Critical Design Review

03/23/2021

Project NextStep

AAE 450 - Spring 2021

PURDUE AERONAUTICS & ASTRONAUTICS

Project Manager - CDR

AAE 450 - Spring 2021

3/23/2021
Dalton Trinh

PURDUE AERONAUTICS & ASTRONAUTICS

Dalton Trinh

Launch Schedule(FY 2022 – 2026)

FY 2022

- **Q1**: N/A
- **Q2**: N/A
- **Q3**: N/A
- **Q4**: Launch collecting, clearing, scouting rovers, and LEO fuel depot

FY 2023

- **Q1**: LEO fuel depot, first two comm satellites
- **Q2**: First observation satellite launch
- **Q3**: Second two comm satellites
- **Q4**: N/A

FY 2024

- **Q1**: Final two comm sats, Starship launches P&T equipment and comms ground station
- **Q2**: Exercise and human research equipment
- **Q3**: N/A
- **Q4**: Initial habitat materials, life support equipment, first **5 colonists** on 6 month rotations

FY 2025

- **Q1**: N/A
- **Q2**: Begin crew return flights
- **Q3**: N/A
- **Q4**: Maintain crew of 5, begin 1 year rotations, launch medical equipment

FY 2026

- **Q1**: N/A
- **Q2**: N/A
- **Q3**: N/A
- **Q4**: Additional habitat materials, life support equipment, increase to **9 colonists** on 1 year rotations

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Launch Schedule(FY 2027 – 2031)

FY 2027
- **Q1**: N/A
- **Q2**: N/A
- **Q3**: N/A
- **Q4**: Maintain crew of 9, begin 2 year rotations, launch medical equipment

FY 2028
- **Q1**: N/A
- **Q2**: N/A
- **Q3**: N/A
- **Q4**: Increase to crew of 13, maintain 2 year rotations, launch medical equipment

FY 2029
- **Q1**: N/A
- **Q2**: N/A
- **Q3**: N/A
- **Q4**: Launch additional habitat materials and life support equipment, maintain crew of 13, maintain 2 year rotations

FY 2030
- **Q1**: N/A
- **Q2**: N/A
- **Q3**: N/A
- **Q4**: Increase to full crew of 19, maintain 2 year rotations, launch medical equipment

FY 2031
- **Q1**: N/A
- **Q2**: N/A
- **Q3**: N/A
- **Q4**: Maintain crew of 19, maintain 2 year rotations, launch medical equipment

- Assume all launch vehicles immediately available for 10-20 launches per year
- Based off of Noah Stockwell's analysis of SpaceX's economics, Starship costs **$120 million** per launch
- All teams take manufacturing and testing time into consideration

Mission Design
AAE 450 - Spring 2021

03/23/2021

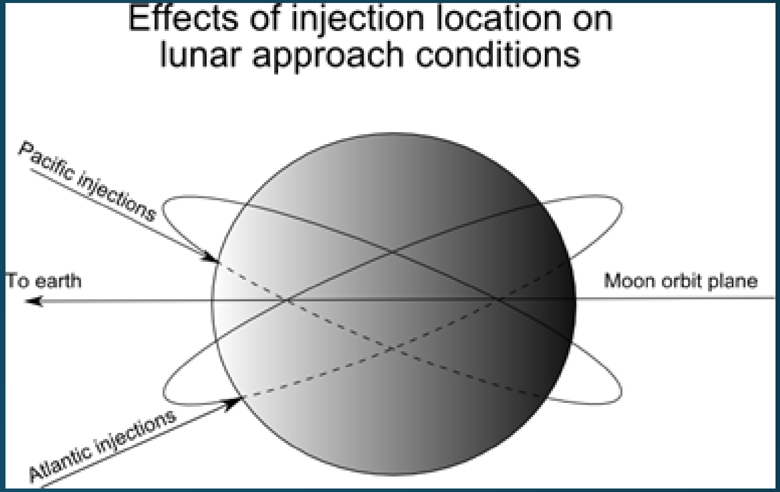
Critical Design Review

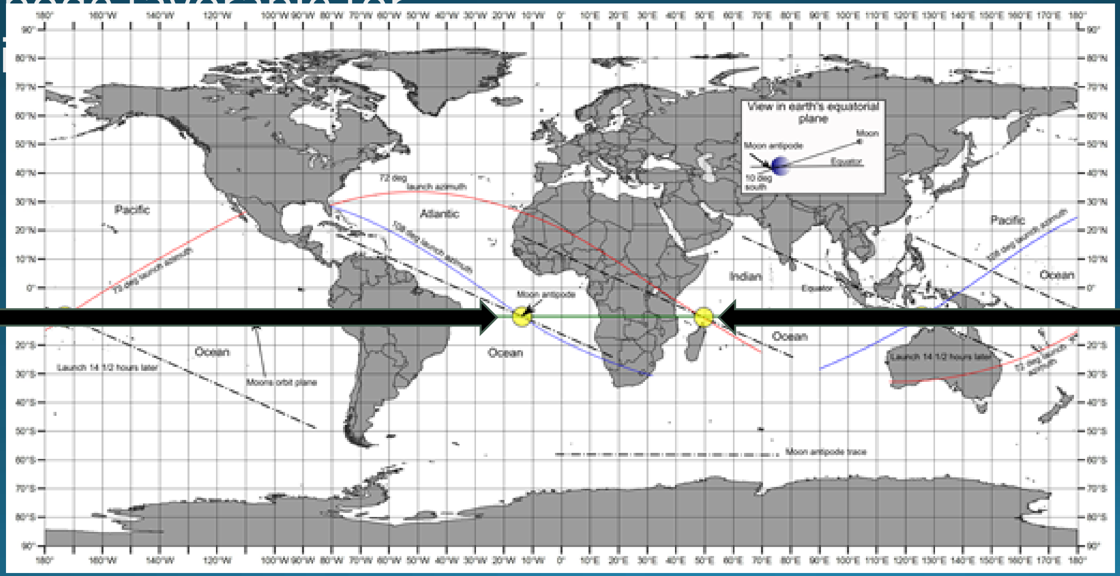
Team Lead: Cody Martin

Team Members: Cody Martin, Daniel Gochenaur, Mohit Pathak, Chad Blackwell, Stephen Grabowski, Matthew Popplewell, Dale Williams, Jarod Villeneuve-Utz, Alex Maietta, Eric Gooderham, Nikhil Gavini, Youssef Noureddine

Mission Launch Windows

- 10 initial launch dates per year
  - Launch dates fluctuate based on needs of mission
- Minimum launch window = 3 days by NASA
- Daily launch windows – 2 per day
  - Safe azimuths: 72° - 108° to avoid landmasses
  - Need to vehicle to meet lunar antipode
    - Happens twice a day (over Indian Ocean and Atlantic Ocean)
  - Atlantic Ocean anti... Southern Pole landi...





Atlantic Antipode

Pacific Antipode

LEO Orbit Specifications

- LEO orbit parameters
  - Launch from Cape Canaveral, Florida
    - Easily accessible launch location near to the equator.
  - Altitude of 600km
    - Allows for the establishment of a refueling depot that requires fewer corrective burns than at a lower orbit
    - Reduced “traffic” due to the high altitude
  - Inclination of 28.5°, ~40° for specific launches
- Earth Ascent
  - Required deltaV of 9.5km/s

Launch Dates

Best Launch Dates Per Fiscal Year										
Year	**2021-2022**	**2022-2023**	**2023-2024**	**2024-2025**	**2025-2026**	**2026-2027**	**2027-2028**	**2028-2029**	**2029-2030**	**2030-2031**
Date 1	11/5/2021	10/7/2022	10/6/2023	10/4/2024	10/31/2025	10/2/2026	10/1/2027	10/27/2028	1/18/2030	10/25/2030
2	12/3/2021	12/2/2022	11/3/2023	11/1/2024	11/28/2025	10/30/2026	10/29/2027	11/24/2028	2/15/2030	11/22/2030
3	12/31/2021	1/27/2023	12/1/2023	11/29/2024	12/26/2025	11/27/2026	11/26/2027	12/22/2028	3/15/2030	3/14/2031
4	1/28/2022	2/24/2023	12/29/2023	12/24/2024	1/23/2026	12/25/2026	12/24/2027	2/16/2029	4/12/2030	4/11/2031
5	2/25/2022	3/24/2023	2/23/2024	2/21/2025	3/20/2026	1/22/2027	1/21/2028	3/16/2029	5/10/2030	5/9/2031
6	3/25/2022	4/21/2023	3/22/2024	3/21/2025	4/17/2026	2/19/2027	2/18/2028	4/13/2029	6/7/2030	6/6/2031
7	6/17/2022	5/19/2023	4/19/2024	4/18/2025	5/15/2026	3/19/2027	3/17/2028	5/11/2029	7/5/2030	7/4/2031
8	7/15/2022	6/16/2023	5/17/2024	5/16/2025	6/12/2026	4/16/2027	4/14/2028	8/3/2029	8/2/2030	8/1/2031
9	8/12/2022	7/14/2023	6/14/2024	6/13/2025	7/10/2026	6/11/2026	5/12/2028	8/31/2029	8/30/2030	8/29/2031
10	9/9/2022	8/11/2023	7/12/2024	7/11/2025	9/4/2026	7/9/2027	6/9/2028	9/28/2029	9/27/2030	9/26/2031

Table 1: Launch Dates From 10/2021 - 9/2031

Rendezvous Trajectories for LEO Depot

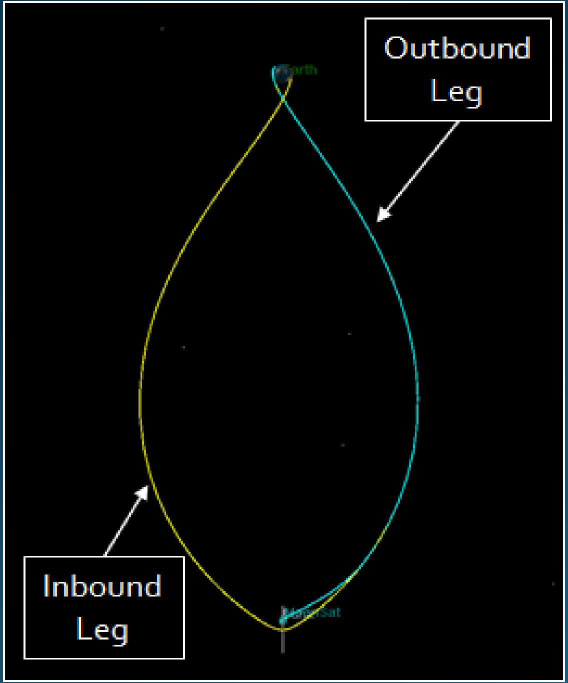
- Able to get a spacecraft and a depot close within the same orbit with minimal ΔV cost
- Launch should be done in accordance with phasing angle to avoid prolonging mission length

Property of maneuver	Value
Thrust	12,000 KN
Mass	270 tons
Burn time	2.733 seconds

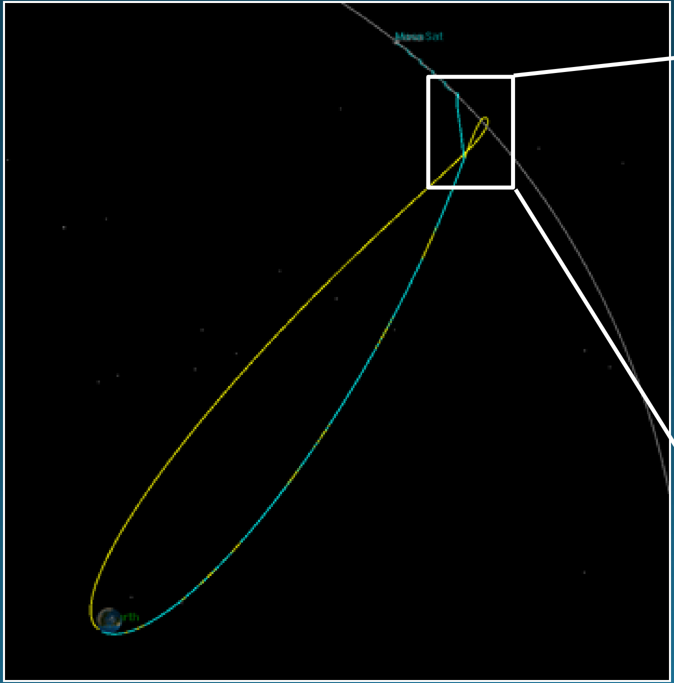
	Delta V without rendezvous (m/s)	Delta V for rendezvous (m/s)
Transfer orbit insertion	84.38	99.20
Circular orbit insertion	83.48	83.59
Total:	168.76	182.79

Lunar Free Return

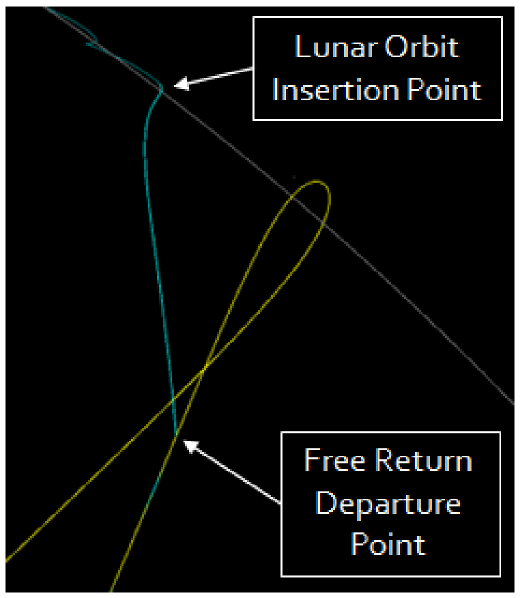
- Free return trajectory designed for crewed missions
- GMAT used to simulate mission and calculate ΔV requirements
  - Model includes Earth, Lunar, and Solar gravity and Solar Radiation Pressure
  - Displayed mission departs on October 10, 2024
  - Simulation can be adapted to other departure dates



Earth-Moon Rotating View

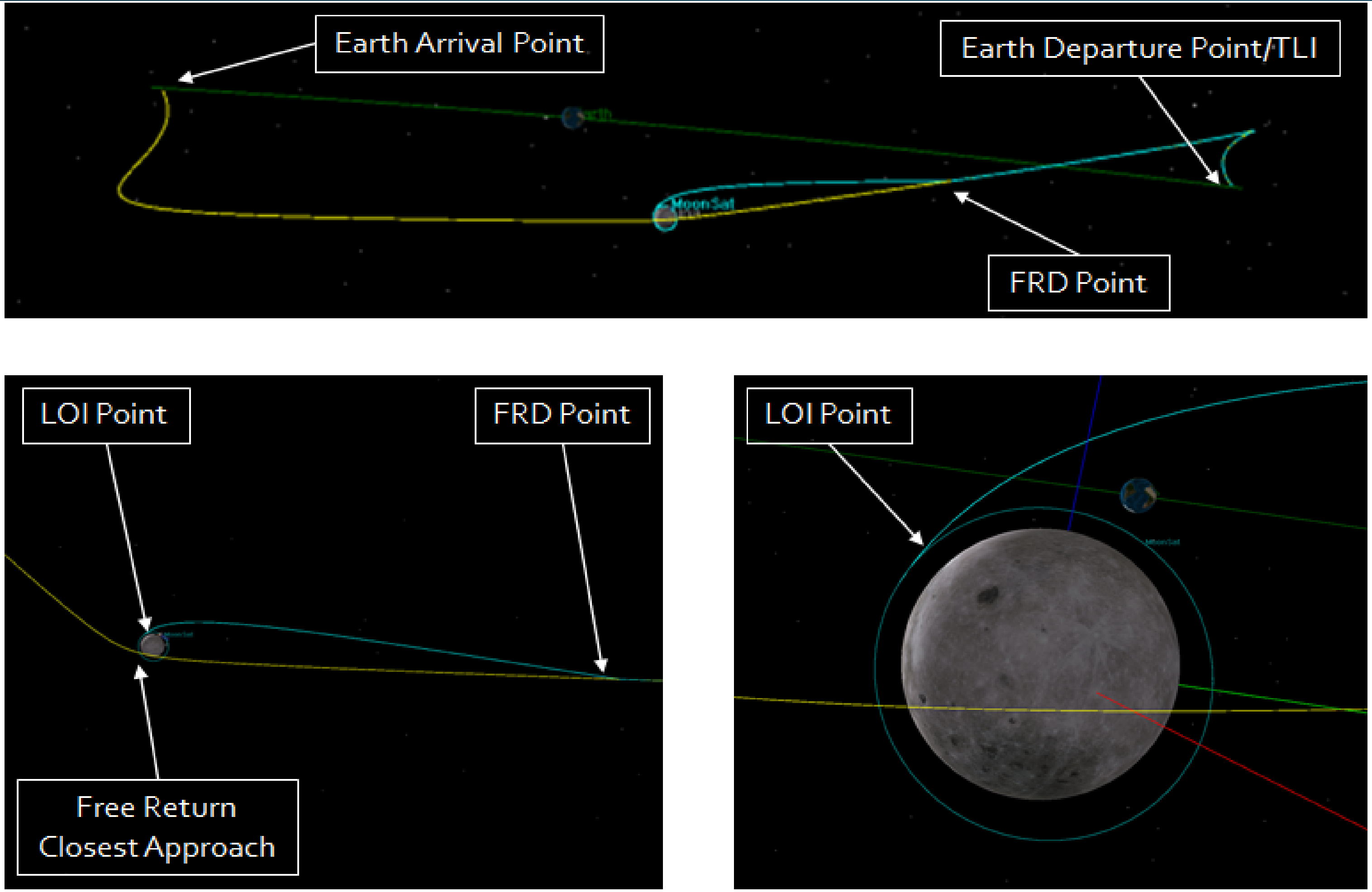


Earth Inertial View



Earth Inertial View, Lunar Arrival

Lunar Free Return (Continued)



Moon Inertial Views of Free Return and Lunar Orbit Trajectories

Maneuver	Delta V Cost (km/s)
Trans-Lunar Injection (TLI)	3.0470
Free Return Departure (FRD)	0.4555
Lunar Orbit Insertion (LOI)	0.6772
Total	4.1797

Trajectory	Time of Flight (Days/Hours)
Complete Free Return	6.116/146.8
Earth to Low Lunar Orbit (LLO)	3.388/82.32

Translunar Trajectory Specific Analysis

- Main Idea: Get ΔV numbers for every specific launch on schedule
  - Useful for Uncrewed Missions (mainly cargo w/o satellites)
- Key Assumptions:
  - Model uses Earth, Lunar, Solar Gravity and Solar Radiation Pressure
  - Lambert Problem propagated into GMAT
  - Departure Time is always 12:00 from Earth Orbit

Sample Translunar Trajectory Breakdown

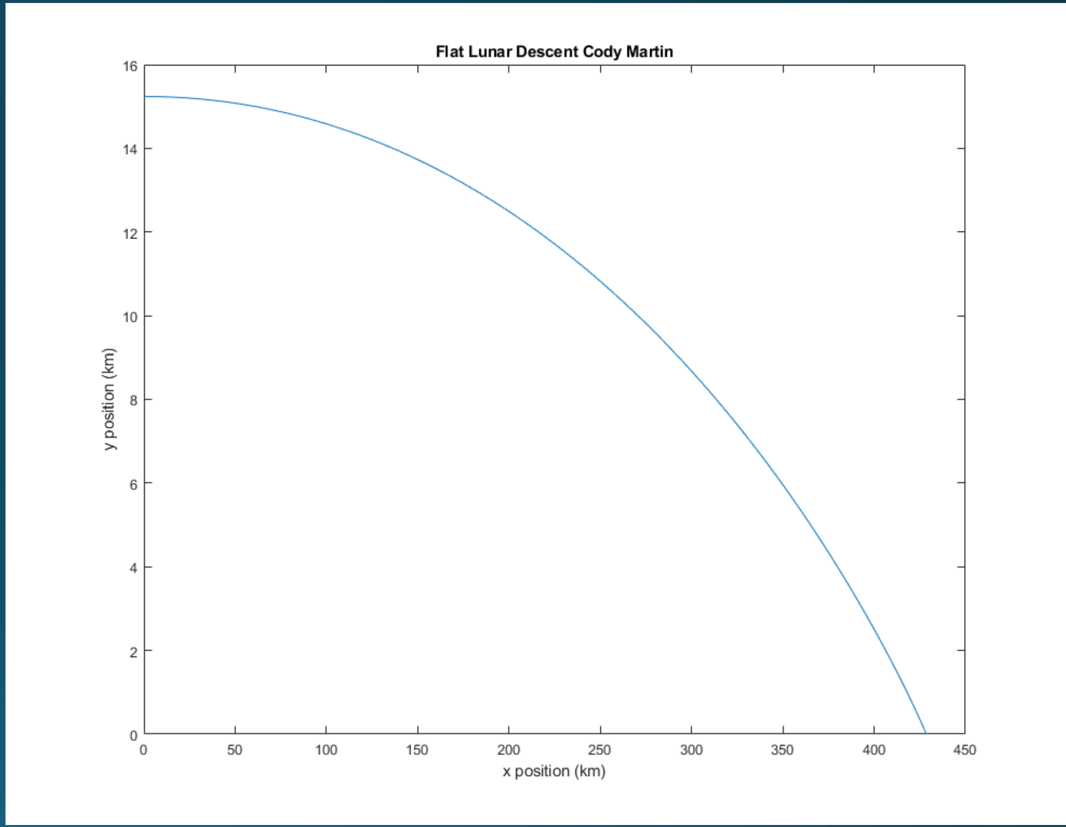
Translunar Trajectory Specific Analysis (cont.)

