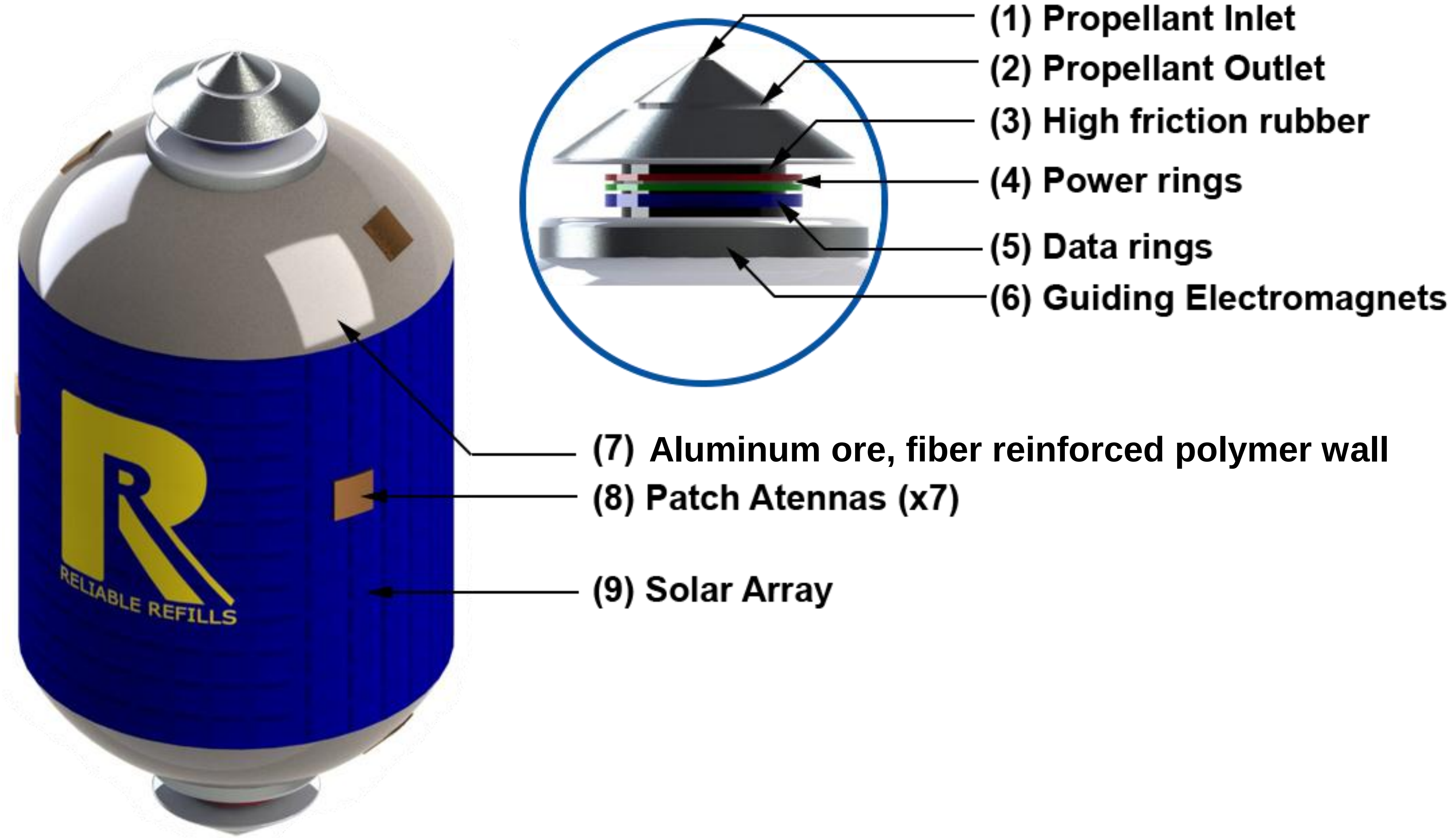
CHORD



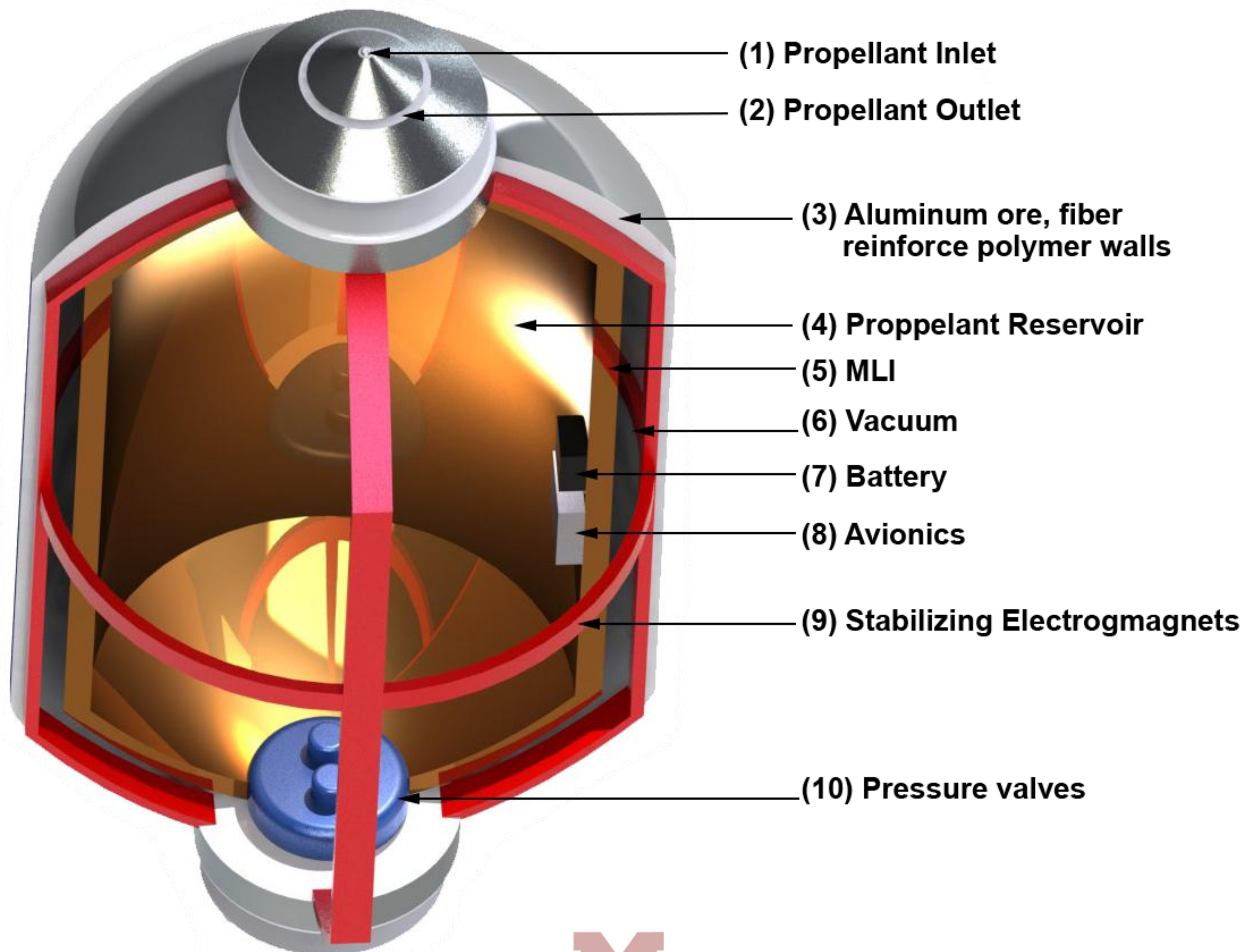
Subsystem Architecture



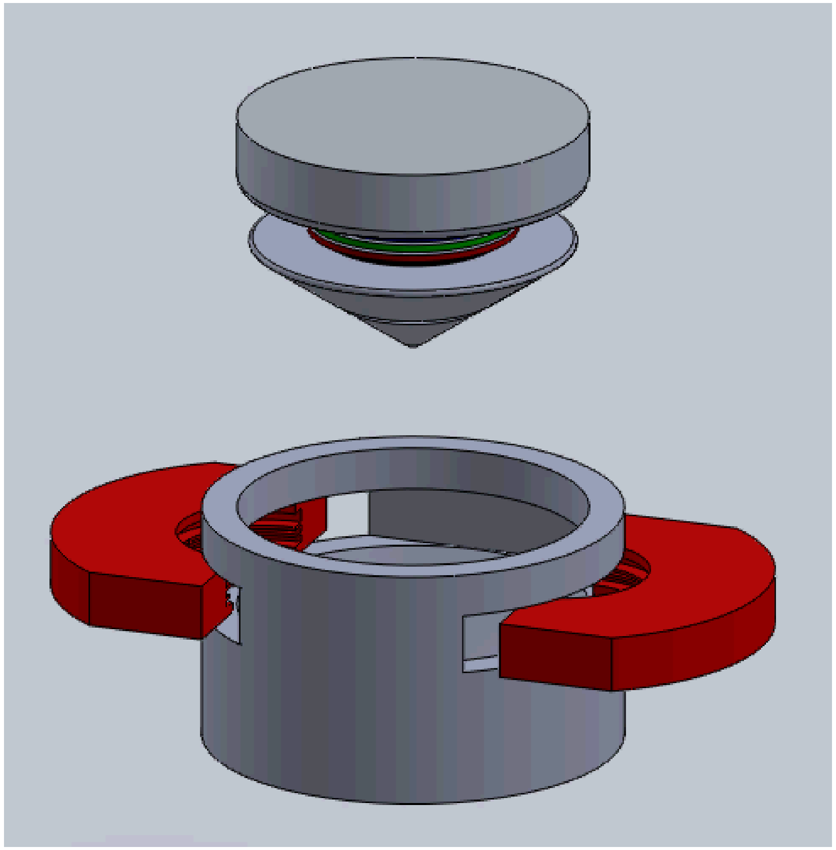
Cartridge Configuration