- Years 1-10 analyzed
  - Spreadsheet separated by Fiscal year in the Drive
  - Date Range: 10/8/2021 - 10/1/2031
  - Minimum of 13 viable launch dates each Fiscal year
- Average Time of Flight: 3.873 Days
- Average Total ΔV Cost: 3.876 km/s

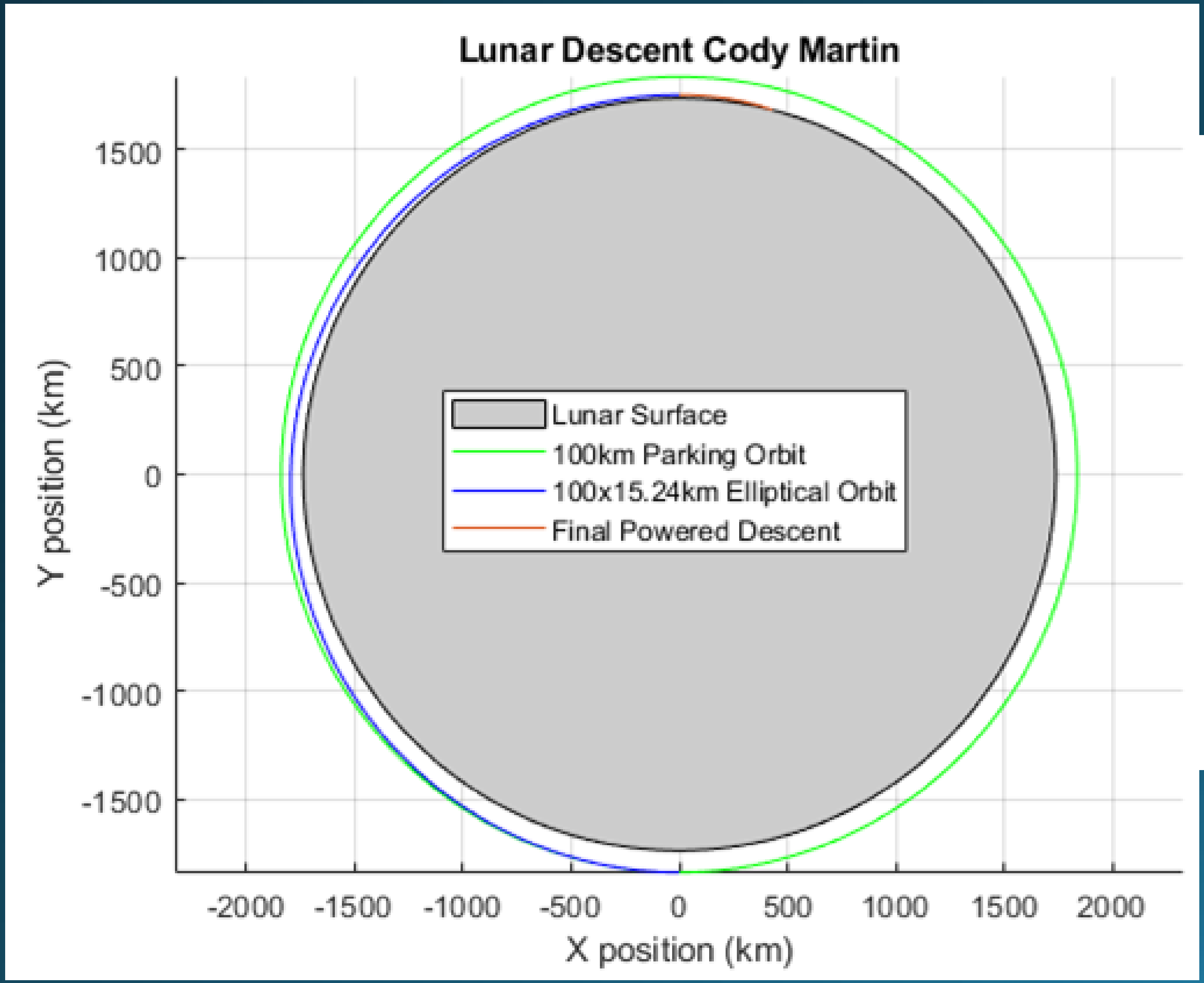
Video of Translunar Trajectory to Moon

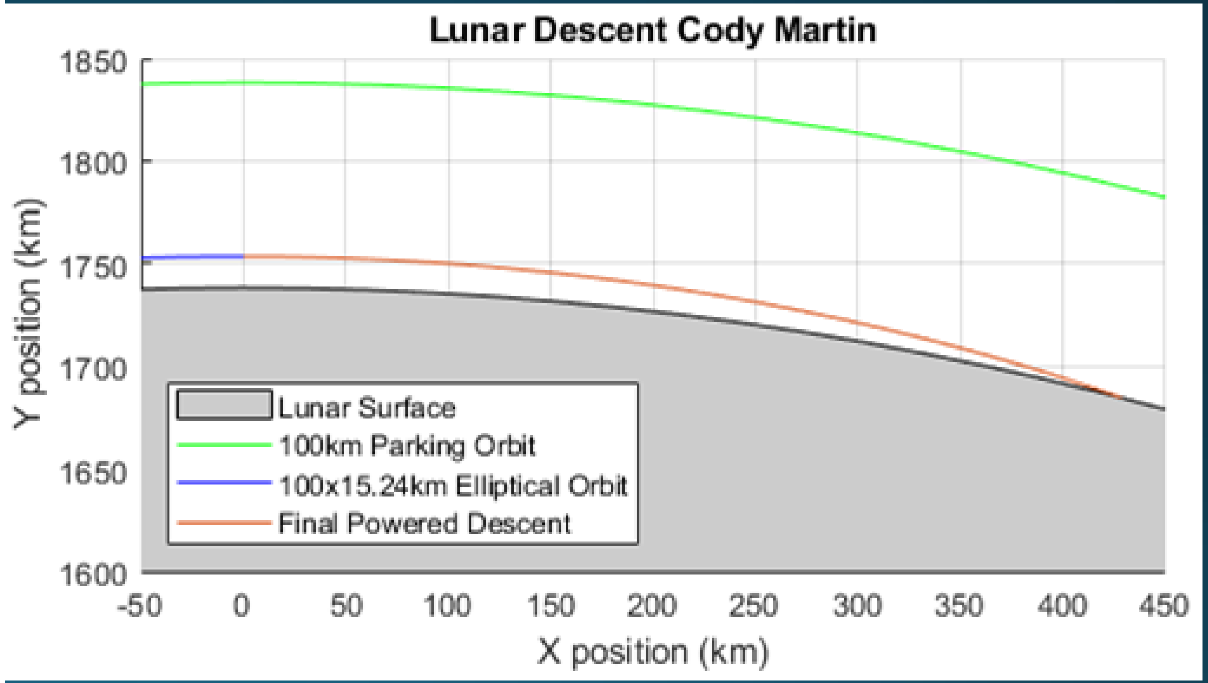
Lunar Descent for Apollo Lunar Module

- Transfer from a 100km polar orbit into a 100x15.24km elliptical orbit
  - Approximate dV cost of about 19.5 m/s
  - ToF to periapsis of 1.9hrs
- At periapsis of this orbit powered descent begins
  - Vehicle touches down about 460 seconds later
  - From engine ignition the vehicle has traveled about 425km along the lunar surface
  - Approximate dV cost of about 2km/s
- To account for additional losses a total dV of 2.5km/s should be used
- Descent should start 194 degrees before target area



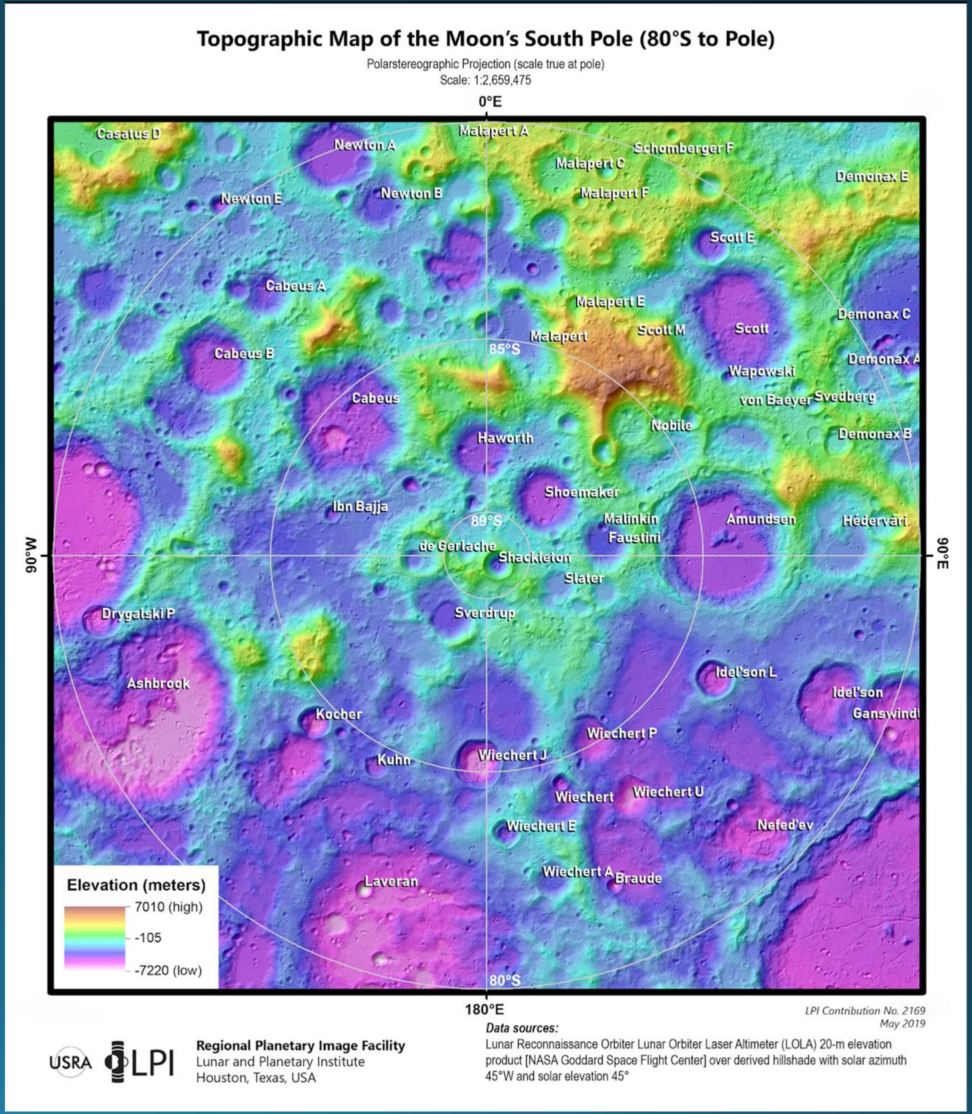
Lunar Descent Continued





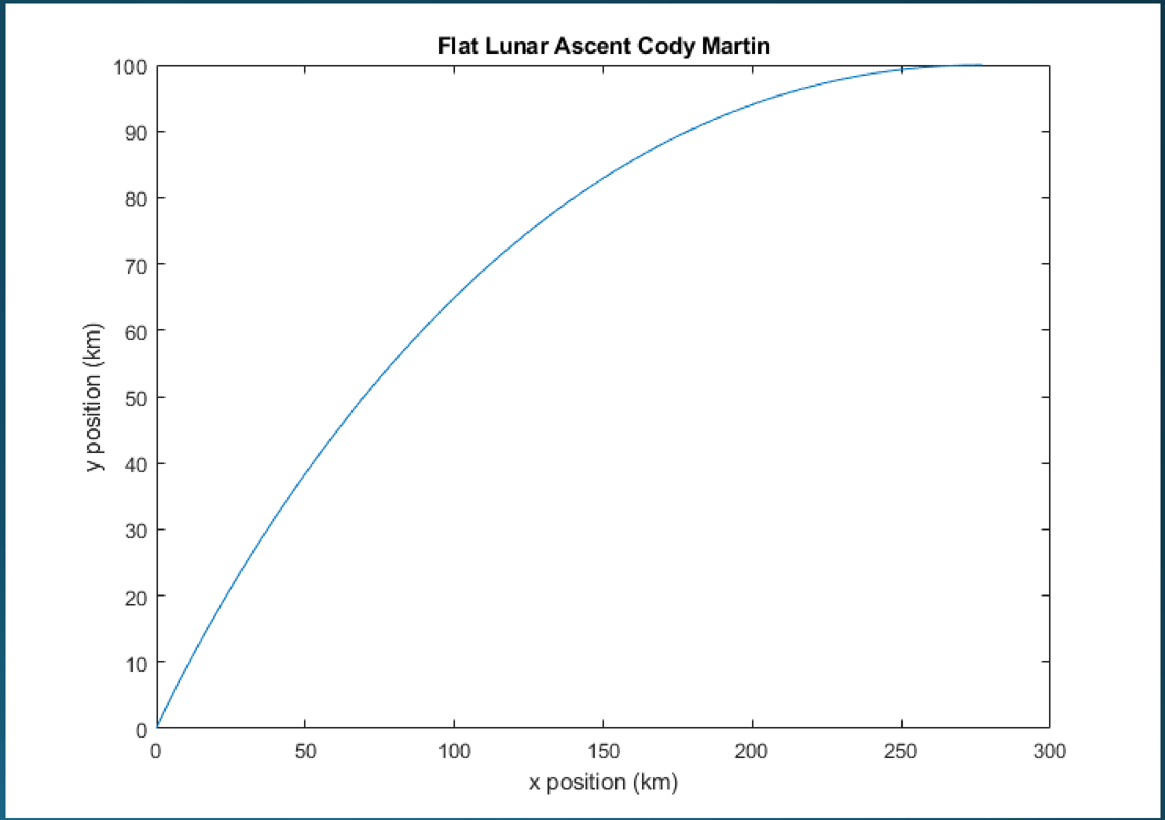
Lunar Descent Continued

- Lunar topography to the northeast restricts approach trajectories
  - Peaks approaching 10 km, located 120 km to the northeast, along Malapert Massif
    - Exact range 15-50°E
    - Vehicle altitude is below 9 km at this distance
- Descent longitude trajectory restricted to 90°-180°E and 0°-180°W
- Far side of the moon poses no ascent risks

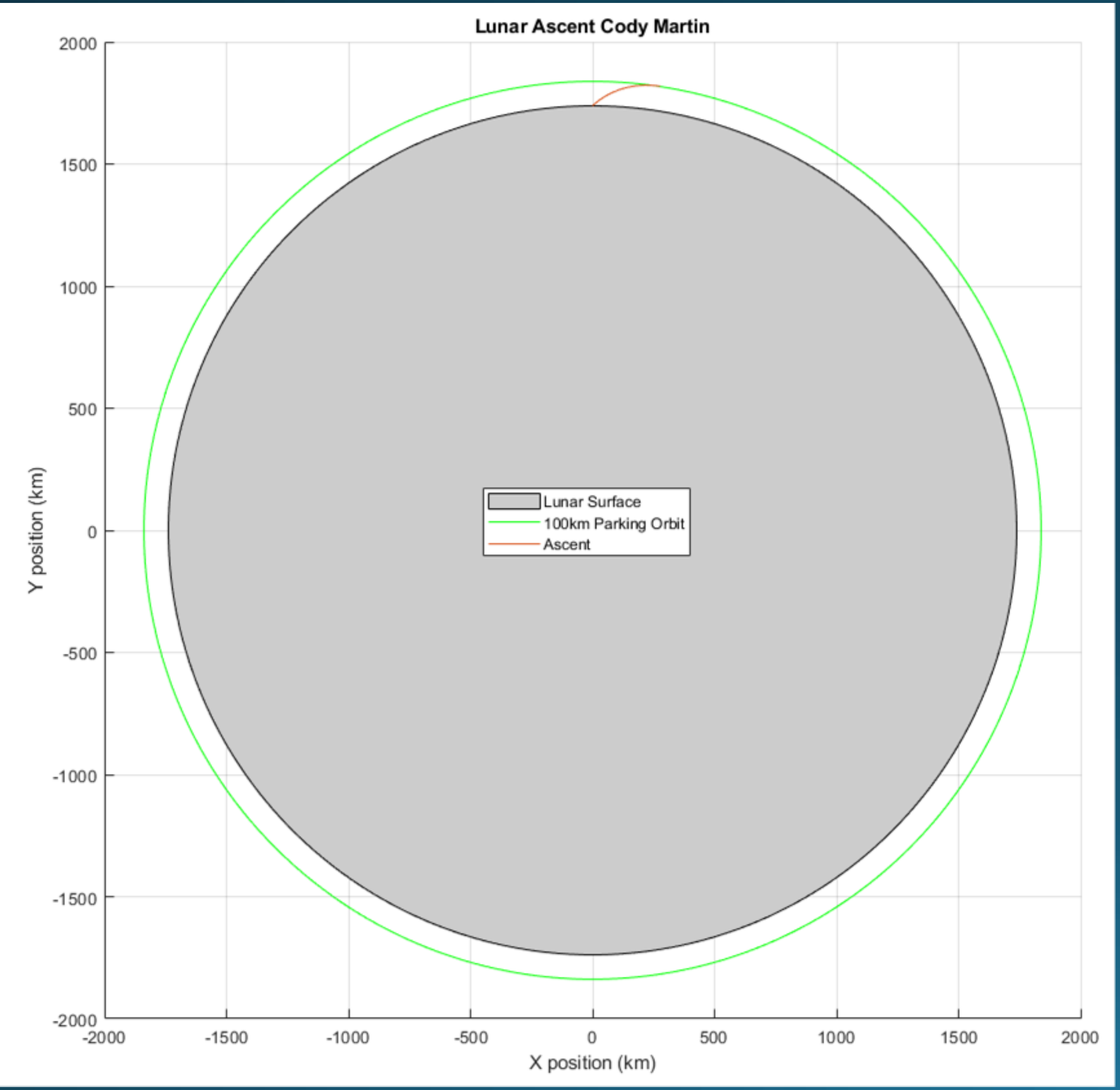


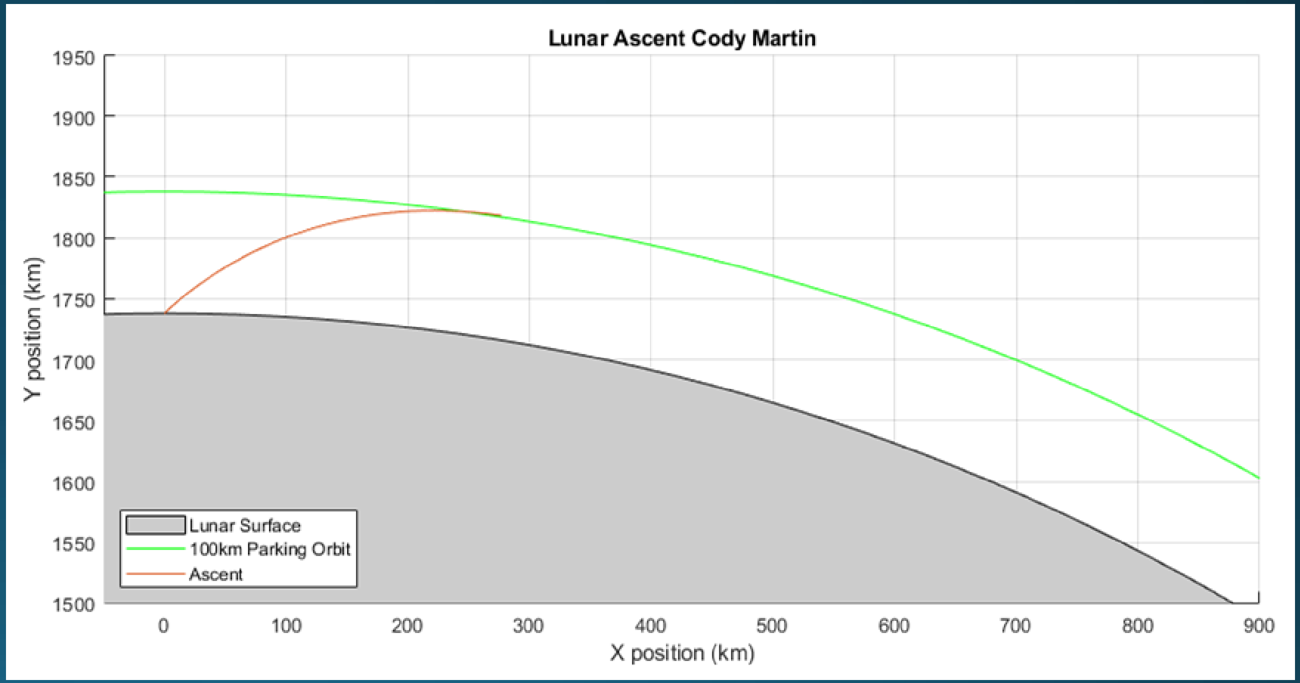
Lunar Ascent for Apollo Lunar Module

- Purpose:
  - Provide insight into what is involved with landing/taking off from the lunar surface
- Key Assumptions:
  - Flat moon, constant thrust and mass flow rate, 2d, data from apollo lunar module
- Launch from Shackleton crater into 100km circular polar orbit
  - Approximate dV cost of about 2.0km/s
  - Total ToF of 440 seconds
  - From engine ignition the vehicle has traveled 277km along the lunar surface



Lunar Ascent Continued





Moon to Earth: Launch Dates

- What effect does the launch date have on ΔV from the Moon to the Earth?
  - Different launch dates will have different relative positions of the Moon and Earth
  - Further distances require more ΔV
- Process was carried out in GMAT with:
  - 4-body problem (Sun, Earth, Moon, Spacecraft)
  - Solar Radiation Pressure
  - Actual Lunar Orbit

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Moon to Earth: Launch Dates

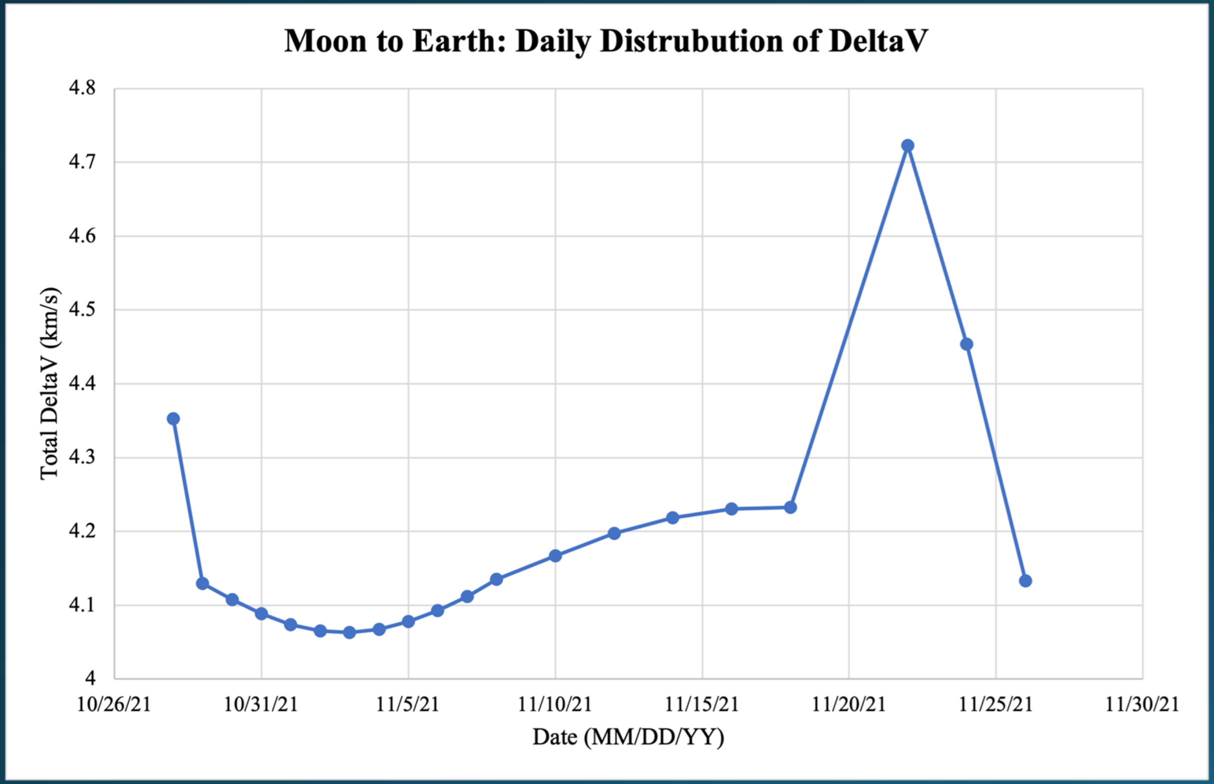

Figure 1. Daily Distribution for All DeltaV Values for Moon to Earth Trajectories from October 16th, 2021 to November 30th, 2021

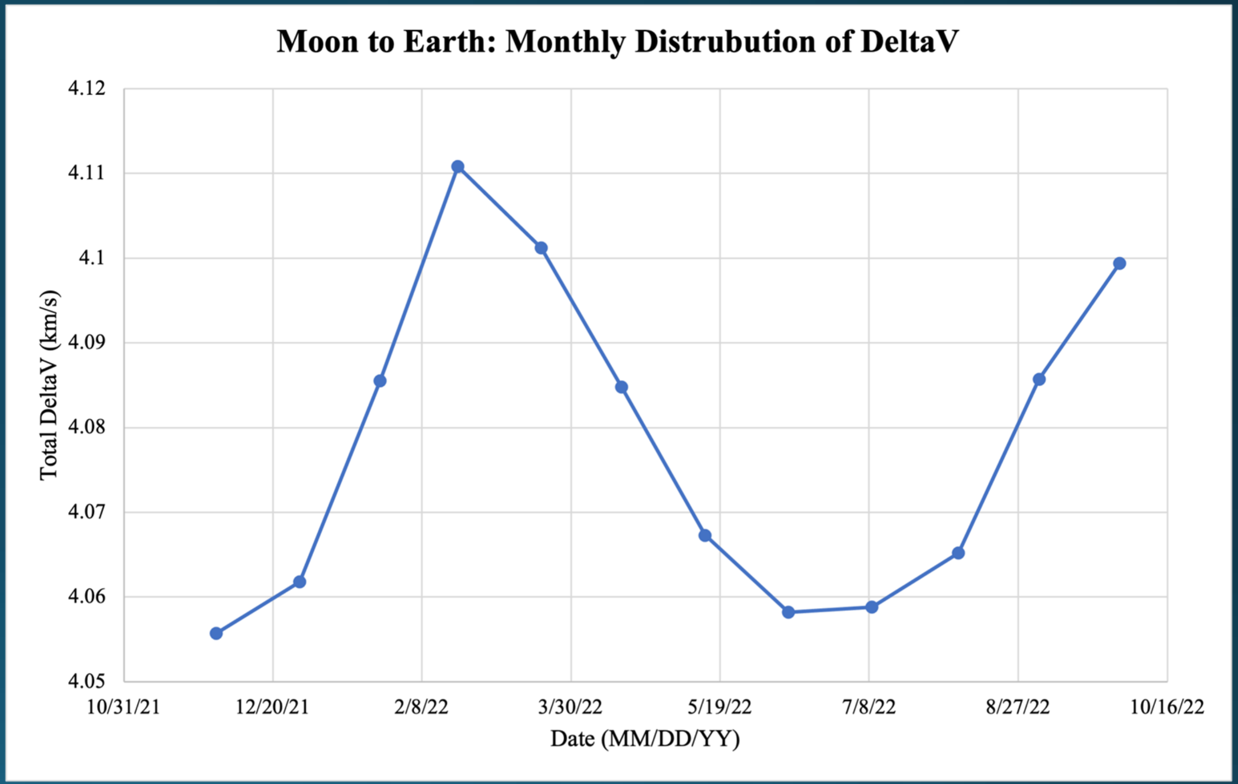

Figure 2. Monthly Distribution for All DeltaV Values for Moon to Earth Trajectories from October 31st, 2021 to October 16th, 2022

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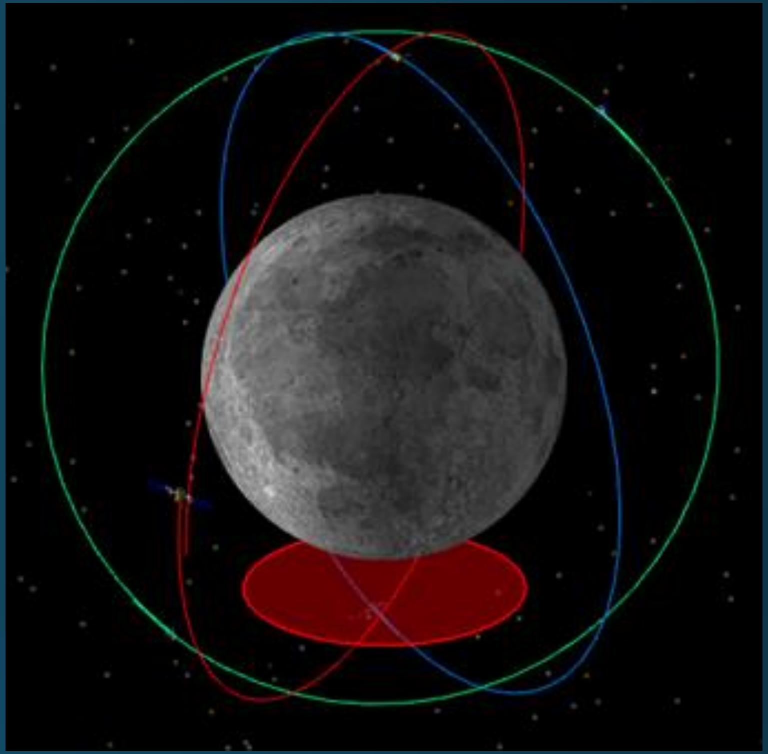
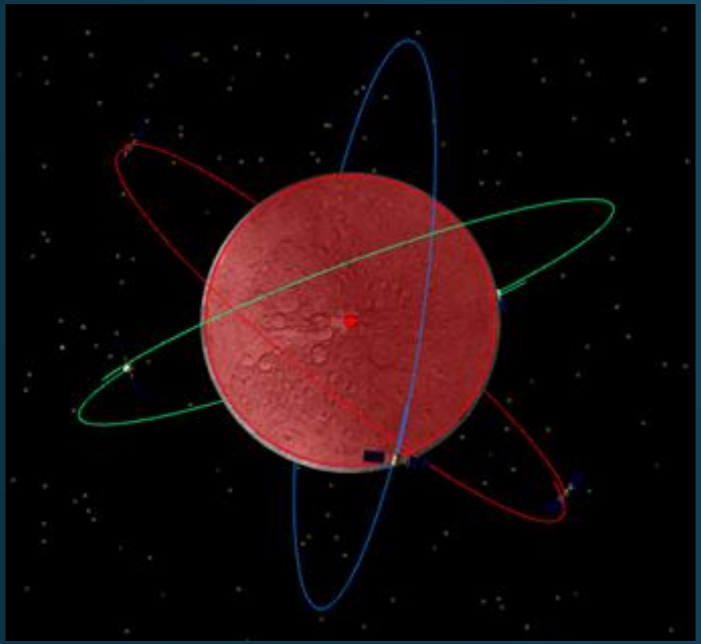
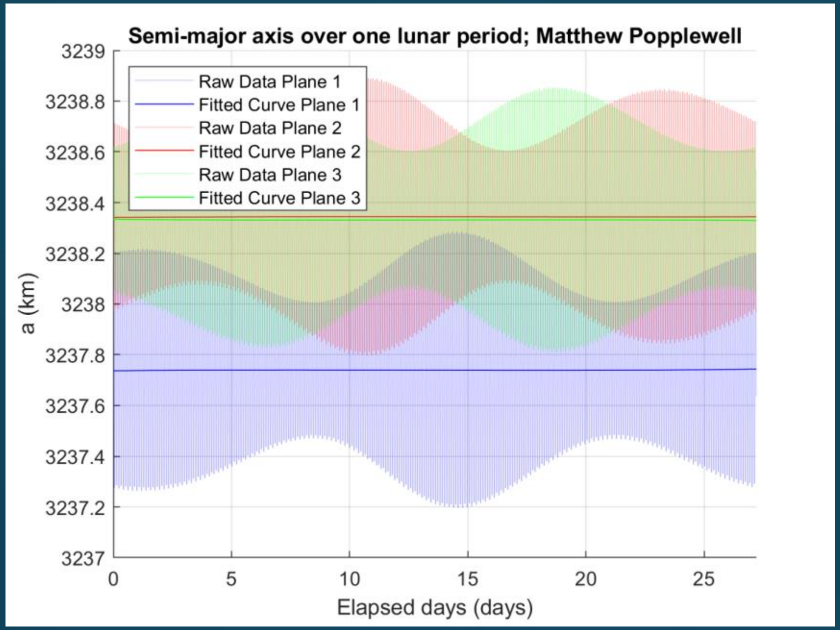
Communication Constellation

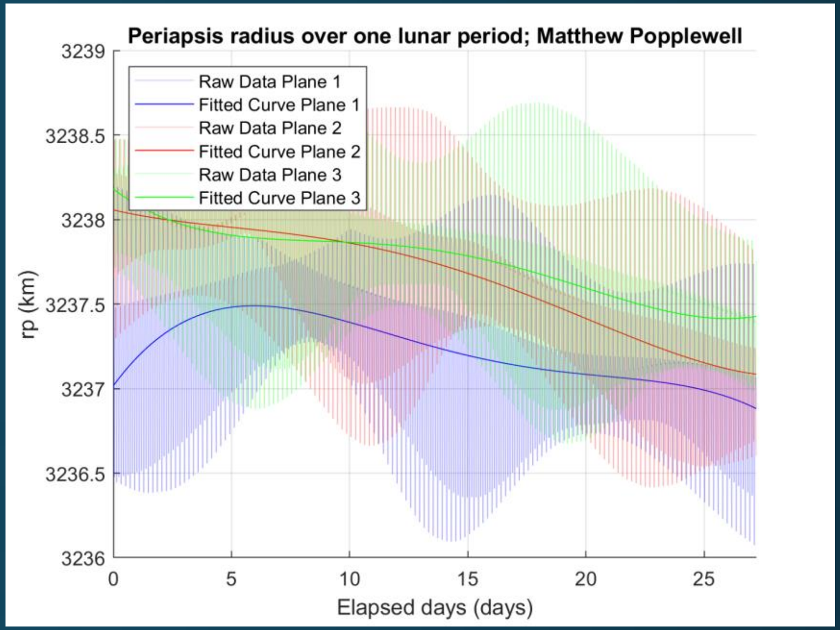
- Walker Constellation configuration was chosen for:
  - Stability
  - Consistent contact with south pole
  - Large surface coverage
  - Potential for expansion
- Choose 6 satellites in 3 orbital planes
  - Continuous and often redundant contact with south pole ground station
  - Cross-link capabilities between satellites
  - Stable - less than 100 m/s per year per satellite for stationkeeping

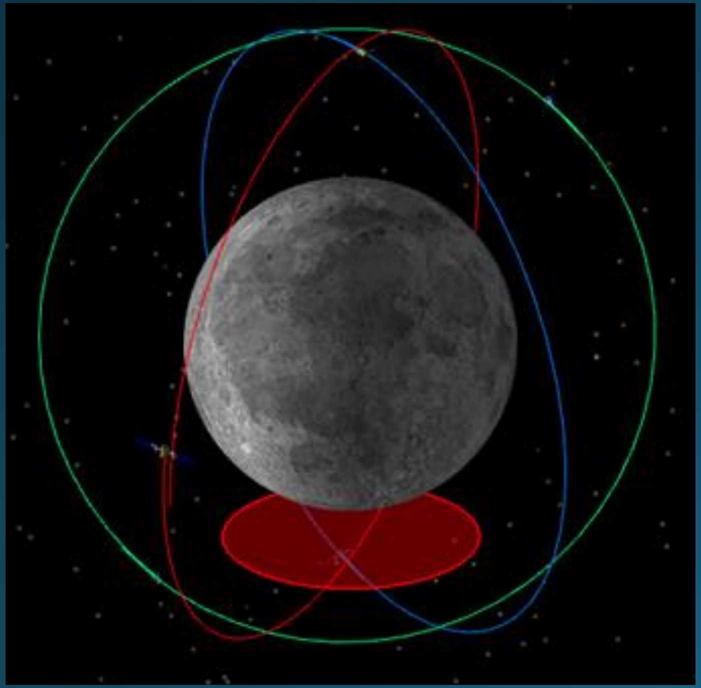


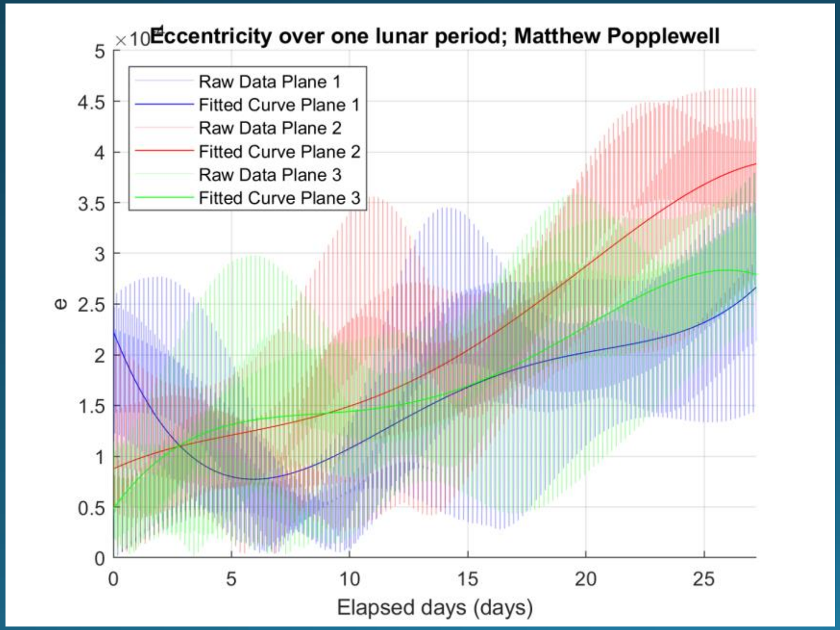
Element	Value
a	3238.2 km
e	0
i	80°
RAAN	0°, 120°, 240°

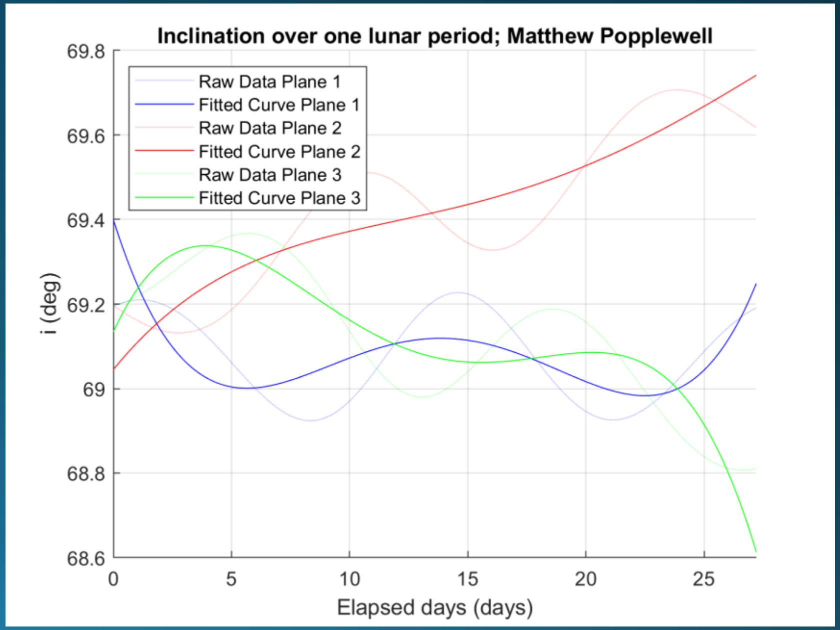



Semi-major axis over one lunar period; Matthew Popplewell
Raw Data Plane 1
Fitted Curve Plane 1
Raw Data Plane 2
Fitted Curve Plane 2
Raw Data Plane 3
Fitted Curve Plane 3
a (km)
3239
3238.8
3238.6
3238.4
3238.2
3238
3237.8
3237.6
3237.4
3237.2
3237
0
5
10
15
20
25
Elapsed days (days)


Periapsis radius over one lunar period; Matthew Popplewell
Raw Data Plane 1
Fitted Curve Plane 1
Raw Data Plane 2
Fitted Curve Plane 2
Raw Data Plane 3
Fitted Curve Plane 3
rp (km)
3239
3238.5
3238
3237.5
3237
3236.5
3236
0
5
10
15
20
25
Elapsed days (days)

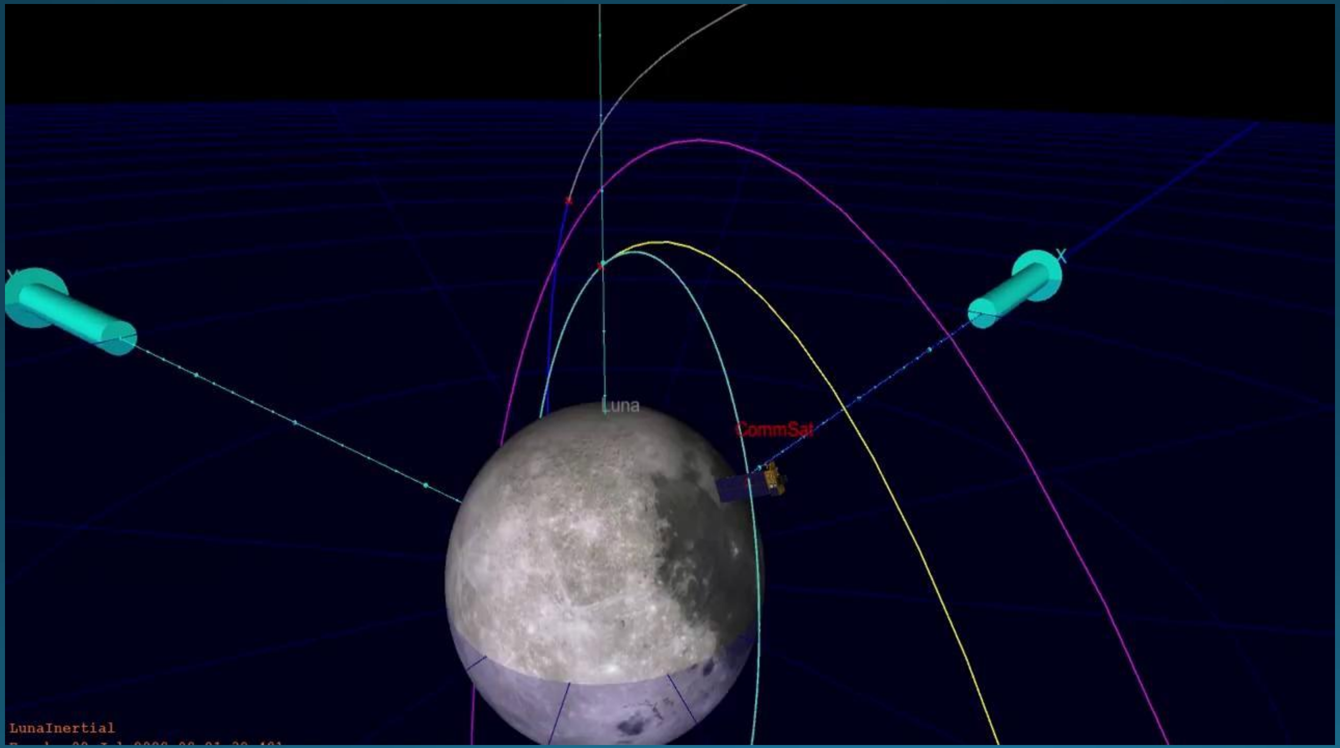



Eccentricity over one lunar period; Matthew Popplewell
×10
Raw Data Plane 1
Fitted Curve Plane 1
Raw Data Plane 2
Fitted Curve Plane 2
Raw Data Plane 3
Fitted Curve Plane 3
e
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Elapsed days (days)


Inclination over one lunar period; Matthew Popplewell
Raw Data Plane 1
Fitted Curve Plane 1
Raw Data Plane 2
Fitted Curve Plane 2
Raw Data Plane 3
Fitted Curve Plane 3
i (deg)
69.8
69.6
69.4
69.2
69
68.8
68.6
0
5
10
15
20
25
Elapsed days (days)

Translunar Trajectories for Communication Satellites

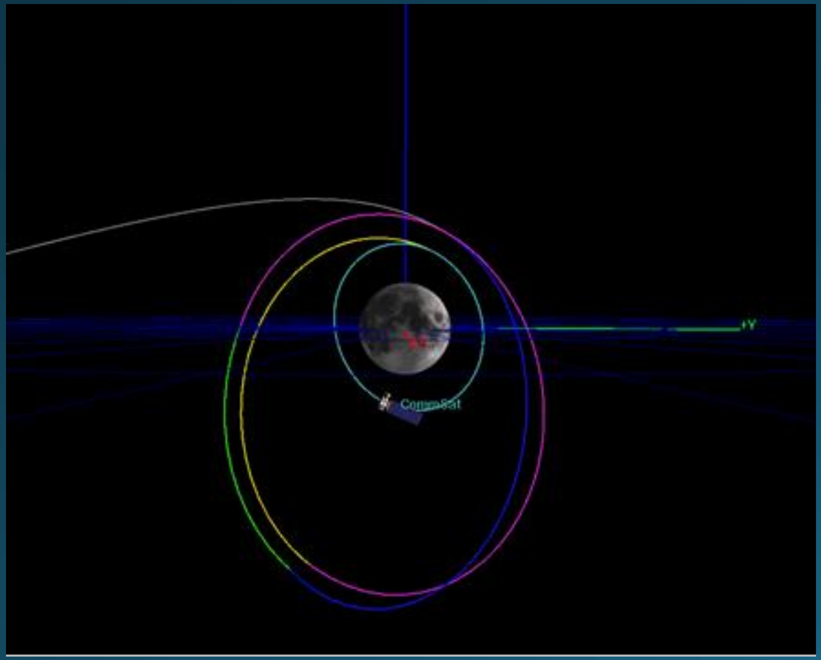
- Launches will require correct phasing
- Three launches will probably be required to set-up the constellation
- Current research into optimal launch windows