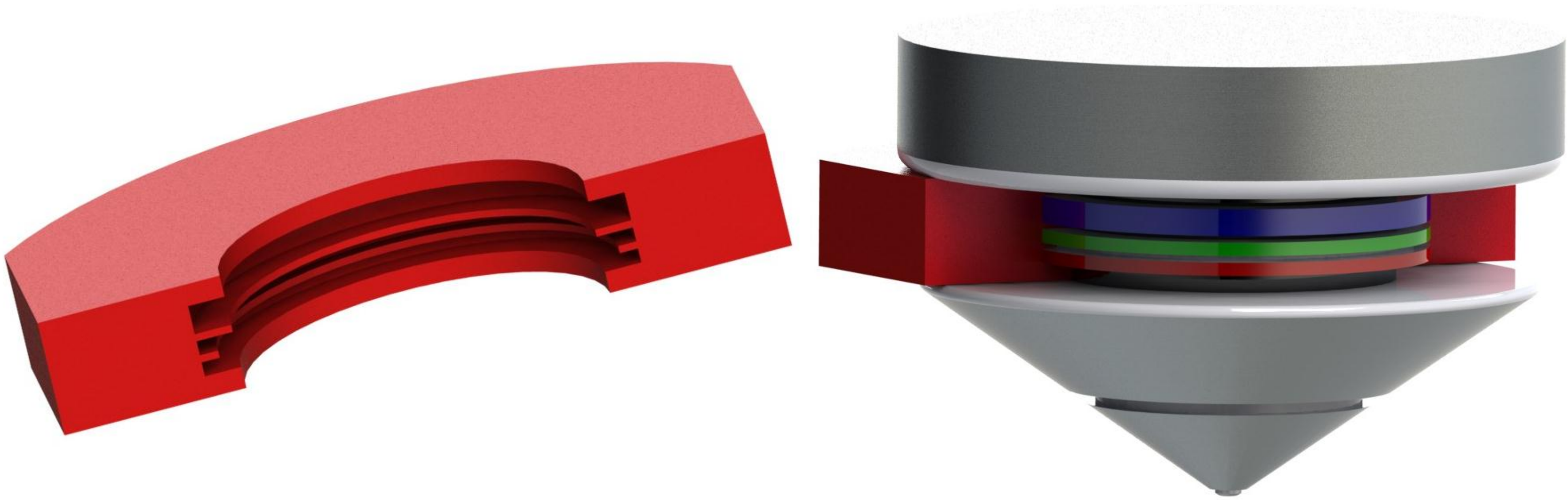
Cartridge Configuration



Docking & Latching Mechanism



Docking & Latching Mechanism



Structural Requirements