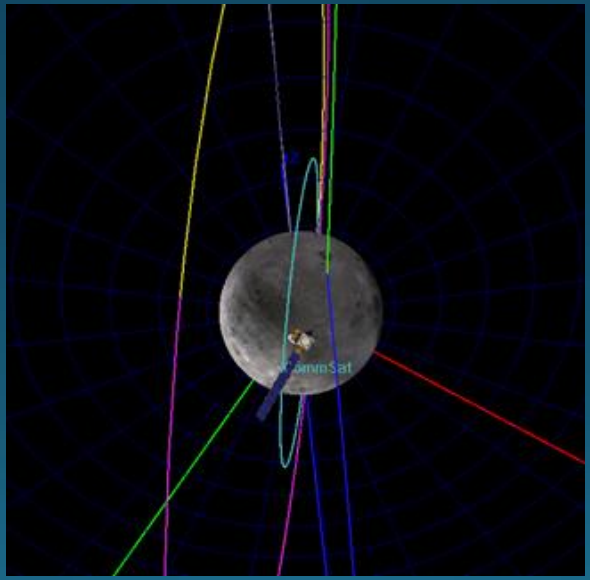
Lunar Arrival and Corrections Animation

Translunar Trajectories for Communication Satellites

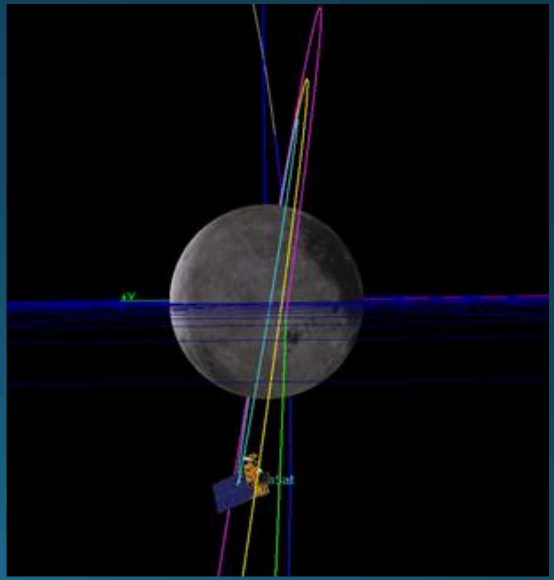
- General translunar trajectory and refinement maneuvers for communication satellite insertion have been developed
- Refinement maneuvering will generally consist of three energy reduction burns and two plane changes



Energy Reduction Maneuvers

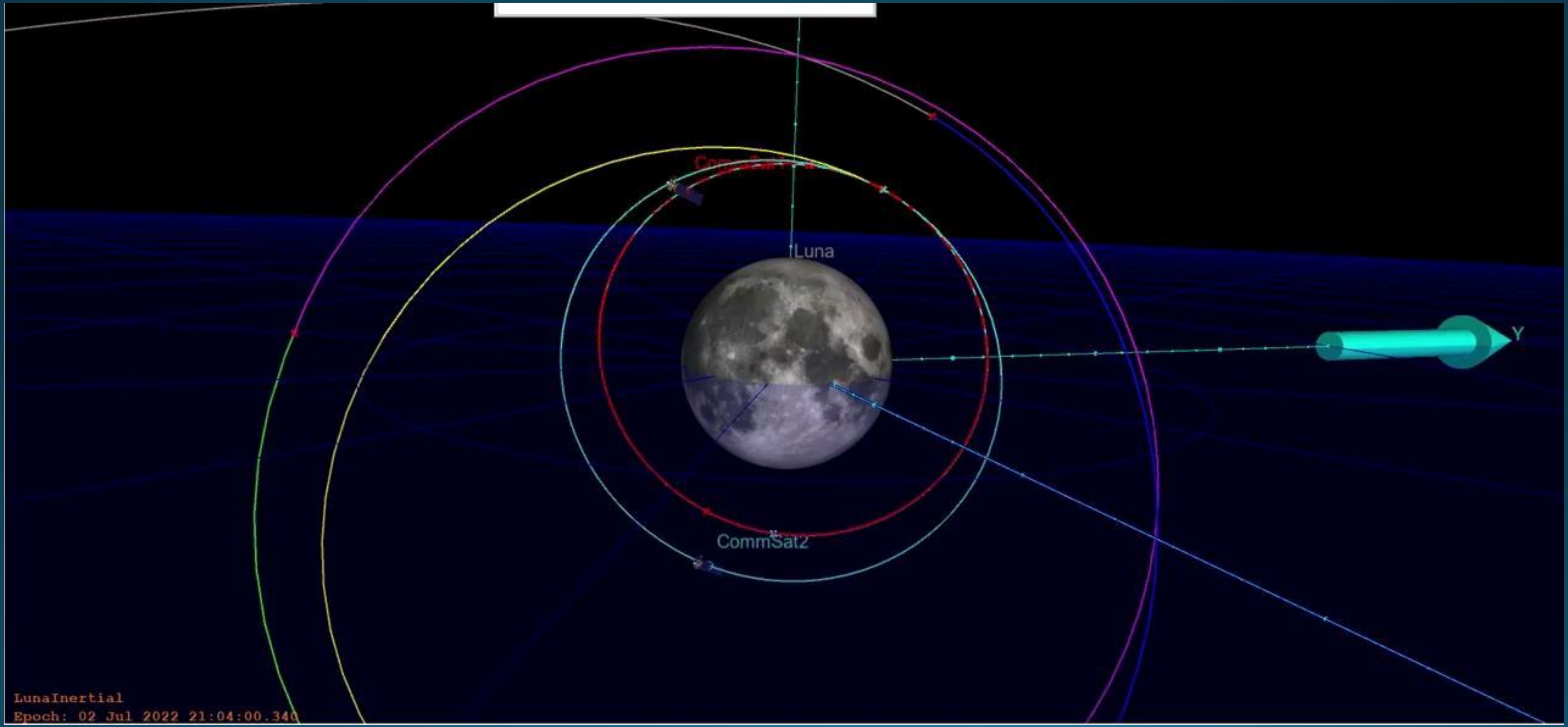


RAAN Adjustment



Inclination Adjustment

Translunar Trajectories for Communication Satellites



Translunar Trajectories for Communication Satellites

Representative ΔV Summary

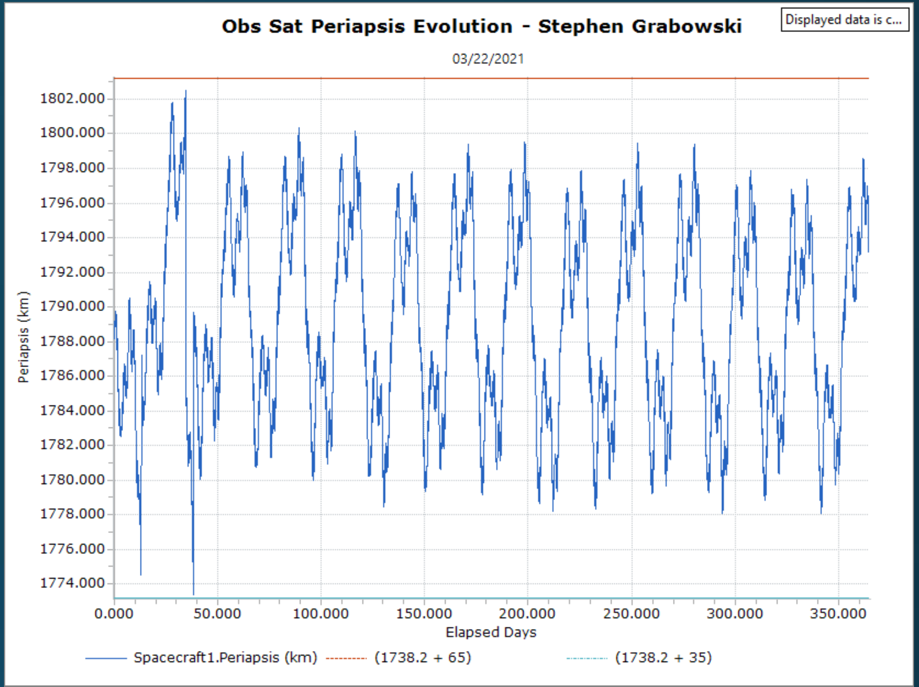
Maneuver Name	V (km/s)	N (km/s)	B (km /s)	Total (km/s)
TLI	3.042	0.000	0.166	3.047
Midcourse Adjustment	0.026	0.070	0.019	0.077
Eccentric Capture	-0.444	0.000	0.000	0.444
RAAN Adjustment	-0.002	-0.063	0.000	0.063
INC Adjustment	0.000	-0.068	0.000	0.068
Periapsis Reduction	-0.039	0.000	0.000	0.039
Apoapsis Reduction	-0.317	-0.002	0.000	0.317
			Total	4.055

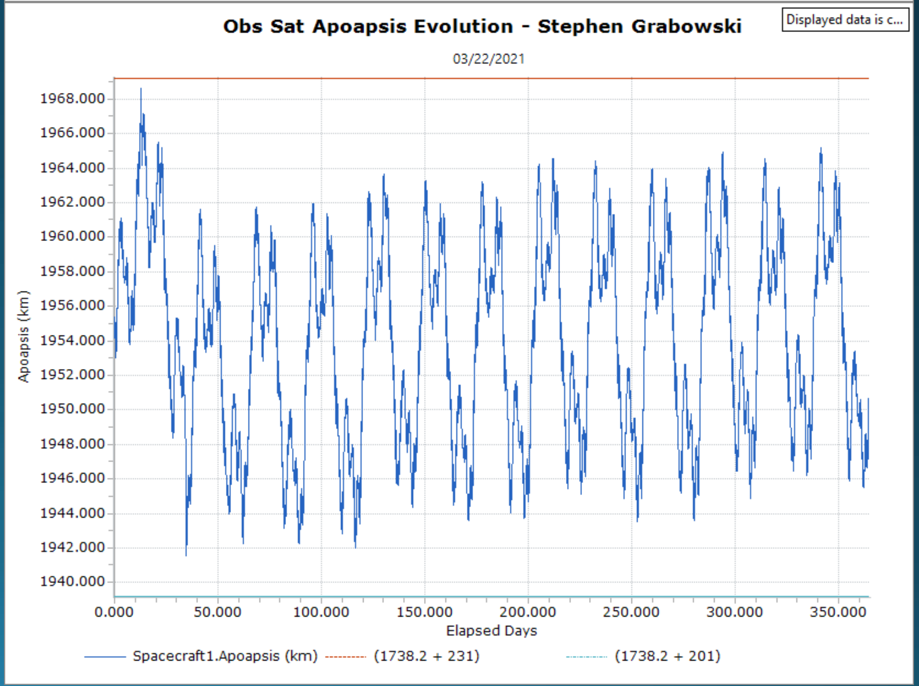
Representative Final Error

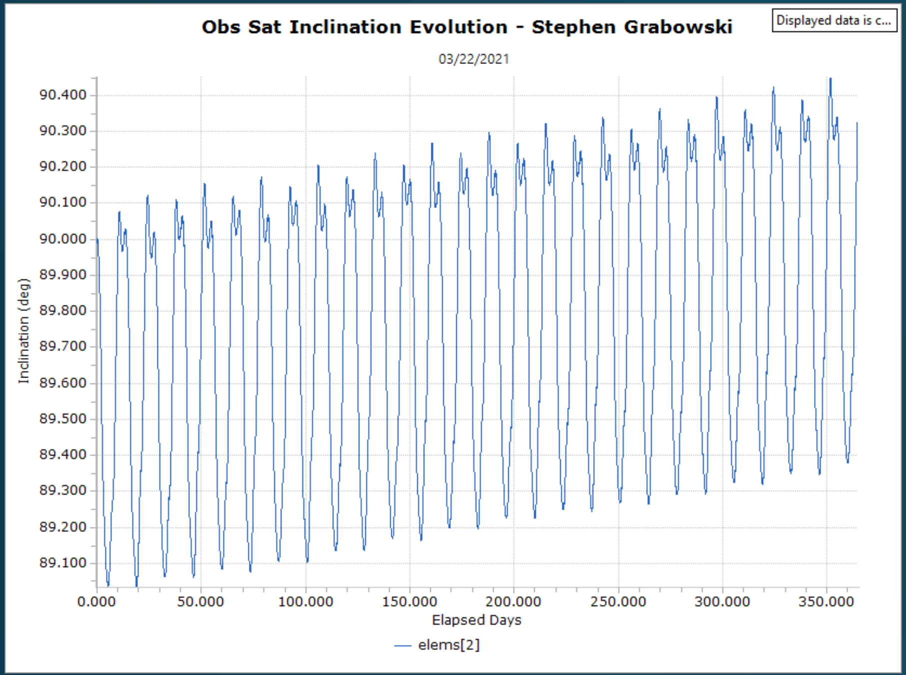
Orbital Parameter	Achieved	Desired	% Error
a	3239.21 km	3238.20 km	0.03
e	0.00	0.00	0.00
Ω	240.00°	240.00°	0.00
i	79.93°	80.00°	0.09

Observation Satellite

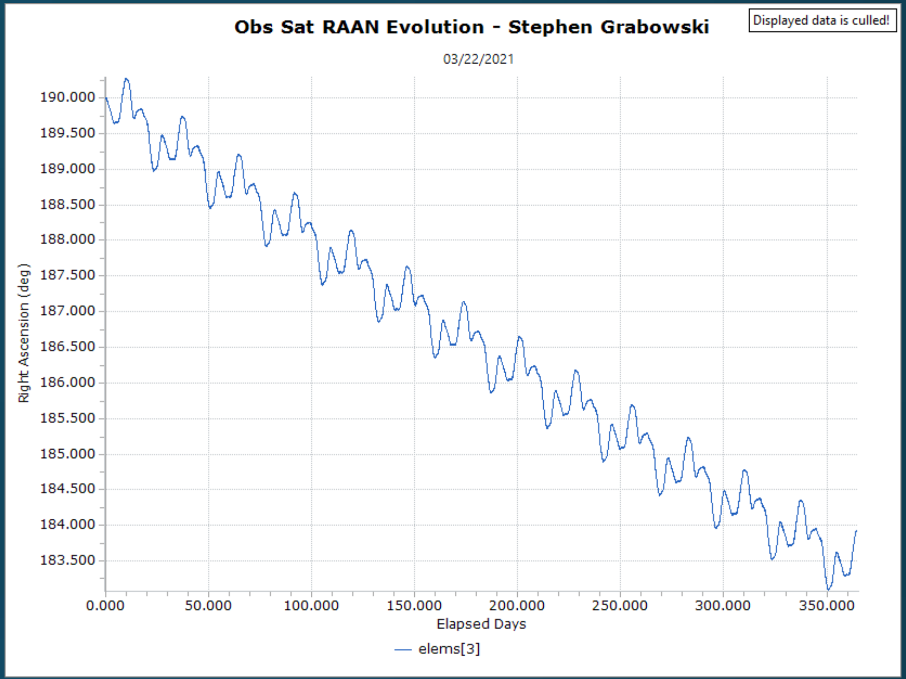
- Quasi-frozen lunar orbit at 50 km x 216 km chosen
  - Periapsis and apoapsis variations naturally bounded
  - Won't eventually impact the Moon like a circular orbit
  - Modeled with Moon $J_{20,20}$ harmonics, Earth, Sun, and SRP
- Requirement to stay within +/- 15 km of nominal altitude when taking images
  - Used as bounds for periapsis and apoapsis
  - Burn targeting no more than once every 13.5 days (half of a lunar sidereal period)
- Yearly delta-v budget of 137 m/s (with impulsive maneuvers)
  - Based on impulsive burn modeling



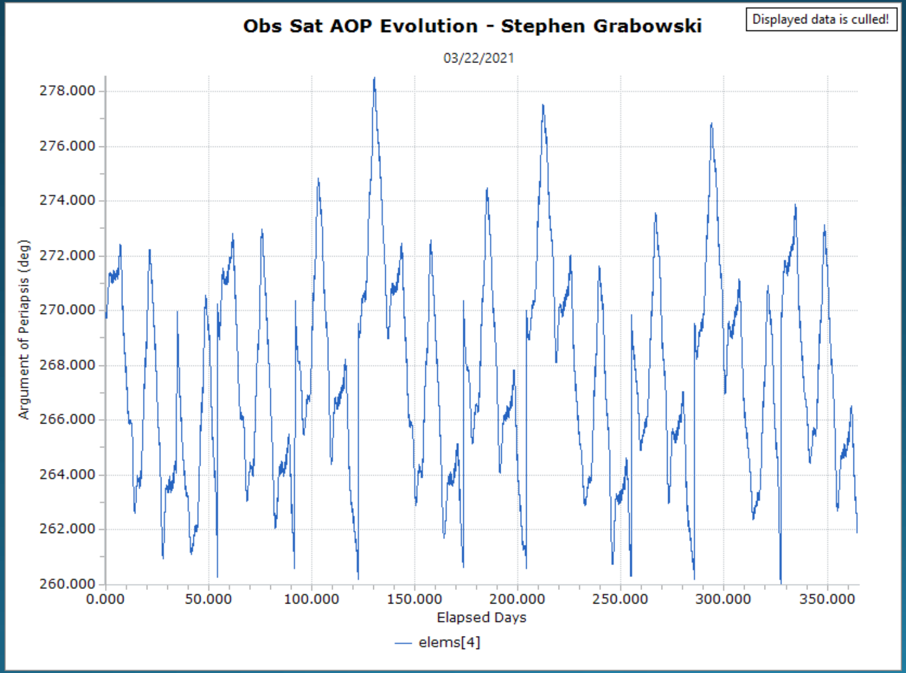




Obs Sat Inclination Evolution - Stephen Grabowski
Displayed data is c...
03/22/2021
Inclination (deg)
90.400
90.300
90.200
90.100
90.000
89.900
89.800
89.700
89.600
89.500
89.400
89.300
89.200
89.100
0.000
50.000
100.000
150.000
200.000
250.000
300.000
350.000
Elapsed Days
elems[2]



Obs Sat RAAN Evolution - Stephen Grabowski
Displayed data is culled!
03/22/2021
Right Ascension (deg)
190.000
189.500
189.000
188.500
188.000
187.500
187.000
186.500
186.000
185.500
185.000
184.500
184.000
183.500
0.000
50.000
100.000
150.000
200.000
250.000
300.000
350.000
Elapsed Days
elems[3]



Obs Sat AOP Evolution - Stephen Grabowski
Displayed data is culled!
03/22/2021
Argument of Periapsis (deg)
278.000
276.000
274.000
272.000
270.000
268.000
266.000
264.000
262.000
260.000
0.000
50.000
100.000
150.000
200.000
250.000
300.000
350.000
Elapsed Days
elems[4]

Communications

AAE 450 - Spring 2021

23 March 2021

Lead: Anna Cismaru

Team members: Alec Leven, Bridget Cavanaugh

PURDUE AERONAUTICS & ASTRONAUTICS

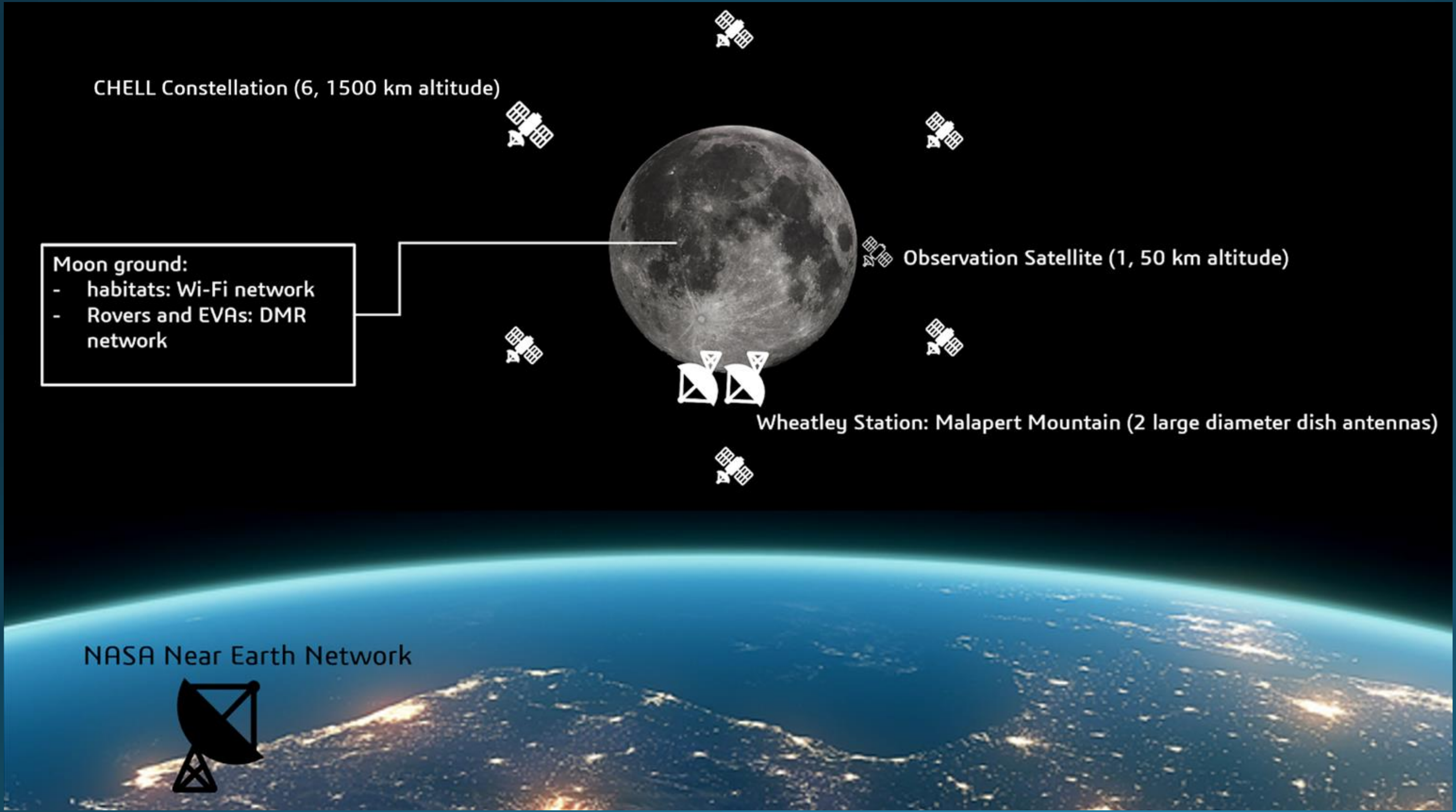
Overview

Overall Goal

Main Purpose

- Ensure that reliable voice communication links exist between all entities that require them for mission execution for the full duration of the mission
- Ensure reliable and efficient transmission of data between vehicles, the colony, Mission Control, and other necessary entities for the full duration of the mission

System Architecture



PURDUE AERONAUTICS & ASTRONAUTICS

Mission Timeline

Year 1

Manufacture satellites

Year 2

Launch observation satellite

Launch first 2 comm sats (Q1), next two comm sats (Q3)

Year 3

❋ humans arrive

Launch last 2 comm sats (Q1)