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

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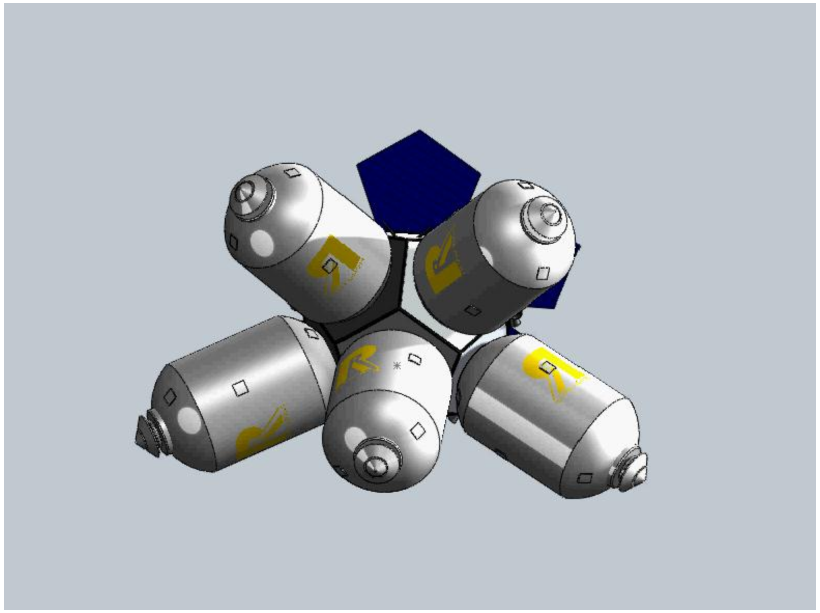
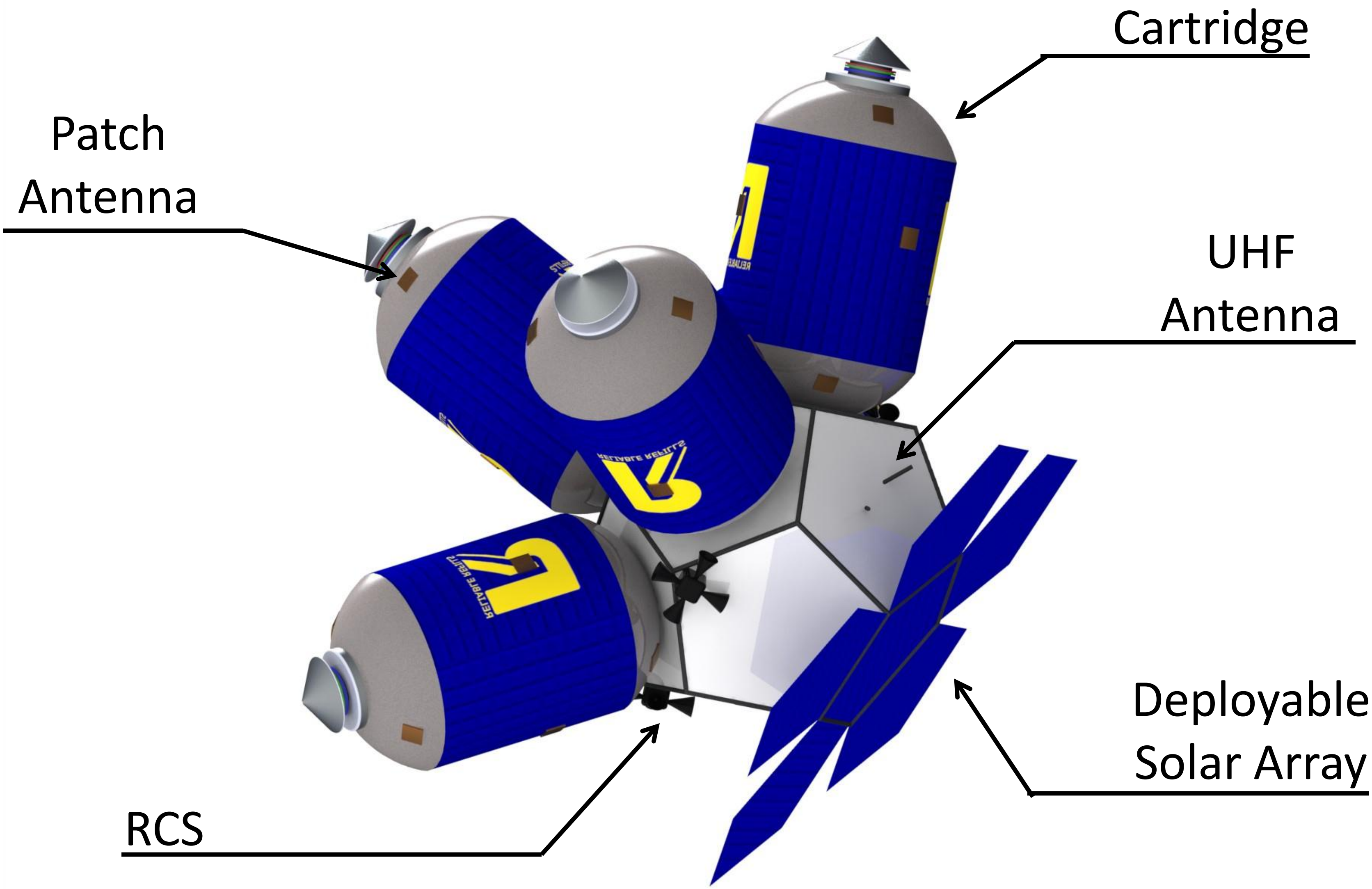
STR-12

Structures

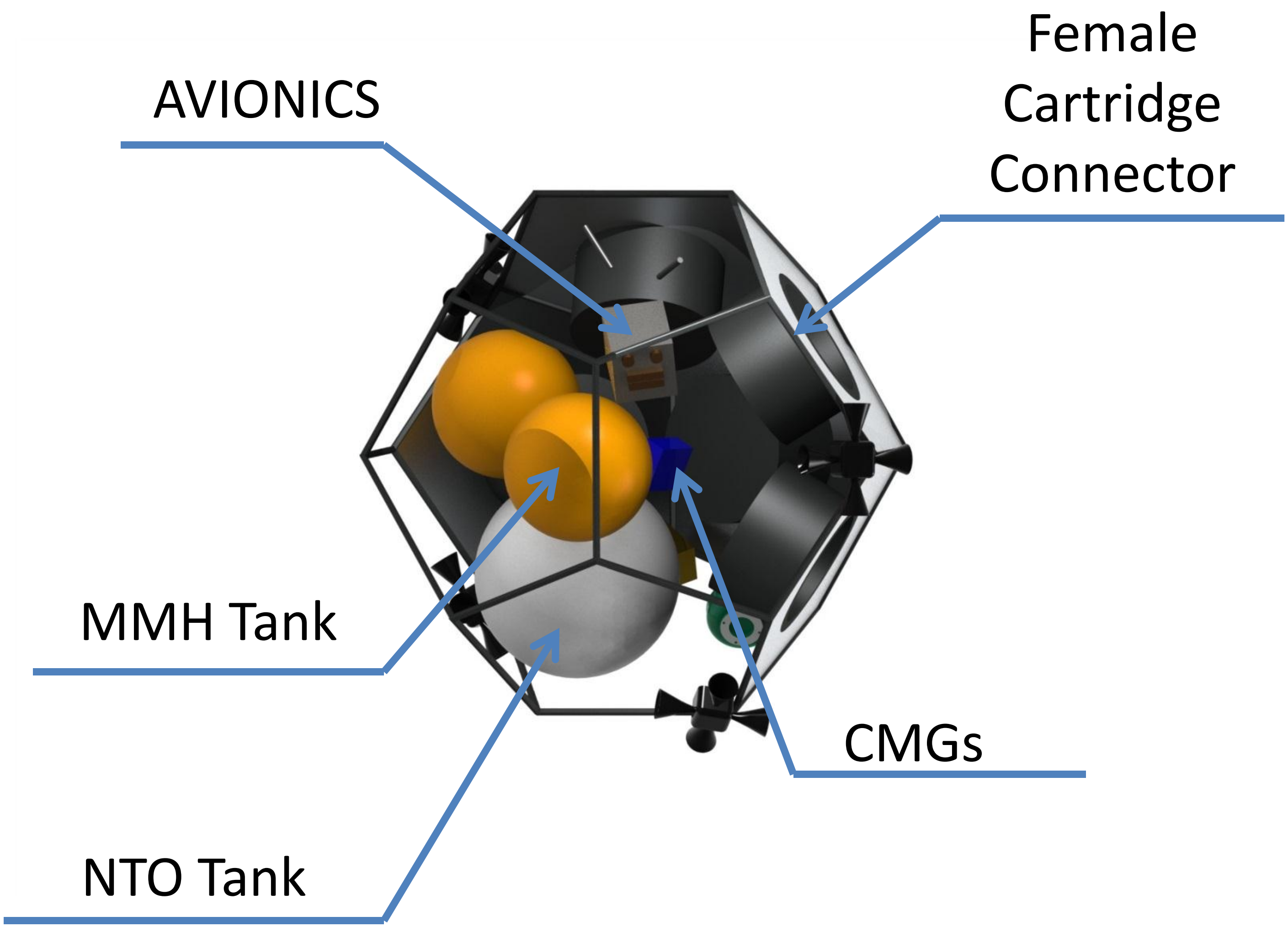
- Dodecahedral for symmetry and versatility
- Design drivers: mass and volume
- Externally mounted sensors and components
- Internally stored fuel and avionics



Structures


Cartridge
Patch Antenna
UHF Antenna
Deployable Solar Array
RCS

Structures


AVIONICS
Female
Cartridge
Connector
MMH Tank
CMGs
NTO Tank

Thermal and Pressure Requirements

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
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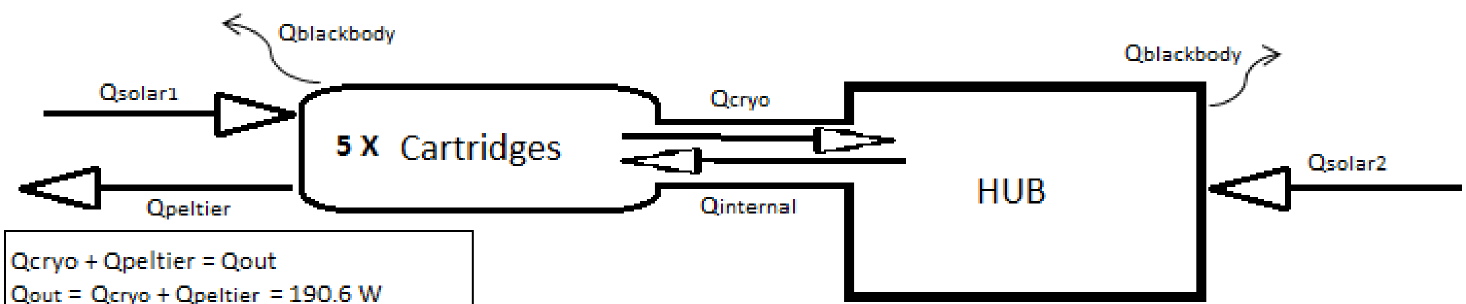
PTS-08	

Thermal and Pressure Control System

- Passive Control
  - Cryogenic Storage Dewar
  - Multi-layer Insulation (MLI)
- Active Control
  - Peltier Thermoelectric coolers
    - Operate down to 233 K
  - Cryocooler
    - Listed cooling capacity at 80 K