Launch materials needed to build ground station, Wi-Fi and DMR equipment

Begin ground station construction

Build 1 DMR and internet tower close to the habitat

Year 4

Continue to expand DMR and Wi-Fi networks as colony grows

Year 5

Finish ground station construction

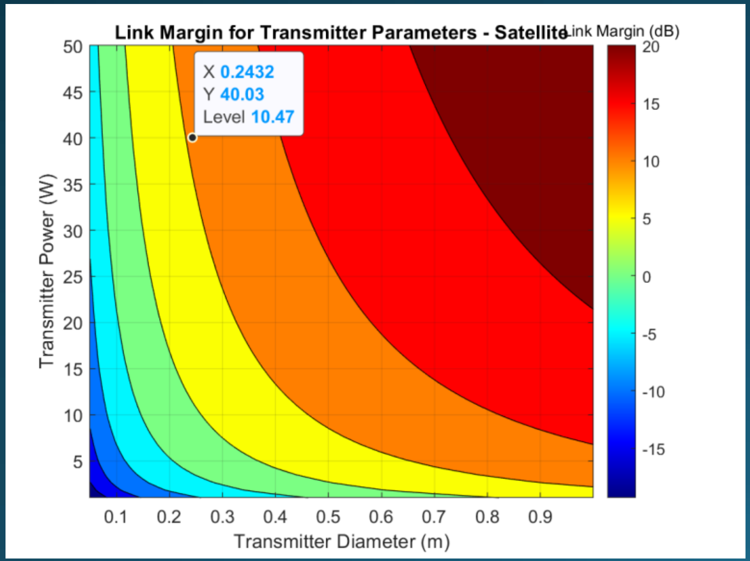
Refined Design

Preliminary Design Review: Resulting Action Items

Action Item Number	Description	Team Member
1	Do required calculations for enabling S or X band voice communications between the Communications constellation and Earth (through NASA NEN).	Alec
2	Do required calculations for enabling S band crosslinking between the Imaging satellite and the Communications constellation.	Bridget
3	Choose all other necessary hardware for the Wi-Fi network in the Colony.	Anna
4	Choose all other necessary hardware for the DMR network in the Colony.	Anna
5	Finalize satellite and ground system power, mass, and volume calculations.	Anna
6	Add all hardware to the Master Equipment List.	Everyone
7	Perform risk and failure analyses.	Everyone

1: Voice Connection between Comm Sats and Earth

- **From link budget, transmitter power and diameter were calculated**
  - Assuming 64 kbit/s data rate
  - Transmitter Power: 40.03 W
  - Transmitter Diameter: 0.243 m
- **Power was increased to ensure a minimal diameter**



***Left*:** Optimizing Map of Link Margin in S-Band for Satellites

Table 1. Link Budget Table for Satellite-NEN Connection

Item	Value
Frequency	2.1 GHz
Transmitter Power	**40.03 W**
Transmitter Beamwidth	41.12°
Transmitter Diameter	**0.243 m**
Transmitter Gain (net)	12.02 dBi
Receiver Beamwidth	0.546°
Receiver Diameter	18.3 m
Receiver Gain (net)	70.5 dBi
Propagation Path Length	381000 km
Data Rate	64 kbps
Link Margin	10.47 dB

2: Imaging Satellite Crosslinking

Images transmitted in S band from imaging satellite to communication satellites

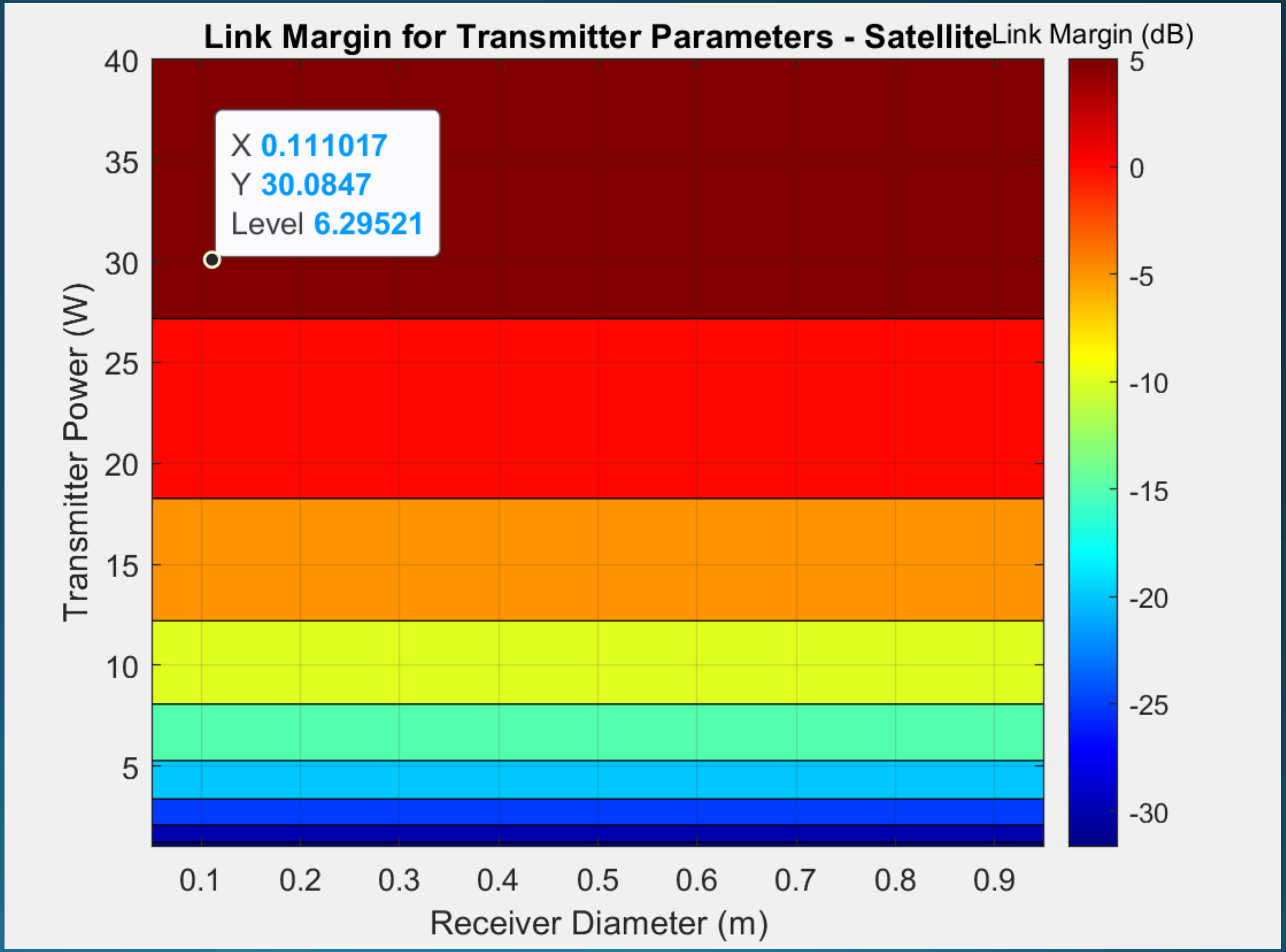
Imaging satellite:

- patch antenna with ~0.1 m diameter

For 6 dB link margin:

- Receiver satellite: patch antenna with ~0.1 m diameter
- transmitter should output at least 30 W of power

Figure 1: Link Margin for crosslinking imaging and comm satellites



2: Imaging Satellite Crosslinking (continued)

S-Band Antenna Wideband - patch antenna chosen for communications satellites to receive images

Figure 1: Image of S-band comm sat patch antenna by Endurosat

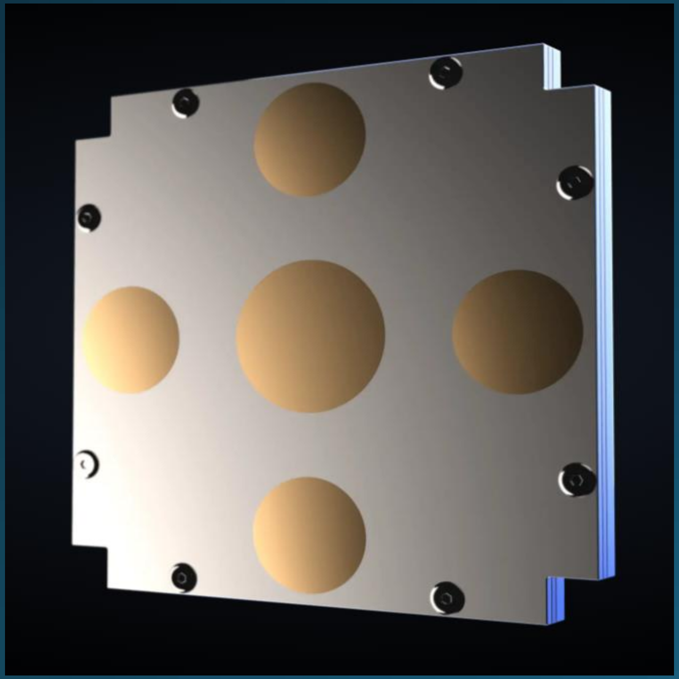


Table 1: patch antenna features

Features	
Frequency Ranges	*2025-2110 MHz and 2200-2290 MHz*
Half Power Beam Width (HPBW)	*70 deg*
Gain	*5+ dBi*
Polarization	*Right Hand Circular*
Mass	*115 g*
Custom Mounting	*X/Y or Z CubeSat mounting*
RF Output Power	*up to 4W*

3: Wi-Fi Network

Type	Purpose	Product	Mass (kg)	Power Use (W)	Dimensions (in)	Unit Cost (USD)
Personal Laptops	Interface for colonist interaction with Earth	Lenovo ThinkPad T14	1.46	n/a	12.9 x 8.9 x 0.7	972
Access Point	Distribute information received and converted at the router to the appropriate machines in the habitat	Ubiquiti UniFi PRO	0.45	9	7.74 x 7.74 x 1.38	150
Modem	Convert RF signal from the cable to IP	Ubiquiti UniFi Dream Machine Pro	3.9	33	17.42 x 1.72 x 11.42	379
Cable	Transmit information from base station to habitats	Ubiquiti USIP Cable Pro	1 box: 12	n/a	1 box: 13 x 13 x 13.4	135
Wi-Fi Base Station Server at Mission Control	Send information received from Earth towards habitats	Ubiquiti EdgeRouter 8	2.3	35	19.06 x 6.46 x 1.73	329

4: DMR Network

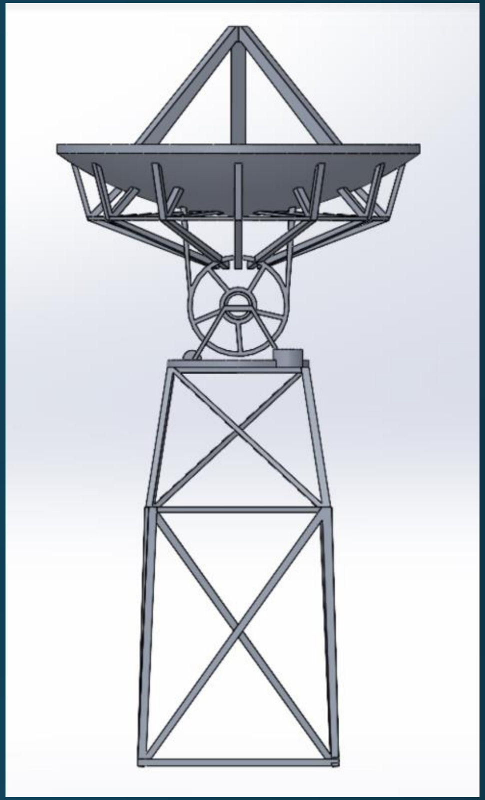
Type	Purpose	Product	Mass (kg)	Power Use (W)	Dimensions (in)	Unit Cost (USD)
Handheld Radio	Voice connection between all members of the colony	Motorola DEP 450	0.3	4	5.0 x 2.4 x 1.7	300
Mobile Radio	Voice connection to rovers	Motorola XPR 5550e	1.8	40	2.1 x 6.9 x 8.1	600
Repeater Unit	Enable communication over longer distances	Motorola SLR 1000 Repeater	4.5	10	11 x 9 x 4	4000
Base Station	Central node for the whole network					
Repeater Unit		Motorola SLR 1000 Repeater	4.5	10	11 x 9 x 4	4000
Antenna		Laird FG4607	1.36	n/a	106 x 1.3 (diameter)	300
Power Source		Samlex SEC-1235M	1.54	n/a	7.28 x 8.19 x 2.4	200

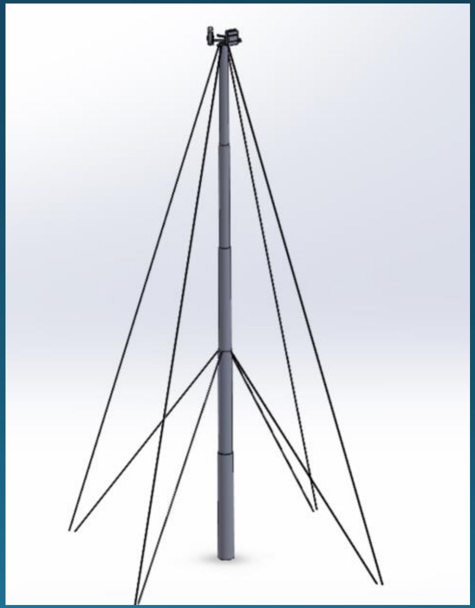
5: Power, Mass, and Volume

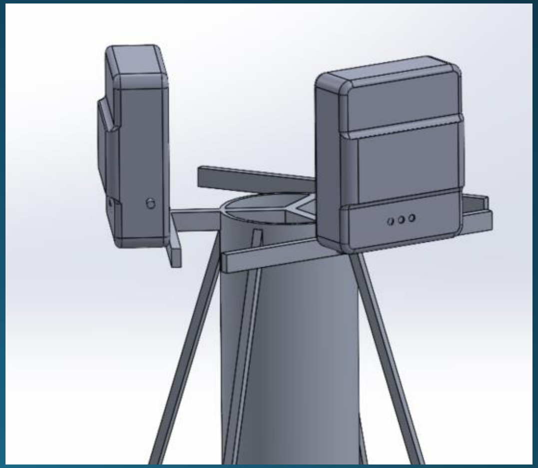
Power for ground systems: **1.222 kW**
Mass for ground systems: **99.9 Mg**
Volume for launch: **54.5 m^3**
*of ground systems only

6. Master Equipment List: Communications

✔ MEL Completed







CAD models provided by Nicky Masso

7. Risk and Failure Analyses

Possible Failure Points:

- Wheatley Station Earth Antenna
  - Mitigation: in the event of failure, CHELL satellites can be used to communicate (voice and data) to Earth until problem is resolved
- Wheatley Station Satellite Antenna
  - Mitigation: in the event of failure, CHELL satellites can downlink to Earth, and NEN can rebroadcast to Wheatley Station Earth
- DMR repeaters
  - Mitigation: multiple repeaters are used for redundancy
- Potential impact by space debris
  - could bump satellites out of orbit
  - could cause damage to satellites
  - could cause satellites to become unoperational
- connection issues/interference by foreign objects causing satellites to have trouble reaching ground stations
- satellite wear and tear over time causing speeds of data transmission to slow

Launch Vehicle

AAE 450 - Spring 2021

03/23/2021

Launch Vehicle Team

Purpose, Requirements, and Assumptions

- Purpose
  - Transport cargo and colonists to LEO, TLI, LLO
- Requirements
  - Minimize cost per Mg to desired orbit
  - Safely transport colonists to LLO starting 2023
  - Transport colonists from lunar colony back to earth after designated habitation cycle
- Assumptions
  - Starship will not be available until 2023 (Q3 or Q4)
  - Adequate supply of in-service launch vehicles

Pre 2023 Launch Vehicles

- Requirements
  - Starship unavailability requires other heavy lift vehicles
  - Transport cargo past LEO at lowest $/Mg
- Falcon Heavy (Expendable)
  - Initial cargo transports to LLO
- Falcon Heavy (Reusable)
  - Fuel depot to LEO
- Falcon 9 (Expendable)
  - Launch satellites into Lunar Orbit

Post 2023 Launch Vehicles

- Requirements
  - Starship unavailability requires other heavy lift vehicles
  - Transport cargo past LEO at lowest $/Mg
- Starship
  - Colonist transport becomes available
  - Fairing size increases from 300m^3 to 1100m^3
- Falcon Heavy
  - Approximately 9.8-10.6 million dollars per Mg to LLO
  - Can be used to supplement Starship if situationally necessary

Launch Vehicle Statistics

Vehicle	Cost per Launch	Fairing Volume (m^3)	Payload to LLO (Mg)	Cost per Mg to LLO (M$ / Mg)
Falcon Heavy Reusable	90 million	295.2	4.00-5.00	18-22.5
Falcon Heavy Expendable	150 million	295.2	14.1-15.3	9.80-10.64
Falcon 9	62 million	240.61	4.00-5.00	12.4-15.5
Starship (with LEO refuel)	120 million	1100	87.1 - 90.7	1.32-1.37

Launch Mission Tool

- User inputs of payload, desired orbit, and timeframe for optimal launch vehicle
- Decides if launches are feasible prior to starship introduction
- Includes array functionality for multiple launches

```
>> payloadmasskg = 4000;
>> destination = {'lunar surface'};
>> timeofmission = {'pre 2023'};
>> LaunchMission(timeofmission,destination,payloadmasskg)

Here is your mission!
Launch Vehicle: Falcon Heavy Expendable
Thrust: 22800.00 kN
Cost: $150 millions
Volume Constraints: fairing size 13 m long by 5.2 m in diameter
Lander: Apollo Cargo Variant
```

```
function LaunchMission(timeofmission,destination,payloadmasskg)
%LAUNCHMISSION the Launch Mission function serves as a tool to allow an
%inputted payload mass, with given time of mission (pre-2023 or 2023),
%and given destination (orbit or lunar surface)
%INPUTS:
% 1. timeofmission: string, period of mission for launch, 'pre 2023' or
% 'post 2023' assuming Starship is available in 2023
% 2. destination: string, destination of payload 'lunar orbit' or
% 'lunar surface'
% 3. payloadmasskg: scalar, mass of payload in [kg]
%OUTPUTS Printed:
% 1. launchvehicle: string, ideal launch vehicle for given parameters
% 2. cost: string, launch cost (approximate) for given parameters in
% [millions of $]
% 3. volumeconstraints: string, volume constraints for given launch vehicle
% 4. thrust: scalar, first stage thrust value in [kN]
% 5. lander: lander vehicle to lunar surface (if 'lunar surface'
% destination)
%
% Launch Vehicles:
% Pre-2023
% 1. Falcon 9 Expendable
% 2. Falcon Heavy Reusable
% 3. Falcon Heavy Expendable
% 3. Starship (post-2023)
%
% Landers (if 'lunar surface'):
% 1. Nova-C (on F9 capable of 100 kg)
% 2. Sky Crane
% 3. Starship (post-2023)

% Assumptions:
% -plan A (Starship available starting in 2023 (destination = 'post 2023')
% -rough calculations of kg to LLO for Falcon 9 and FH (Hohmann after GTO)
% -Nova-C private lander available for small surface payloads before 2023
% -Starship is actually ~$200 million per launch and is assumed to be
% refueled in LEO, able to send 100 tons to LLO
```

Lunar Descent Module

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Summary

- 3 Phases of Mission
  - Phase 1: Pre-Starship (2021-2023 Q4):
    - Modified Apollo Lander Module
    - Limited Launch Schedule and Capability
    - LEO and LLO Missions prioritized
  - Phase 2: Starship, No LLO-Refueling (2024 Q1-Q4):
    - Limited Launches
    - Initial Cargo Launch and First Humans Land
  - Phase 3: Fully Reusable Starship (2025 on):
    - Increased launch amounts
    - majority of mass sent

Important Figures

Vehicle	Cost (Million Dollars), Payload to Moon	Payload (Mg)	Passengers
Starship	850	91	100
Apollo	360	5	0

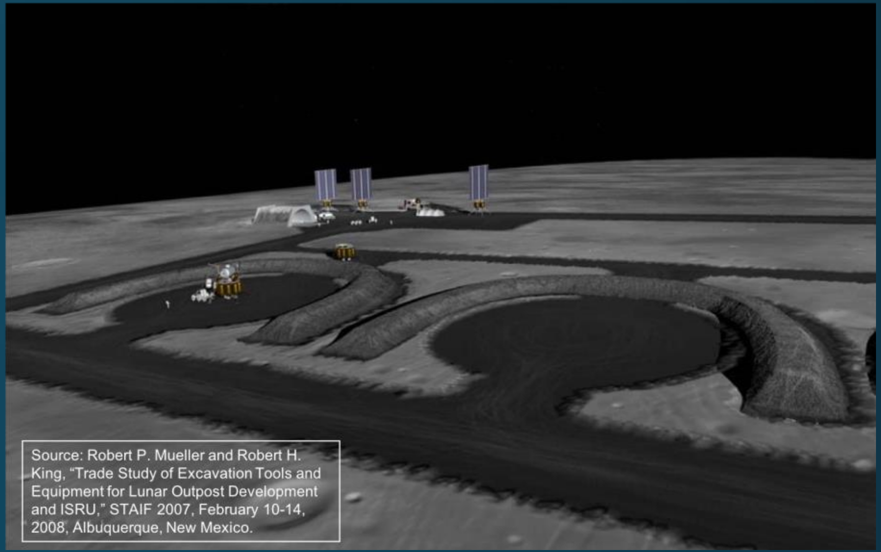
Initial Manned Mission Timeline

- First Starship lands in 2023
  - 100 ton payload consists of entirely cargo
    - Payload dimensions: 9m diameter and 18m height
  - Autonomous lunar rovers began assembly and construction of human habitat
- Second Starship lands in 2024 with 5 crew and cargo
  - Stays on lunar surface for 6 months
  - Will carry 3 Lockheed Martin Ascent Elements to ferry crew
    - Lockheed Martin Ascent Element Dimensions: 3.6 m diameter and 5.3 m height
- 3rd Starship launches and orbits moon at 6 month stage
  - Ascent Elements ferry crew to 3rd starship to return to earth

Blue Origin Descent Element and Lockheed Martin Ascent Element

Images obtained from:https://www.blueorigin.com/blue-moon/lunar-transport

Landing/Launch Pads



- Sizing
  - 4 different launchpads
    - Each 24m diameter
  - Reduce regolith ejection around base
    - Limit large projectiles from damaging surrounding equipment or habitats
    - Protect solar panels from dust accumulation
    - Build ring around launchpad to further reduce additional ejection
  - Serve as launchpads for ascent stages
- Logistics
  - 452.4 m^2 per launch pad
  - Regolith clearing at a rate of 0.0688m^3/min from single regolith clearing rover
    - 109.6 hours per pad

Propellant Depots

AAE 450 - Spring 2021

3/23/2021

Brad Bulczak, Noah Niklaus, Trevor Pfeil, Theresa Sitter, Sarah Wagenaar

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Updated Mission DV Values

	CREWED	
	mission leg	**Delta V (km/s)**
1	earth ascent --> 600 km orbit	9.5
2	rendezvous with leo depot	0.01
3	TLI	3.1468
4	FRD	0.19963
5	LOI	0.950233
6	rendezvous w lunar depot	0.01
7	LLO (100 km) --> lunar surf	2.5
8	lunar surf --> LLO	2.2
9	rendezvous w lunar depot	0.01
10	LLO --> earth reentry	0.34896
11	starship landing	mp reqd for landing calculated

	UNCREWED (CARGO), JUST TO LUNAR SURF	
	mission leg	Delta V (km/s)
1	earth ascent --> 600 km orbit	9.5
2	rendezvous with leo depot	0.01
3	TLI	3.1809
4	lunar circularization	0.8928
5	LLO (100 km) --> lunar surf	2.5

where values have +0.1 km/s added for GMAT modeling inaccuracies

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Depot Minimum Mass Requirements

Analyzed mission profiles including :

1. Crewed vs. uncrewed missions
2. One way trips vs. return missions

Minimum mass of propellant at each depot to accommodate all mission types:

- LEO Depot Required Storage: 1065.121 Mg
- Lunar Depot Required Storage: 429.421 Mg

Flight Counts

For a crewed mission from Earth → Lunar Surface (100 Mg of payload)

- 5.5 tankers to load LEO depot
- 1 Starship with payload to the lunar surface

For a crewed mission from Earth→ Moon → Earth (100 Mg of payload to Moon)

- 7 to load LEO depot to refuel the lunar tankers
- 2 to load the LEO depot
- 1.33 lunar tankers to load Lunar Depot
- 1 Starship with payload to the lunar surface

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Depot Design, Tank Sizing

- Use cylindrical tanks with hemispherical ends
- Within a case that protects from debris that is attached to the dock
- Tank dimensions for LEO (using Falcon Heavy as LV)
    - LOX needs two tanks with r = 2.5 m , h = 18.5m
    - LCH_4 needs two tanks with r = 2.5 m, h = 13.3m
- Tank Dimensions for Lunar (using Starship as LV)
    - LOX needs one tank with r = 2.4 m, h =16.32m
    - LCH_4 needs one tank with r = 2.4m, h = 11.75m

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Depot Construction Plans

- Use Falcon Heavy for LEO Depot construction
  - Falcon Heavy Fairing Dimensions: $r = 2.6$ m , $h = 6.5$ m
  - LOX requires 6 launches and LCH_4 requires 4 launches
  - Assembled in LEO
- Use Starship and/or Falcon Heavy for Lunar Depot construction
  - Start construction soon after Starship is available to use
  - For crew returns starting year 2025, will need lunar depot ready before
- Add Shields / Thermal Systems and Begin Depot fueling

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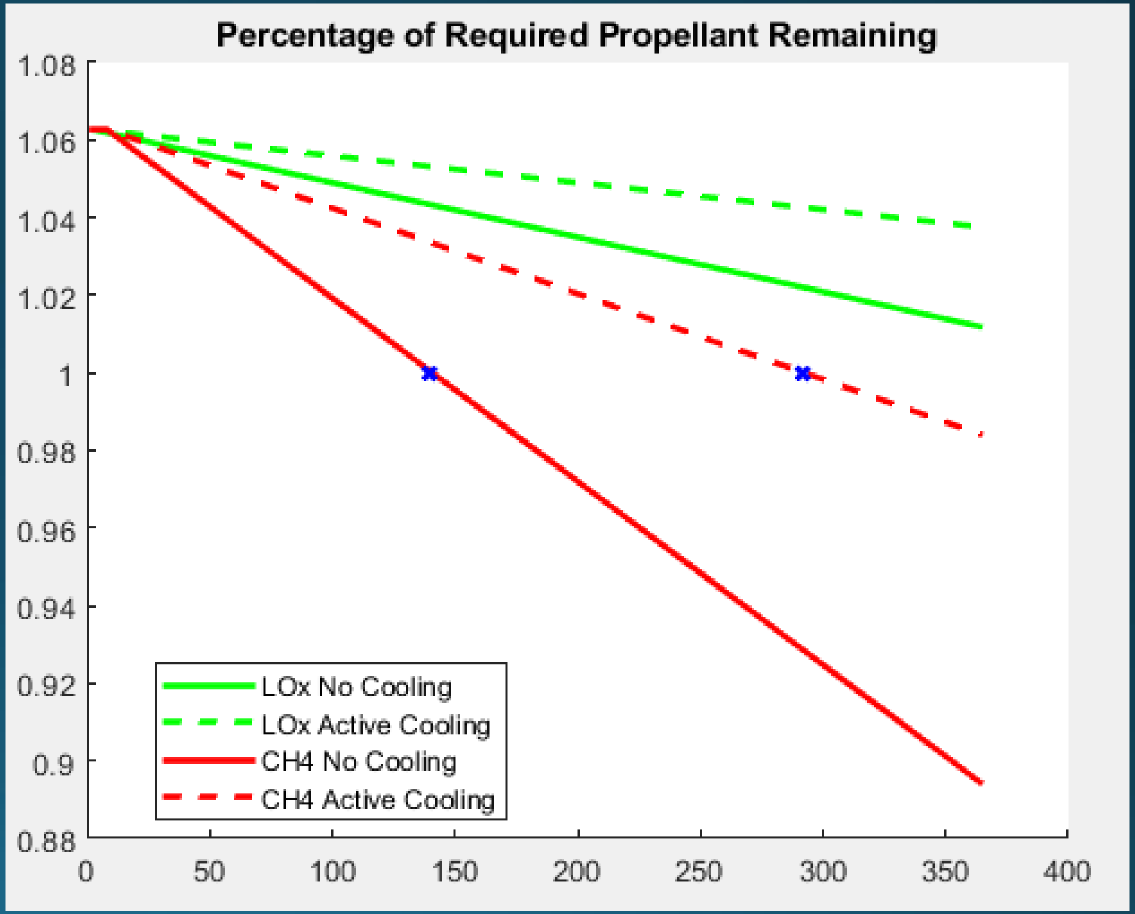
Thermal Boil Off for Stored Propellant

- Expected heat load of 0.6W/m²
- Active cooling capacity of 300W
- No cooling daily methane boil off: 113.6064 kg
- No cooling daily LOx boil off: 119.7066 kg
- Cooled daily methane boil off: 53.0456 kg
- Cooled daily LOX boil off: 59.1458 kg
- For fully loaded LEO depot (1162 Mg) maximum storage period of 292 days with cooling or 140 days with no cooling



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Next Steps

- Finalize depot system mass and power sizings
  - controls systems, thermal systems
- Finalize depot construction launch #'s and dates
- Finalize propellant transfer method

Backup Slides

Depot Minimum Requirements

For an uncrewed mission from Earth ⟶ Lunar Surface:

- With 1 full refueling stop in LEO, can take up to 100 Mg of payload
- LEO Depot min. required storage: 984.493 Mg

For a crewed mission from Earth ⟶ Lunar Surface:

- With 1 full refueling stop in LEO, can take up to 100 Mg of payload
- LEO Depot min. required storage: 1065.121 Mg

For crewed mission from Earth ⟶ Lunar Surface ⟶ Earth Surface:

- Will require refueling at both LEO and lunar depots
- Payload delivered to lunar surface: 100 tons, Return Payload: crew of 19 (3.705 Mg)
- LEO Depot min. required storage: 378.983 Mg
- Lunar Depot min. required storage: 411.834+17.587 Mg = 429.421 Mg

PURDUE AERONAUTICS & ASTRONAUTICS

Flight Counts

For an uncrewed mission from Earth → Lunar Surface:

- To deliver 984.493 Mg of fuel to LEO depot requires 5.33 tankers (i.e, 6 flights) from earth
- 1 Starship with payload to the lunar surface

For a crewed mission from Earth → Lunar Surface (100 Mg of payload)

- To deliver 1065.121 Mg of fuel to LEO depot requires 5.77 tankers (i.e, 6 flights) from earth
- 1 Starship with payload to the lunar surface

For crewed mission from Earth → Lunar Surface → Earth Surface:

- To Deliver 429.421 Mg of fuel to lunar depot requires 2.33 tankers (i.e, 3 flights) from LEO depot
  - Fully refueled by LEO before departure
  - Requires multiple refuels of LEO depot
- To Deliver 378.983 Mg of fuel to Leo depot requires 2.05 tankers (i.e, 3 flights) from earth
- 12 total flights to fuel both depots
- Payload delivered to lunar surface: 100 tons, Return Payload: crew of 19 (3.705 Mg)

Systems - Habitat

AAE 450 - Spring 2021

03/23/2021
Critical Design Review

Team Lead: Sean Anderson

Team Members: Dylan Anderson, Sarah Baxter, Lara Cackovich, Seth Cantrell, Derek Carpenter, George Carroll, Wellington Froelich, Jason Kelly, Christian Mandrell, Hunter Mattingly, John Matuszewski, James Pannullo, William Wyatt Stahlschmidt

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Summary of Changes

- Total mass increased from 166 Mg to 186 Mg
- Total volume increased from 4250 m^3 to 4715 m^3
- Number of modules increased from 7 to 8
- Port diameter increased from 2.0 m to 2.5 m
- Floor height raised from 1.701 m to 2.644 m
- Revised airlock module design, combines the airlock and connector modules
- Revised regolith support structure
- Revised total cost

Purpose & Problem

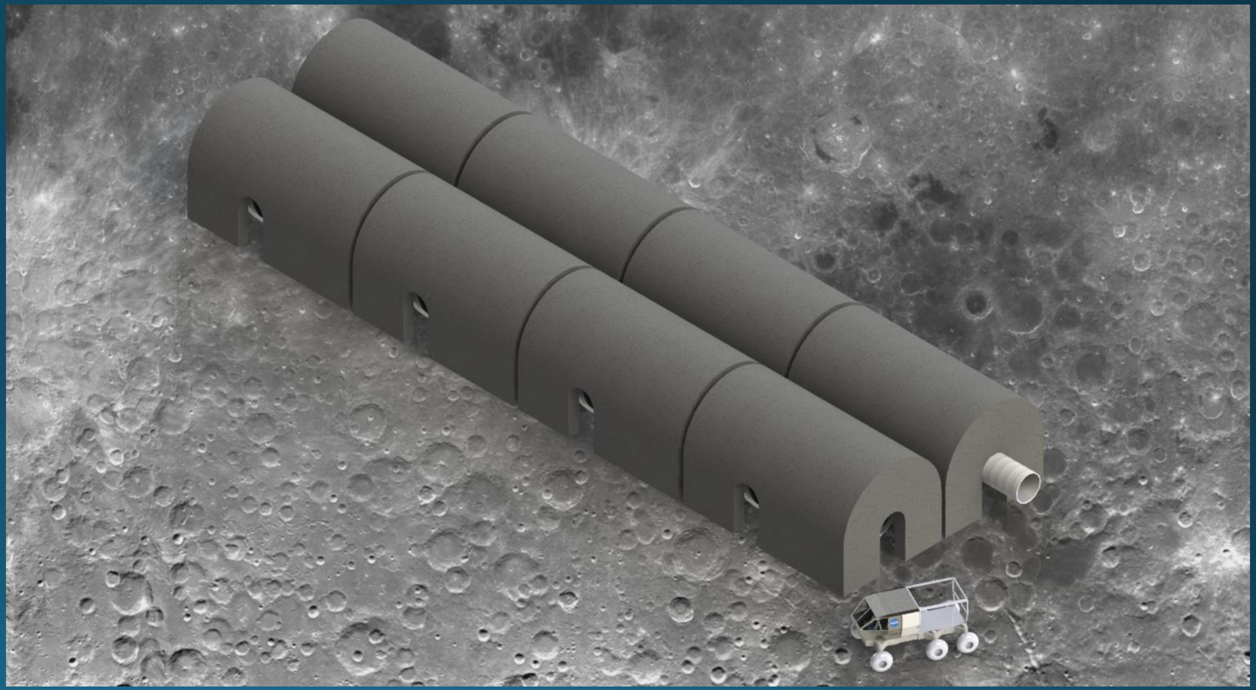
A permanent lunar surface base is a key part of colonizing the Moon. The base will protect the crew from radiation and micrometeorite debris while serving as a place for the crew to live and work on the lunar surface.

- **Requirements**
  - Habitat modules must fit in Starship
  - Habitat should be designed to be modular and easily expandable
  - The modules should protect the crew from radiation and micrometeorite debris
  - Overall Volume/person = 103 m^3/person
  - Minimum ceiling height = 3.1 m
- **Need to Determine**
  - Type of habitat module
  - Shape and sizing of the habitat modules
  - Layout of the modules
  - Mass, power usage, and volume of the habitat
- **Assumptions**
  - Starship is ready by 2024 and capable of sending at least 90 Mg to lunar surface
  - Starship cost $117M per launch

Solution: Armstrong Base

The proposed lunar habitat is an inflatable/rigid hybrid structure comprised of 8 habitat modules and 12 airlocks. The design allows for modularity and scalability while meeting crew needs.

- **Total Mass:** 186 Mg
  - Habitat: 83.8 Mg
  - Power: 102.0 Mg
  - Furnishings: 14.0 Mg (20% of Structure)
- **Total Power Needed:** 200 kW
- **Total Volume:** 4715 m^3
  - Habitat
    - Pressurized: 4516 m^3
    - Habitable: 3223 m^3
  - Power: 326.4 m^3
- **Crew Size:** 19
- **Total Habitat Cost:** $36.66B
  - Habitat materials, power materials, launches, manufacturing, and operating

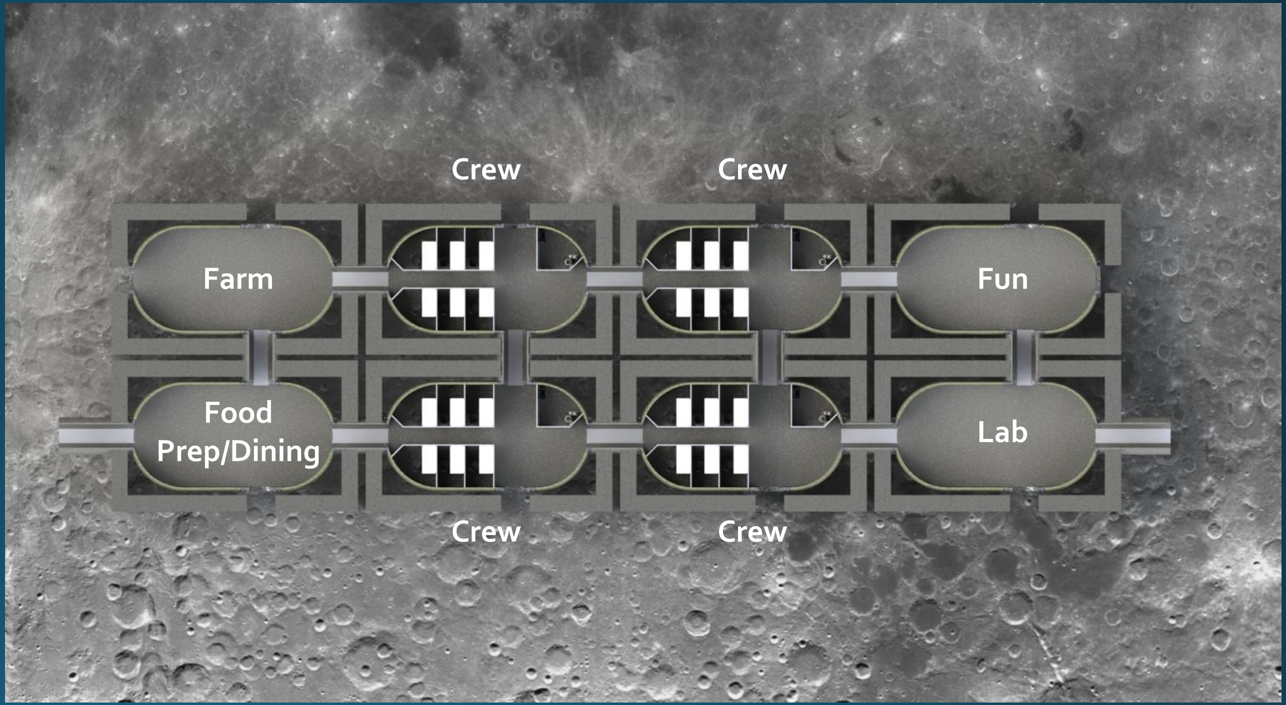


CAD Models by John Matuszewski

PURDUE AERONAUTICS & ASTRONAUTICS

Overview

- **Construction & Materials**
  - Inflatable/Rigid Hybrid Pill-shaped module
  - External cage supports regolith
- **Layout**
  - 4 crew modules, 1 farm, 1 kitchen/dining/misc., 1 lab, 1 fun module
  - Allows up to 12 egress points (2 included)
- **Modularity**
  - 2 Simple designs: habitat and airlock
  - Allows for scalability
  - Sustainable growth
- **Safety**
  - Min. of 2 exits per module
  - Every module accessible from any module even if one is compromised



CAD Model by John Matuszewski

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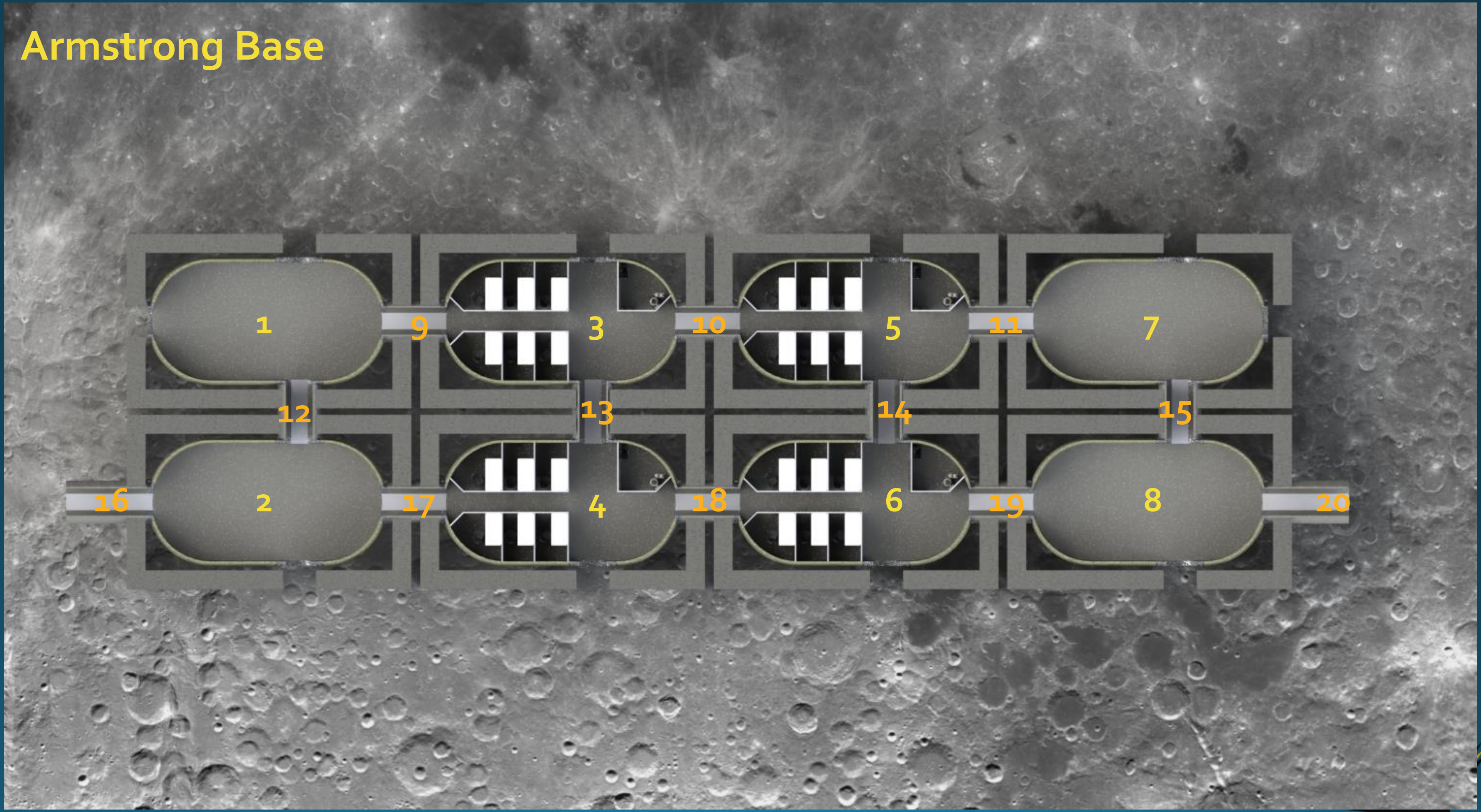
Module Names

1. Aldrin Module
2. Collins Module
3. Bean Module
4. Shepard Module
5. Cernan Module
6. Mitchell Module
7. Schmitt Module
8. Scott Module
9. Conrad Airlock
10. Gordon Airlock
11. Evans Airlock
12. Lovell Airlock
13. Swigert Airlock
14. Roosa Airlock
15. Worden Airlock
16. Haise Airlock
17. Irwin Airlock
18. Young Airlock
19. Mattingly Airlock
20. Duke Airlock



Armstrong Base Cost

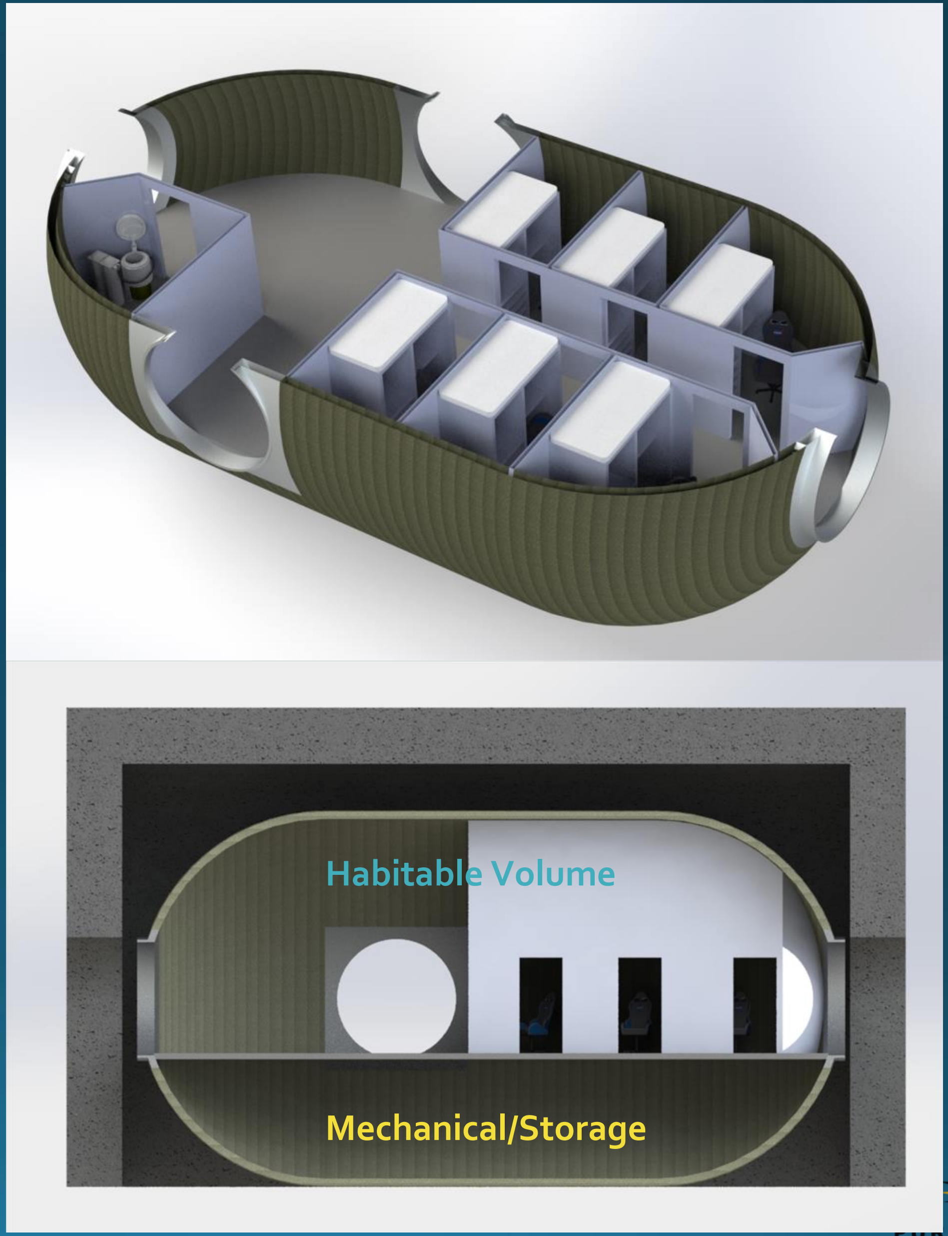
Respective costs on the previous slide were calculated through material prices per mass. These financial estimates are based on current retail material prices, as wholesale prices require commercial purchase order requests.