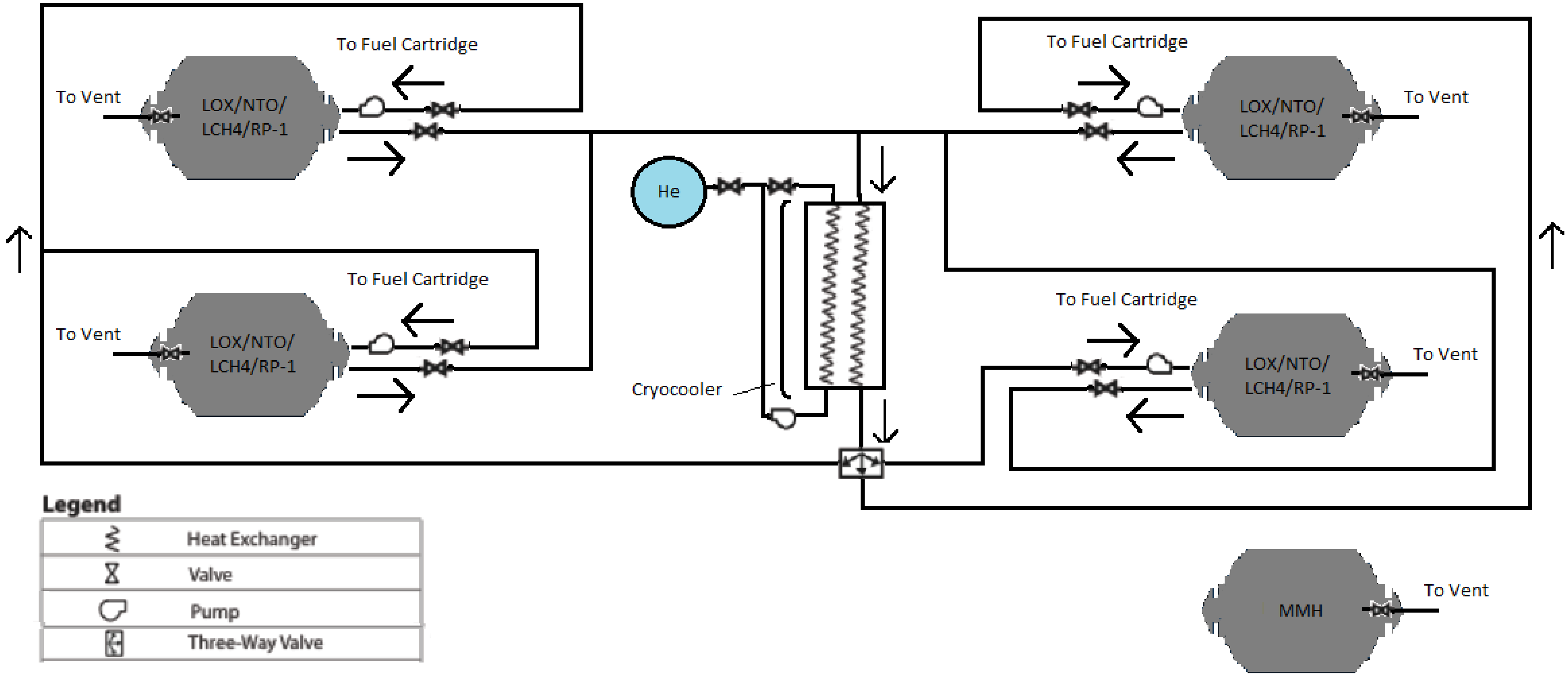
Qcryo + Qpeltier = Qout
Qout = Qcryo + Qpeltier = 190.6 W

Qblackbody = 194 W
Qsolar2 + ∑ Qsolar1 - Qblackbody = 14.6 W
Qin = Qinternal + 14.6 W = 190.6 W

Qpeltiermax = 172 W
Qcryomax = 42 W @77 K

Thermal and Pressure Control System

- Propellants pumped individually through the cooler and heat exchanger
- Hypergolic propellants separated



Guidance and Control Requirements

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

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ADCS-09

GNC and ADC Subsystems

- Control Modes
  1. Stabilization and sun tracking
  2. Cartridge rendezvous and docking
  3. Mass, center of mass, and moment determination
  4. Client rendezvous and cartridge transfer
- Selected Actuators

Type	Strength	Number	Model
Control Moment Gyroscope	89 Nm	4 (arranged in square for redundancy)	Scaled from Astrium CMG 15-45S
Reaction Control Rockets	400 N	5 banks of 4 thrusters for attitude and position control	SpaceX Draco Rocket Engine

GNC and ADC Subsystems

- Selected Sensors

Type	Sensitivity	Update Rate	Model
IMU (gyro, accel, mag)	0.35 deg RMS pitch/roll 1.0 deg RMS heading (3-axis)	100 Hz	Microstrain 3DM-GX3-45
Star Trackers	+/- 0.003 deg	30 Hz	Sodern Hydra Star Tracker
Sun Sensors	+/- 0.1 deg +/- 70 deg view (2-axis)	5 Hz	Sinclair SS-411 Two-Axis Digital Sun Sensor
GPS	+/- 2.5 m	4 Hz	Microstrain 3DM-GX3-45
Docking Sensor	Position from 2000 to 0.5 m	Unspecified	Neptec TriDAR
Cameras (computer vis.)	Position for near approach	10 Hz	Malin Space Science Systems ECAM

Communication and Ground Station Reqs

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

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COM-08

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.

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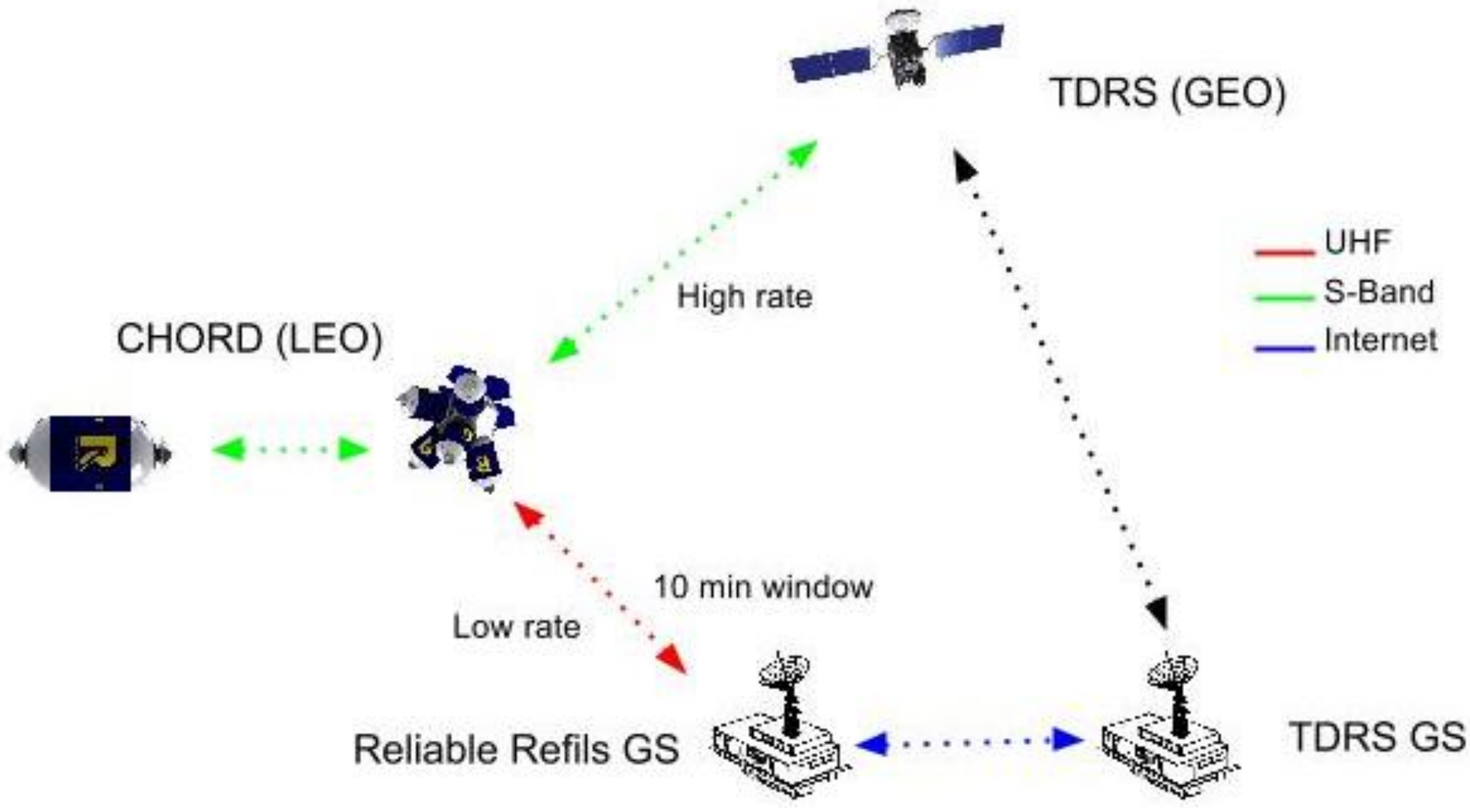
GS-04

Communications

10 minute pass time!

Cartridge to Hub	Hub to GroundStation	Hub to Relay
Status Ping	Status Beacon	High-Rate Telemetry
S-Band	UHF band	S-Band
Patch Antenna	Crossed Monopole	Patch Antenna
Each docking face	Opposite non docking faces	Each docking face
Outward gain	Omni-directional gain	Dual use of Antenna
~10 bytes at 0.5 Hz	~150 Bytes at 0.1 Hz	~500 bytes/s
Cartridges use same antennas	Ground station built at Reliable Refils Management Facility	Use of TDRS service provided by NASA
Monitor Cartridge health prior to docking	Nominal operations. Analyze beacons and Uplink Commands	Monitor CHORD while docking

Communications



System diagram with individual links

Electrical Power System Requirements

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

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EPS-10

Electrical Power System

- Power Requirements:
  - 1.9 kW - nominal
  - 3.4 kW - during docking
  - Largest power draws:
    - Cryocooling system - 400 W peak/200 W nominal
    - CMGs - 252 W peak/176 W nominal
- Energy Requirements:
  - 10.8 MJ - per nominal orbit
  - 18.8 MJ - per docking orbit

Electrical Power System

- Ga-As solar panels
  - 51 m^2 facing the sun
  - Provides at least 5.6 kW of power over 20 years
- 15 lithium-ion batteries on board
  - 3 of which are reserved as backups
  - Sustains 2 successive docking orbits
  - 10.9 MJ capacity in total
- Voltage are regulated at 5 V, 28 V, and raw battery voltage of 3.6 V

Command & Data Handling Reqs

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

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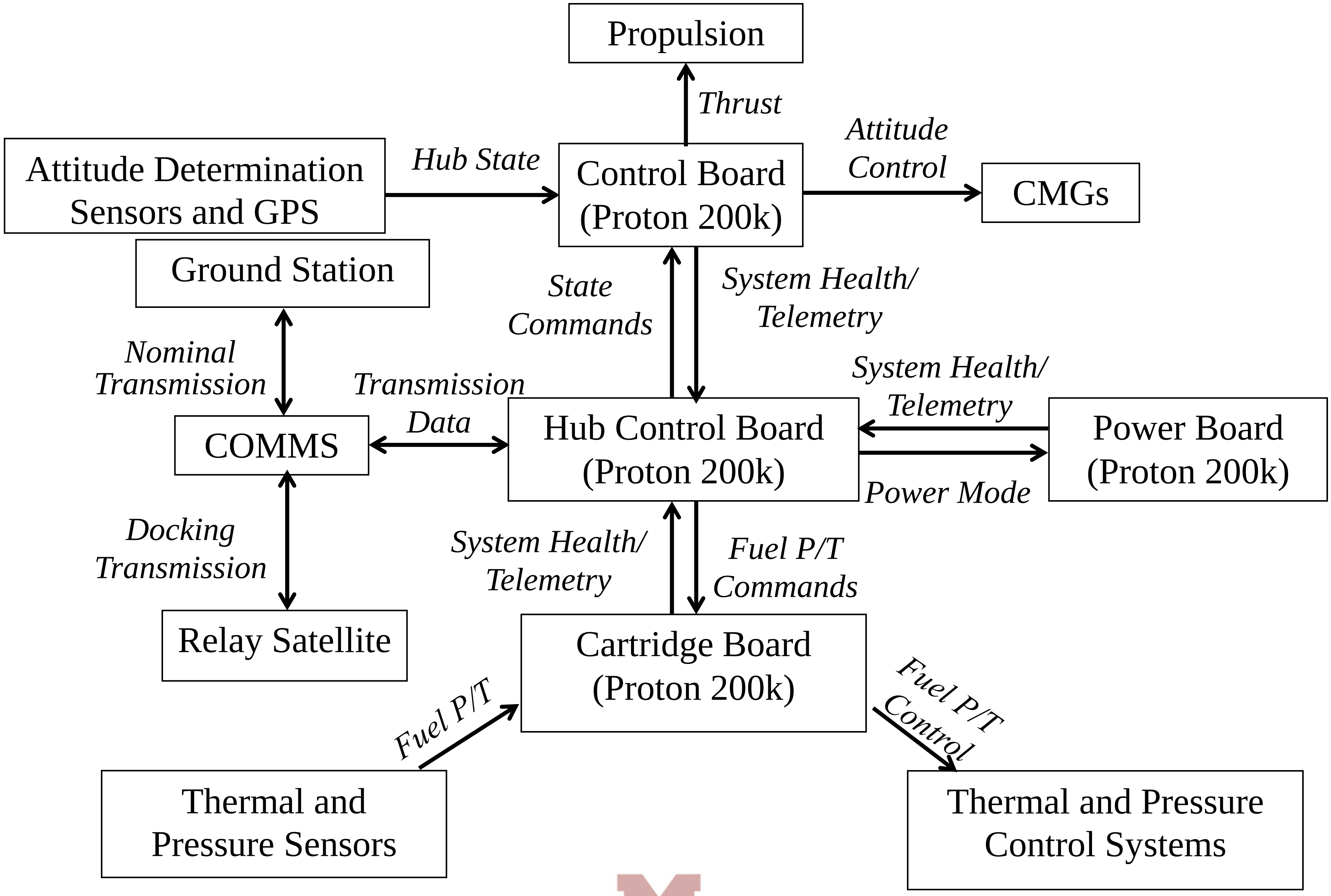
CDH-12