- **Habitat and Power Materials and Launch Cost**
  - Total: $8.314B
- **Manufacturing cost**
  - Estimated total cost of $155,322,720 for each year of habitat manufacturing
    - 3 years, one for each launch group
  - Total: $466.0M
- **Operating cost**
  - Includes crew salaries, ground support, and NASA personnel
  - $303M / year / person
  - Total: $27.88B
- **Grand total over 10 years: $36.66B**

https://science.howstuffworks.com/satellite10.htm
https://www.indeed.com/cmp/Nasa/salaries?job_category=install

Habitat Module

- **Overview**
  - Used WDM to determine base shape and layout
  - Ran optimization code to find dimensions
  - Flexible with the potential uses - i.e. any module could be later optimized for any task
- **Mass, Power, Volume Statistics Per Habitat**
  - Mass: 7.758 Mg
  - Power: 0 kW (for the structure)
  - Volume: 540.2 m^3
  - Cost Est.: $1,090,000 each

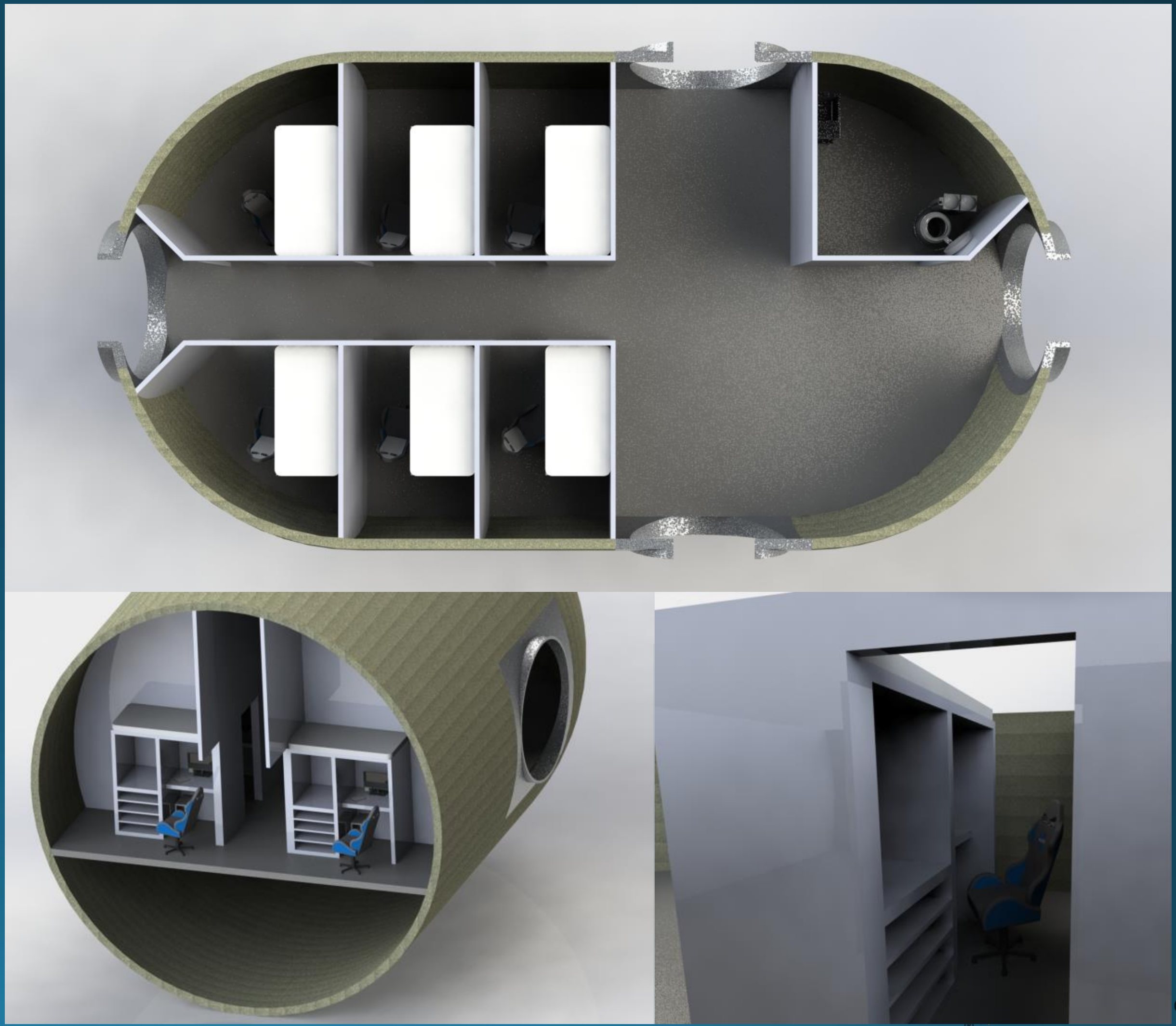


CAD Models by John Matuszewski

Crew Module Layout

- **Each crew member as private bedroom**
  - 6 Bedrooms total per Crew Module
  - 24 Bedrooms total in colony
- **Includes bunkable bed, desk, storage, chair, computer, and floor-mounted TV**
- **Bathroom includes 2 ISS toilets, 2 shower stalls, 1 sink**
- **"Flex Corner" can be a storage room, lounge, open space, etc.**
  - Different for each module
- **Walls, doors shipped separately and are mounted to the floor and hard points**

CAD Models by John Matuszewski



Food Prep/Dining Module Layout

- **Amenities**
  - Living Room, Dining Area, Kitchen with Bar, Bathroom (1 Toilette), Food Storage, Washer & Dryer
- **Features**
  - Communal living space, open floor plan
- **Colors & Textures**
  - Light (white and beige) → create bigger feeling of room
  - Wood → earth like feeling
- **Interior Mass: 1.465 Mg**
- **Interior Price: $12,085**

PURDUE AERONAUTICS & ASTRONAUTICS

Food Prep/Dining Module Layout

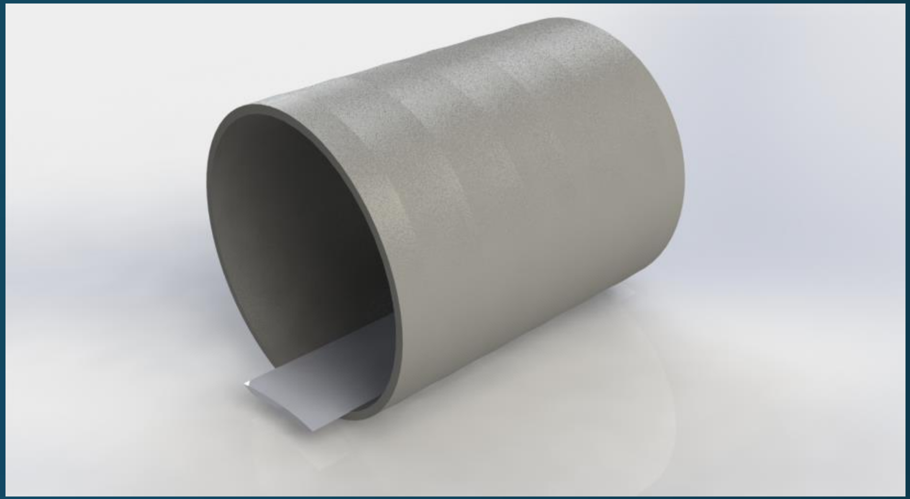




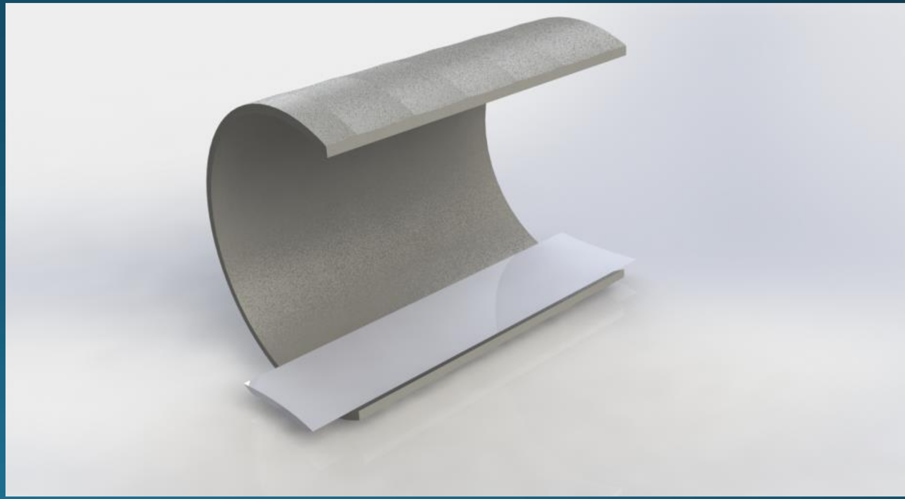

Note: These are Preliminary Models as Basis for CAD Models
- By: Lara Cackovich

Airlock Module

- **Safety: Fire and Depressurization Event evacuation**
- **Maximum Capacity of 13 persons in airlock**
    - Sets maximum module capacity for non-critical activities
- **Modular connection, multiple escape routes, ease of movement between modules**
- **Mass, Power, Volume**
    - Mass: 643 kg
    - Power: 0 kW (structural)
    - Volume: 16.2 m^3

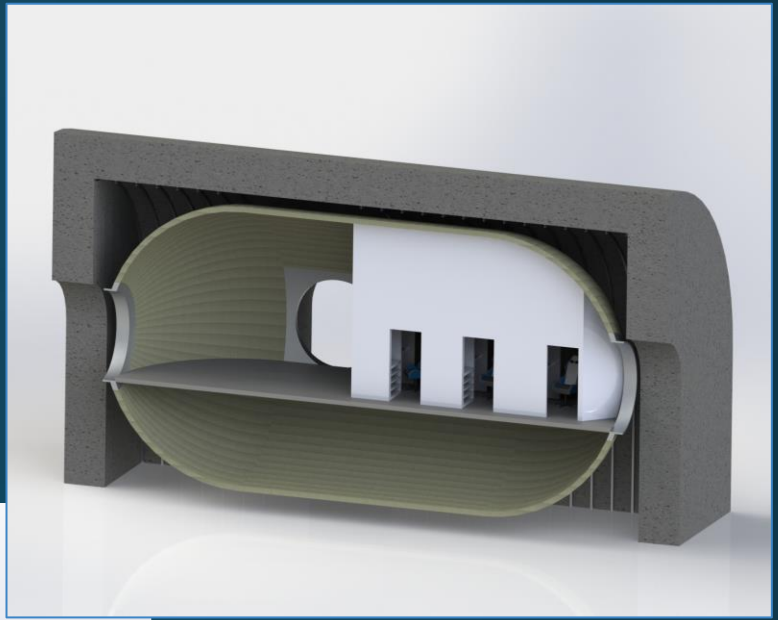


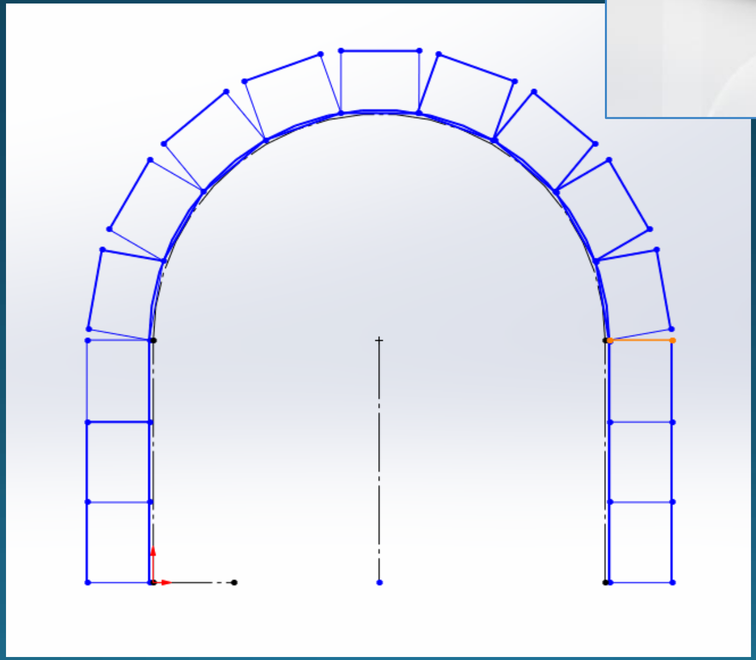
CAD Models by John Matuszewski



Radiation Shielding

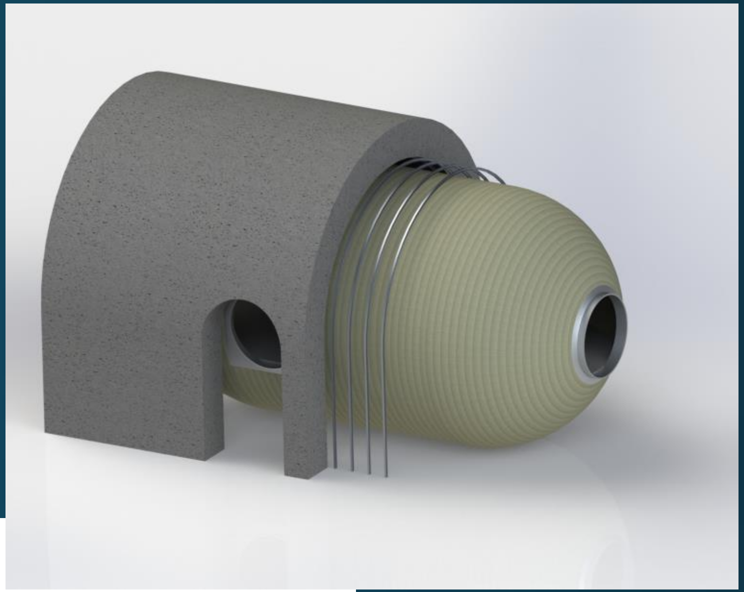
- **Requirements**
  - < 50 msv a year
  - 200 kg/m^3 of regolith
- **Assumptions**
  - Low levels of water ice
  - Density of 1.71 kg/m^3
- **Regolith Layer**
  - 1.165 m deep
  - Volume: 584.61 m^3
  - Mass: 999.68 Mg
- **Regolith Bags**
  - 1.165 X 1.165 X 1.5 m
  - 3481.56 kg per bag
  - 300 bags per module
  - Volume: 2.026 m^3
  - Mass: 0.925 Mg



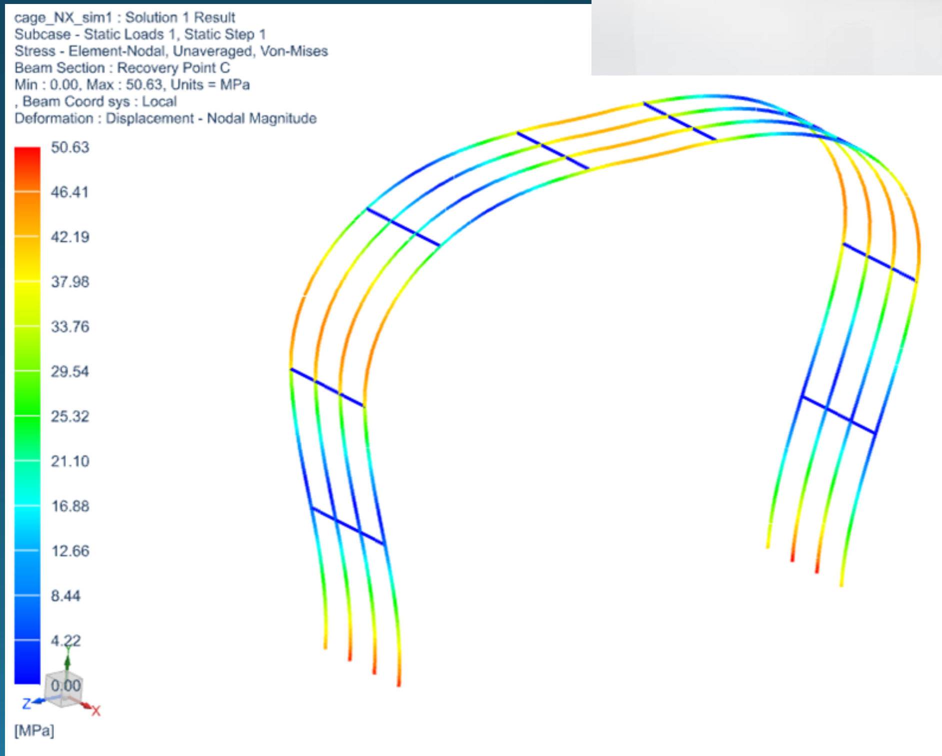


CAD Models by John Matuszewski

Regolith Support



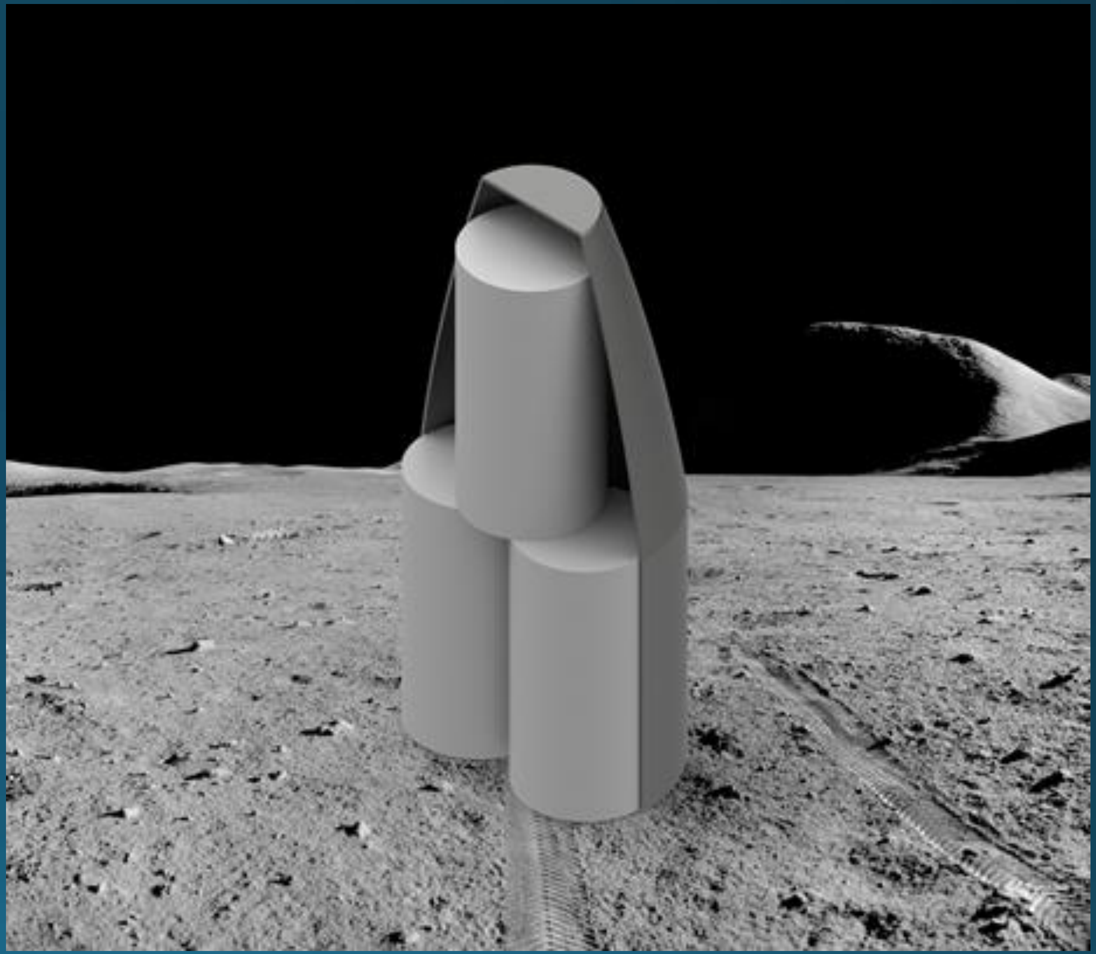
- **Requirements**
  - Structure is independent of inflatable habitat
  - Support 1.165 m thick regolith load
  - Safety Factor of 1.65
- **Regolith Support Cage**
  - 6061-T4 Aluminum
    - Yield Strength: 110 MPa
    - Density: 2700 kg/m^3
  - Mass: 2.110 Mg
  - Volume: 0.7815 m^3



CAD Model by John Matuszewski
FEA Model by George Carroll, updated by Christian Mandrell