Command & Data Handling



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	Accelerated radiation degradation
6	Improper orbit injection of cartridge or client	12	Micrometeorite and debris damage or puncture

Very Likely	4					
	3	1				
	2	3	11	2, 10	8	
Not Likely	1		12	4	5,6	7, 9
		1 Small Impact	2	3	4	5 Large Impact

Future Ventures

- L2
- GEO
- Martian Orbit
- Gas Station in Spa

Conclusion

- Commercial Venture
  - Create a profitable business
  - Provide a valuable product for customers
- Space Infrastructure
  - Support larger, more advanced deep space missions
  - Allow cheaper, more frequent high Earth orbit missions

Questions?

THANK YOU

Please visit

www.reliablerefills-inc.com

for more information!

RELIABLE REFILLS

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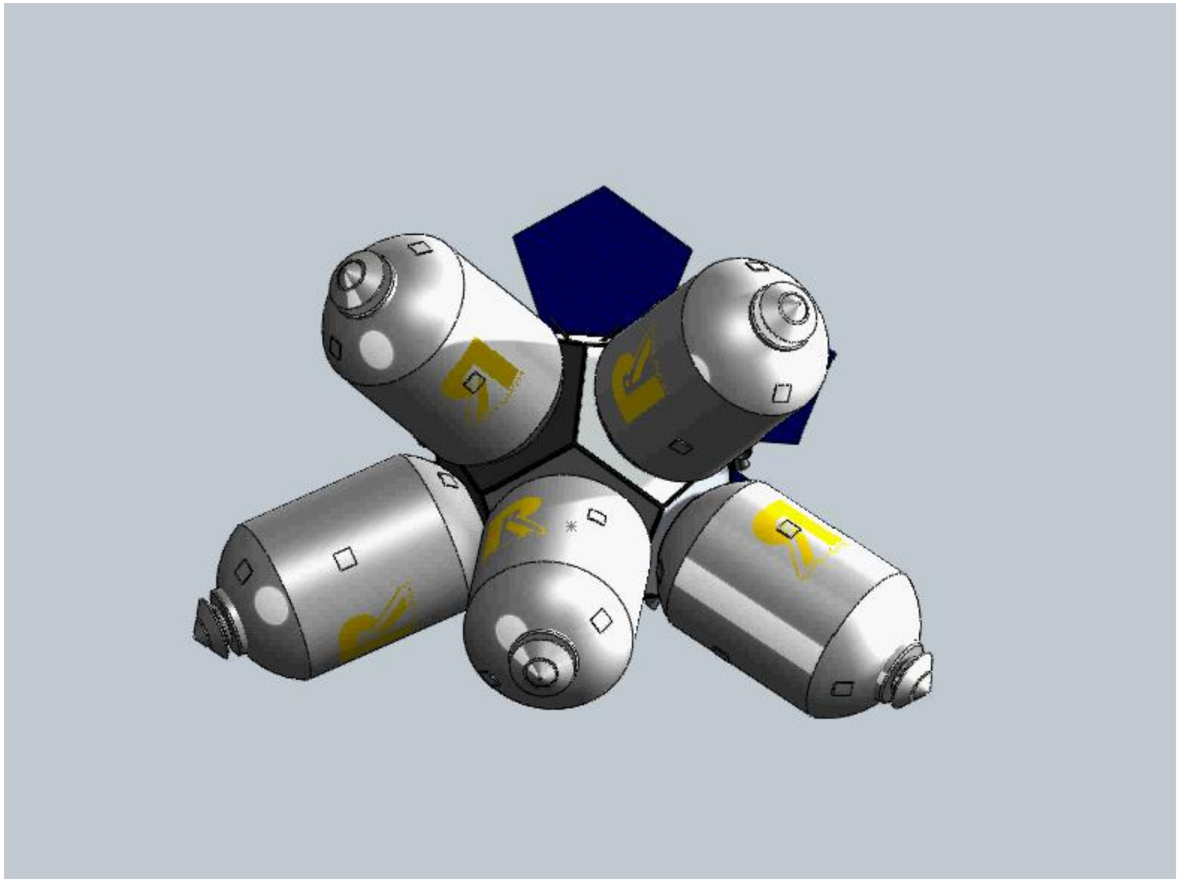

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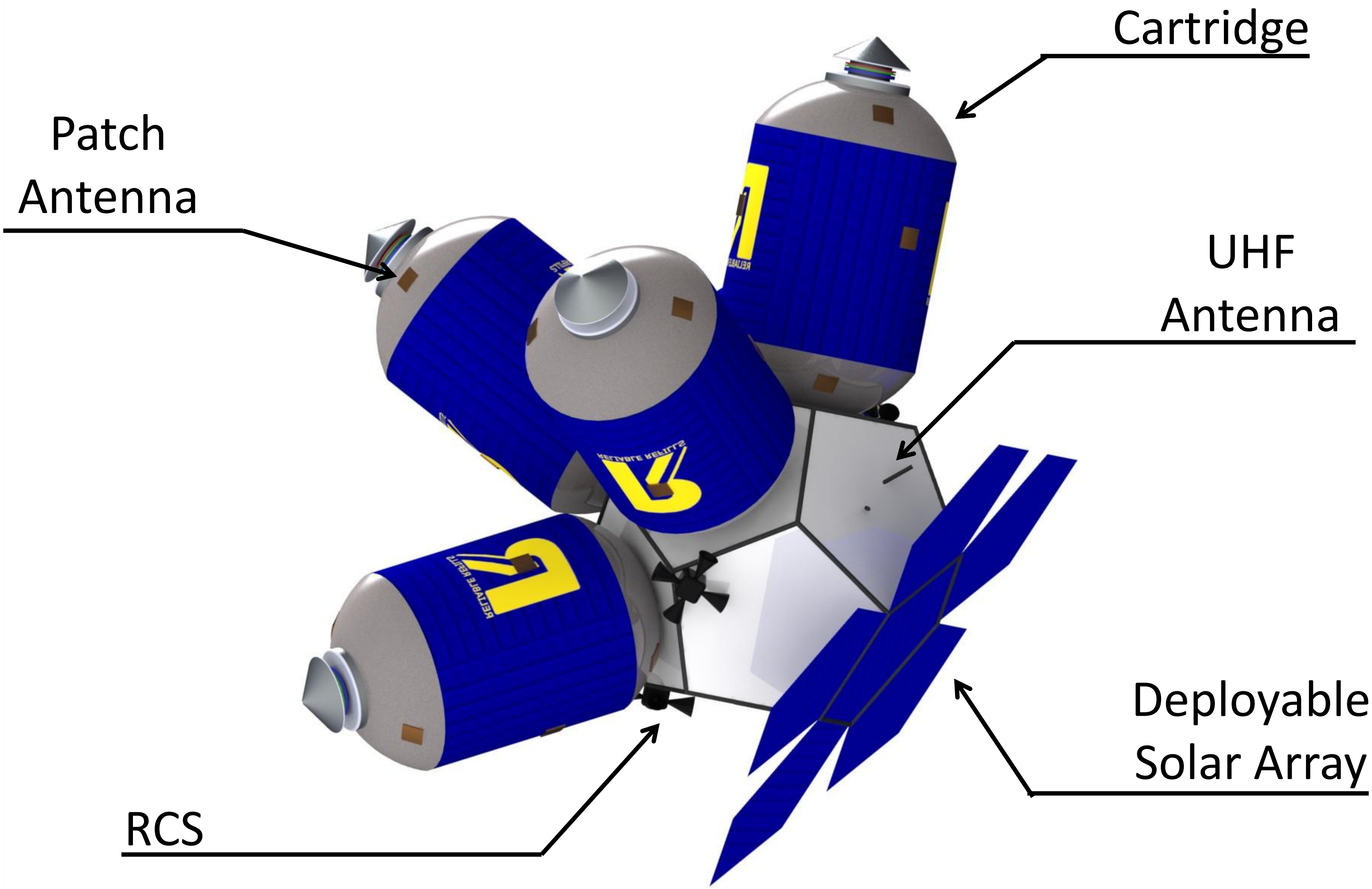
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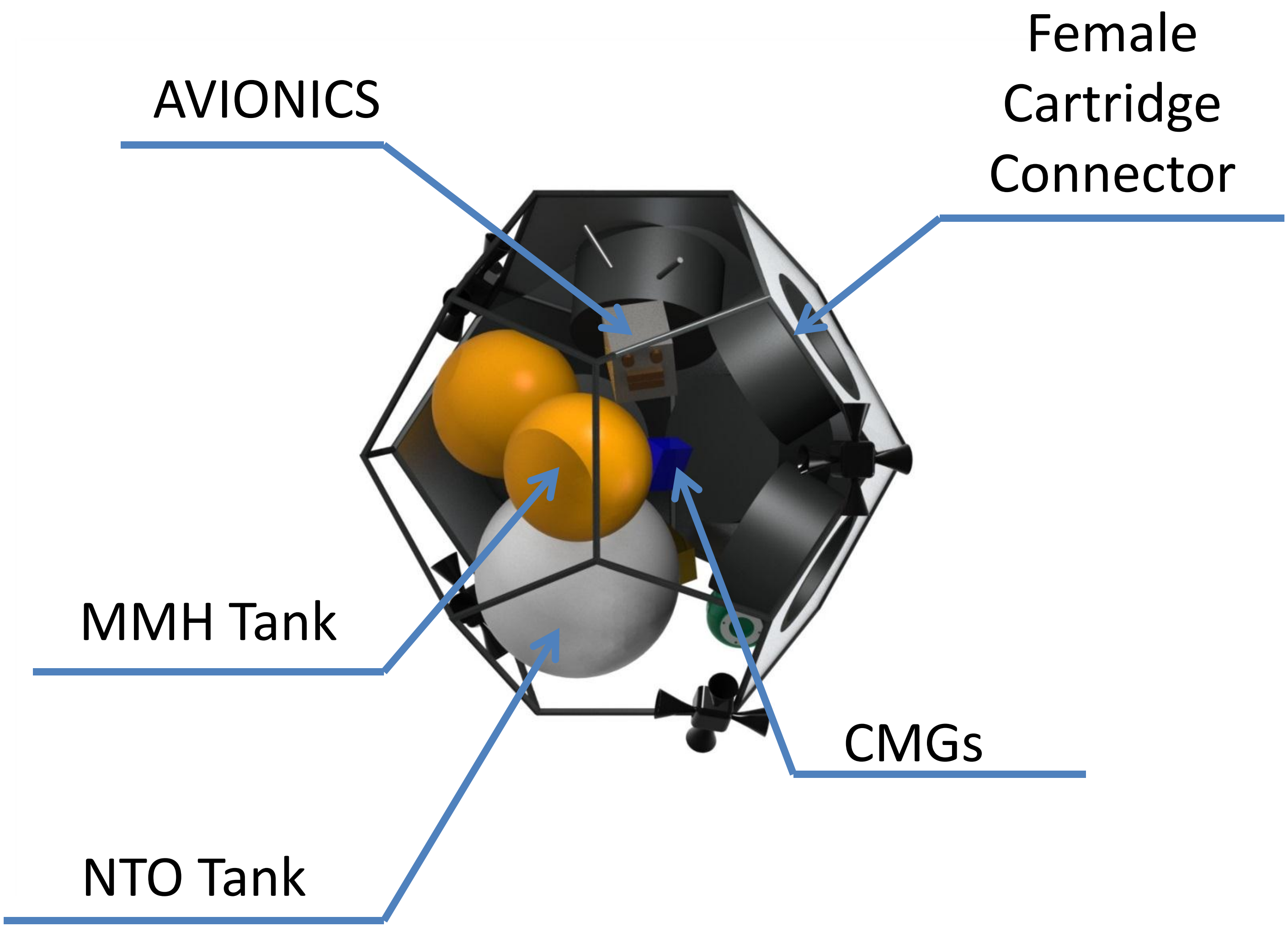
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