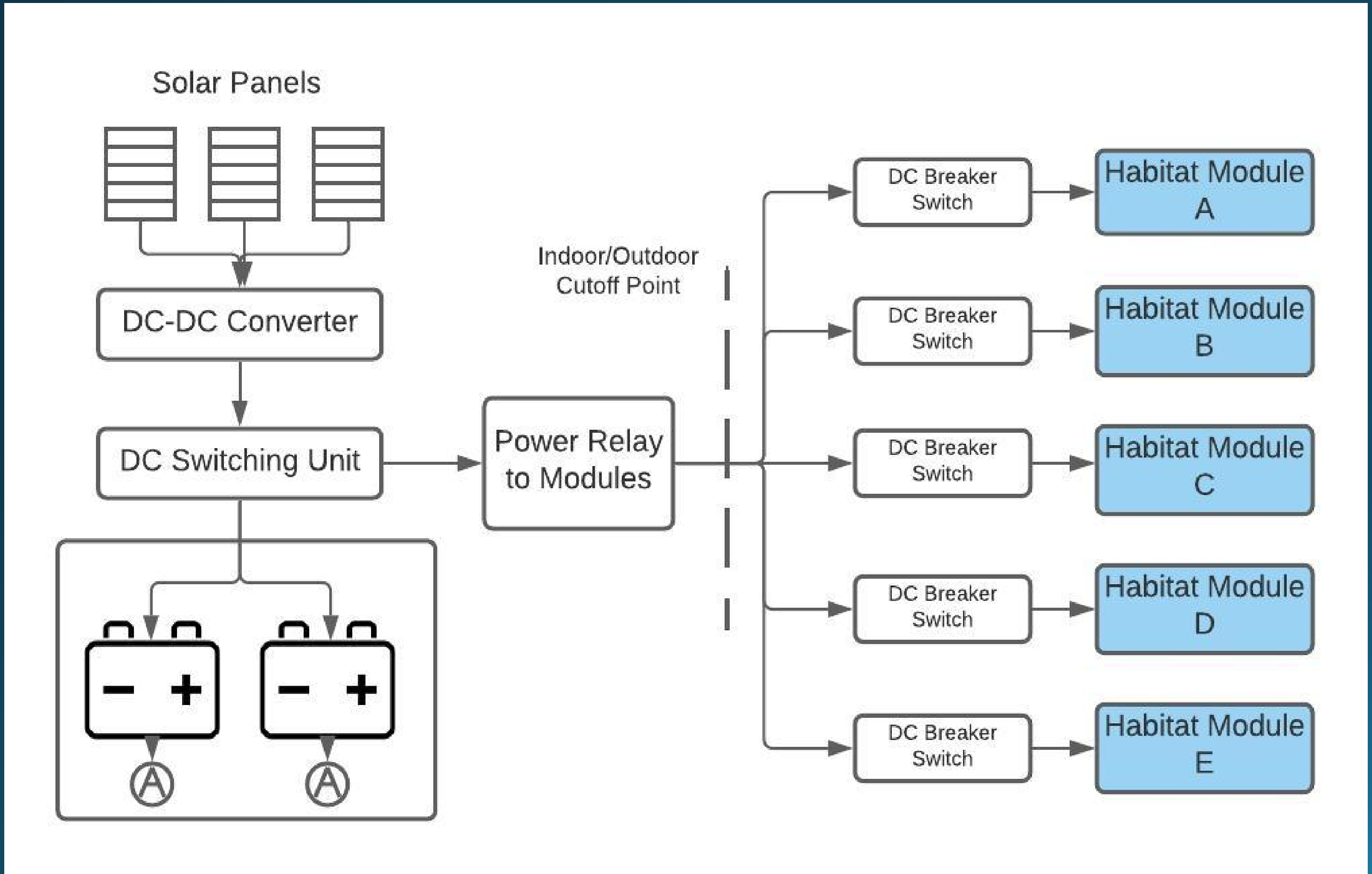
Payload Packing

- **Starship payload model**
  - Habitats shall fit inside of Starship payload bay
  - Transport missions should fit 3x habitat modules
  - Transport missions should fit 6x airlock modules
- **Assumptions**
  - Habitats compress by 50% in both radius and length for transport



CAD Model by Blake Gossage

Power System Diagram

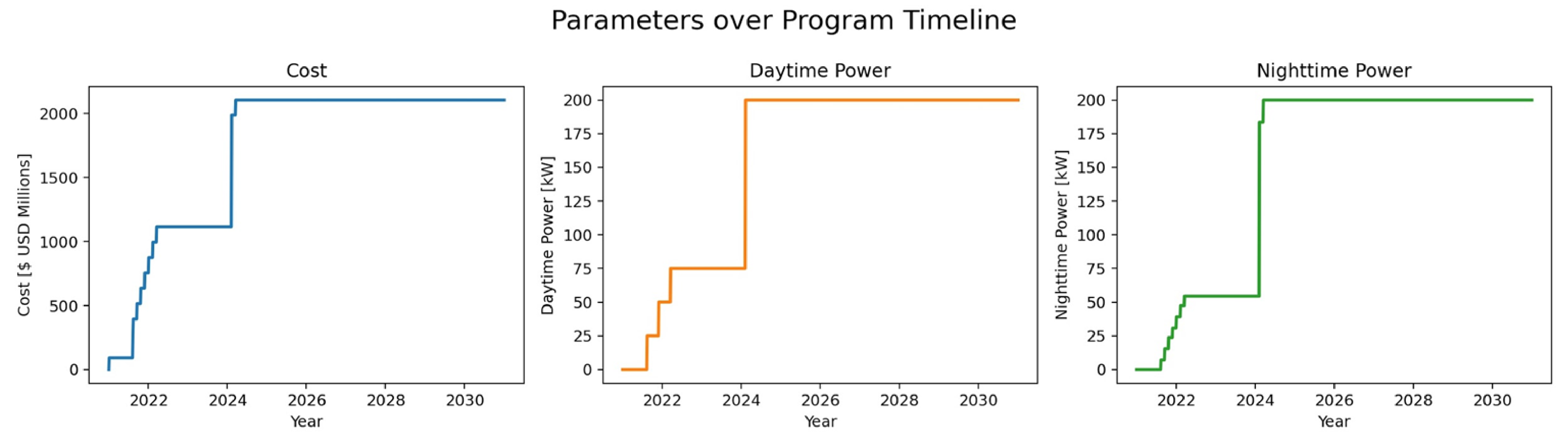


- Power provided from solar panels
- DC Converter lowers voltage to operating voltage (120 V)
- DC Switching Unit handles channel routing and fault tolerance between batteries and habitat
- Each module obtains power through relay and breaker switch

Power Generation and Storage

- **Background**
  - The system is designed as a solar array that will be supplemented by battery banks that will provide power to the colony
  - Preliminary power will be 100kW for roughly 10 colonists that will be expanded as the mission progresses to roughly 200kW for 19 colonists
- **Requirements**
  - The system shall provide power sufficient for habitat operation at all times.
  - The system shall maintain voltage levels within 5% of desired levels
  - The system shall store enough power to sustain habitat through lunar night
  - The system shall be modular and easily expandable

Power Usage and Cost



- **Power Cost with launch: $2.106B**
- **Power Mass: 102.0 Mg**
- **Power Volume: 326.4 m^3**

Action Items

- Finalize all floor plans
- Incorporate interior layout into model
- Move renders from Solidworks to Blender
- Create more animations and videos of the habitat
- Incorporate ECLESS, Farm, Labs, Fun module, power generation, etc. into habitat model
- Add egress/ingress specific airlock with dust mitigation

Systems - Life Support

AAE 450 - Spring 2021

03/24/2021

Team Lead: Aaron Baum

Team Members: Dylan Anderson, Marcus Fuller, Wilson Barce, Blerton Ferati, Blake Gossage, Ray Huang, Riley Harwood, Sanjidah Hossain, Hunter Mattingly, Reid Trafelet, Marcus Fuller

Problem: Environmental control

- Background
  - The moon is an inhospitable environment, with extreme conditions not suited for human habitation. Therefore, a highly controlled habitat environment is necessary.
- Constraints:
  - The system must maintain a breathable atmosphere
  - The design should close the mass loop to minimize recurring costs
- Assumptions:
  - NASA estimates are accurate
  - Life support requirements scale linearly with population

Solution: ECLSS

The Environmental Control and Life Support System (ECLSS) is the umbrella term for the subsystems employed to maintain the atmosphere within the colony, as well as recycle other critical resources.

Summary of Changes

- Revised total mass: 2.5 Mg per Habitat
  - Revised recurring mass needs: .0023 Mg (2.3 kg) per Habitat/day
- Revised total volume: 6.1 M^3 per Habitat
- Calculated total power: 9 kW per Habitat
- Calculated cost for updated system: $6550 per Habitat

Summary of Changes

- Added Sorbent bed to Oxygen Regeneration system
  - Used for CO_2 capture
- Finalized Water Recovery design
  - 1.5 M^3 Volume
  - 350 kg Mass
  - 2.1 kW Power
  - $185,000 total cost
- Finalized Fire Suppression system

Oxygen Regeneration Subsystem

Background:

- Need a method to convert CO_2 into a H_2O

Solution:

- Bosch Reactor
- Bosch reactors have a closed mass loop, turning CO_2 and H_2 into H_2O and C
  - Other alternatives have a hydrogen deficit, resulting in mass losses over time.

- Mass: 1025 kg initially, 12.9 kg/day for filters
- Volume: 1.07 M^3
- Power: 1.5 kW
- Cost: $1600

Pressure Storage Subsystem

Background

- The pressure storage subsystem is responsible for maintaining air reserves for both normal and contingency use for atmospheric control within a habitat or rover.

Constraints

- System must contain the amount of air needed at any specific time which is determined the number of crew, oxygen consumption per person, duration between oxygen resupply, and oxygen regeneration.
- System must satisfy any mass, volume, or reliability constraints required for a corresponding subsystem.

Pressure Storage Subsystem

Solution

- ISS High Pressure Gas Tank
  - Large tank, shielded for orbital debris
  - Mass: 544 kg Volume: 427.6 liters Pressure: 23.44 MPa
  - Recommended for initial habitat pressurization and contingency for failed resupply.

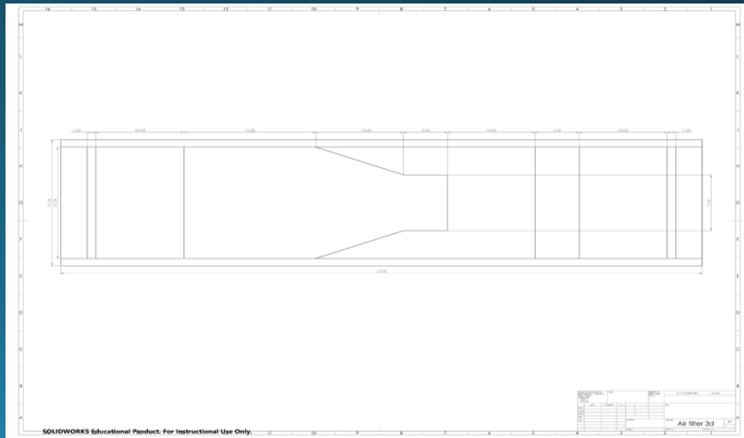
- Orbital ATK Composite Overwrapped Pressure Vessel
  - Smaller tank, high reliability
  - Mass: 16.8 kg Volume: 87.0 liters Pressure: 31.00 MPa
  - Recommended for rover oxygen supply and contingency for depressurization event

Trace Contaminant Control Subsystem

Solid contaminants will be captured using a two phase filtration system. Trace gas contaminants will be removed by the Oxygen Regeneration System, and additional filters.

Mass: 76.8 kg
Volume: .5935 m^3
Power: 25 W
Cost: $1350

All mass and volume calculations for contaminant control are per habitat.
Trace gas filters must be replaced after 1-3 months, necessitating a 13.6-4.5 kg/month mass requirement.



Waste Management Subsystem

Background

- Due to the low gravity and hostile environment present on the moon, waste management systems will have to act differently from existing systems on Earth and in microgravities such as on the ISS.

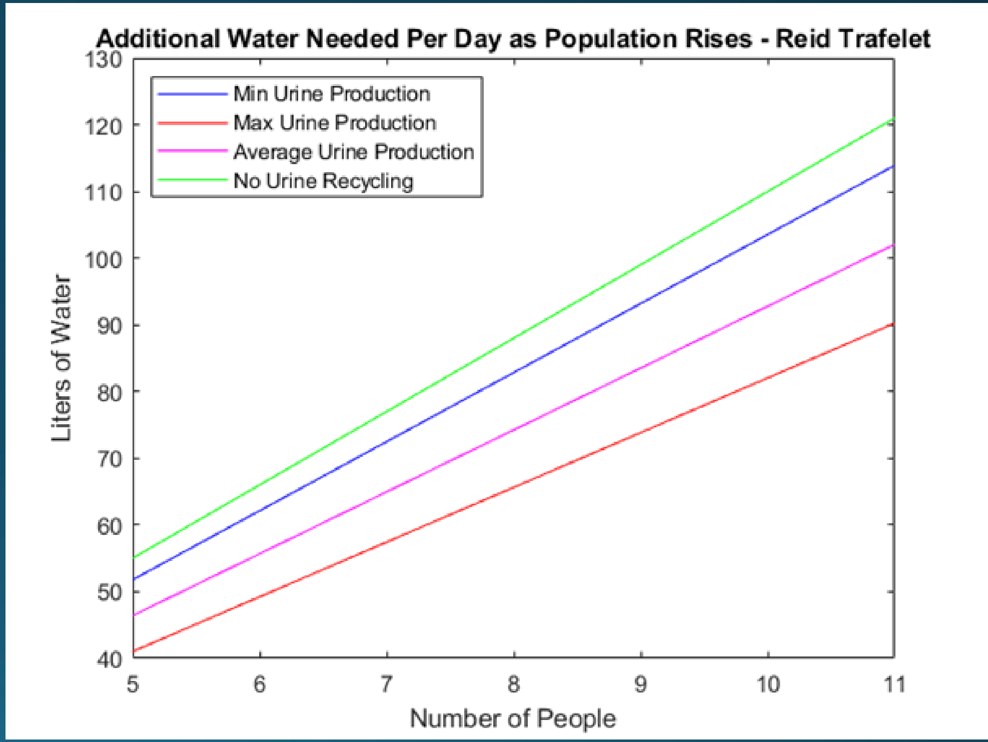
Constraints

- Low gravity and materials needed restrict the possible of traditional plumbing and waste management systems.
- System has to be hygienic to minimize spread of germs and pathogens
- Created waste has to be removed from colony to prevent it from creating a negative effect on the colonist and the colony as a whole.

Waste Management Subsystem

Solution

- Waste Digester
    - Waste Digester can convert 0.035 liters of methane per dry gram of human waste
    - Waste Digester requires 4.925 kW for batch completion
- Urine Recycling
    - Urine recycler can process 18.13 kg of waste for a 24 hour period
    - Urine Recycler requires 424 W when processing and 108 W when in standby mode



Waste Management Subsystem

	Mass	Power	Volume	Cost
Digester	9.5 kg	4925 W	0.01 m^3	$250
Urine Recycler	350 kg	424 W	1.5 m^3	$2000

Water Recovery Subsystem

Background

- As more water that can be recovered, less water takes up launch mass and volume also reducing risk and increasing colony sustainability.

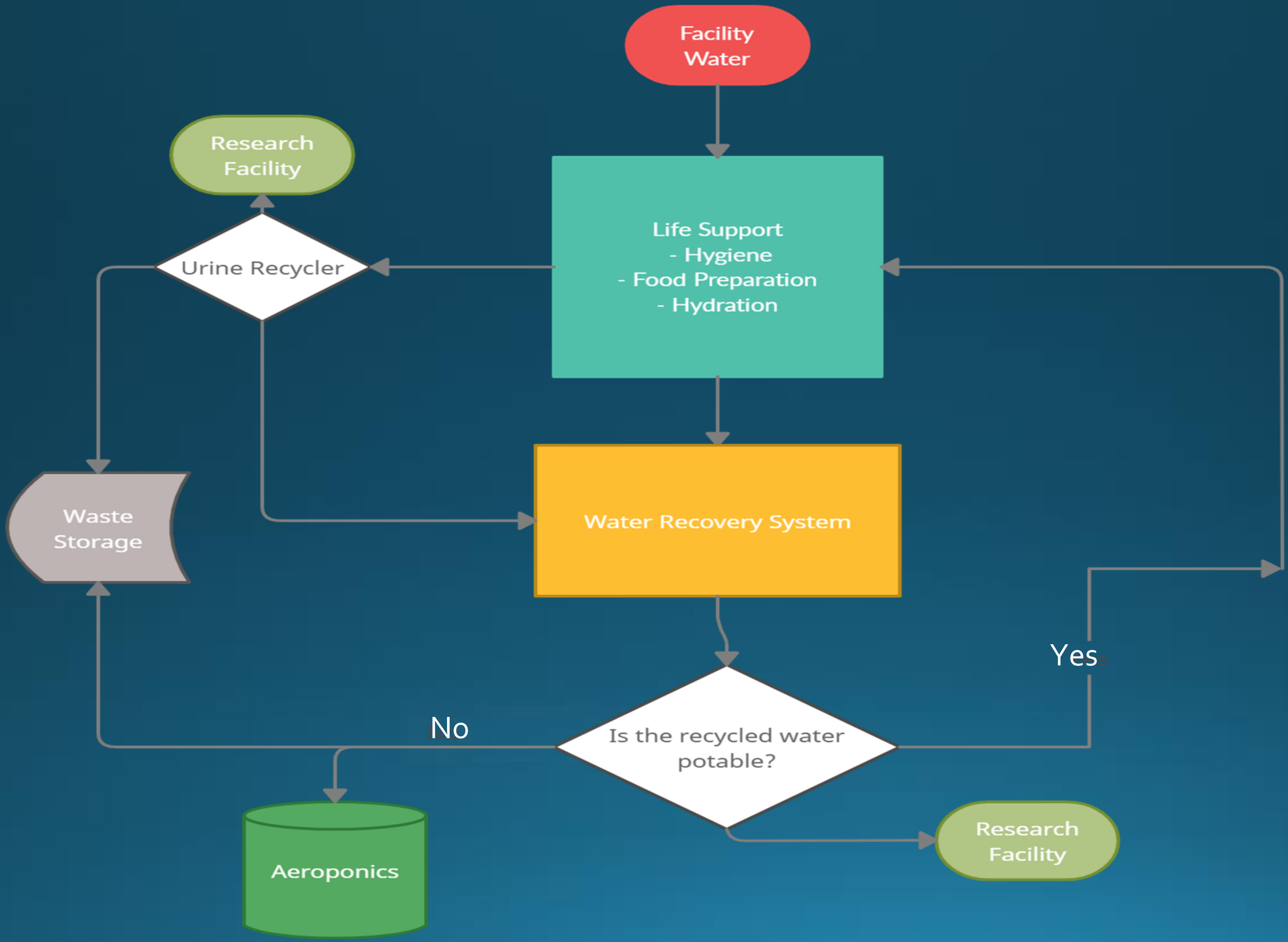
Constraints

- Water for life support, drinking, food, and hygiene needs to be pure enough for safe consumption.

Solution

- Mass: 350 kg
- Power: 2.1 kW
- Volume: 1.5 m^3
- Total Cost: $185,000.00

Water Recovery Subsystem



Fire Detection and Suppression Subsystem

- Dual fire detection system - photoelectric sensors in ducts scanning for smoke particles and radiant heat sensors in ceiling to detect anomalous high temperatures in cabin (ISS Heritage)
- 3 stage fire suppression system based on aerospace industry suppression systems
  1. Handheld Suppression with Halon 1211/Pressurized CO_2 canisters
  2. Halon 1301 Deluge system
  3. Gas Purge and cycling system

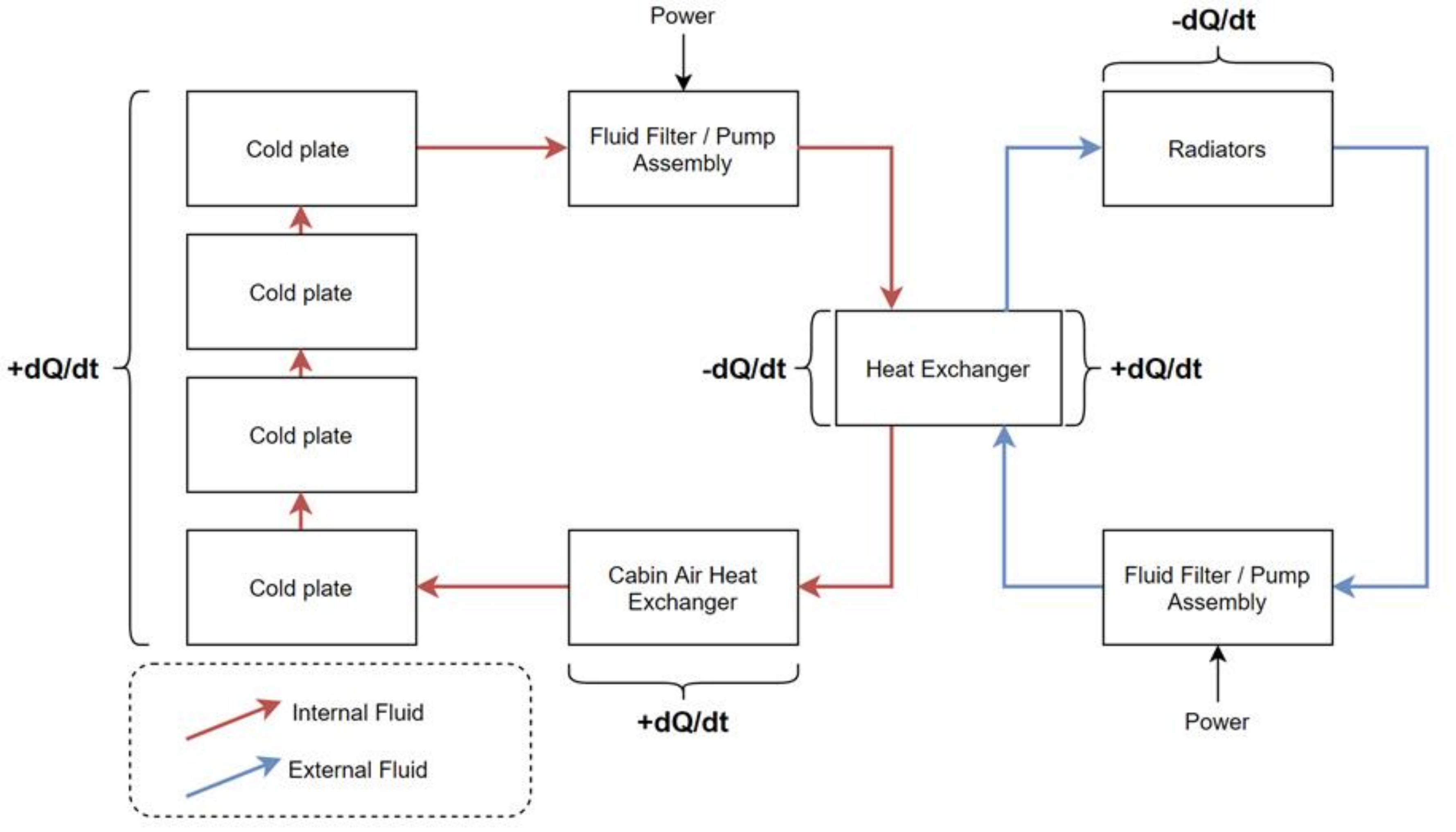
Problem: Thermal Control

- Background
  - Needed to absorb, transfer, and remove internal heat load from cabin air and internal components
- Changes since PDR:
  - Added resistive heaters to exposed module hull (contingency), radiators (contingency), and external fluid lines (survival)
  - Sized radiators
  - Updated cost, mass, volume, and power requirements

Summary of Changes

- Revised total mass: 2 Mg total
- Revised total power requirement: 7.3 kW
- Calculated cost for updated system: $52.3 million

Solution: ATCS

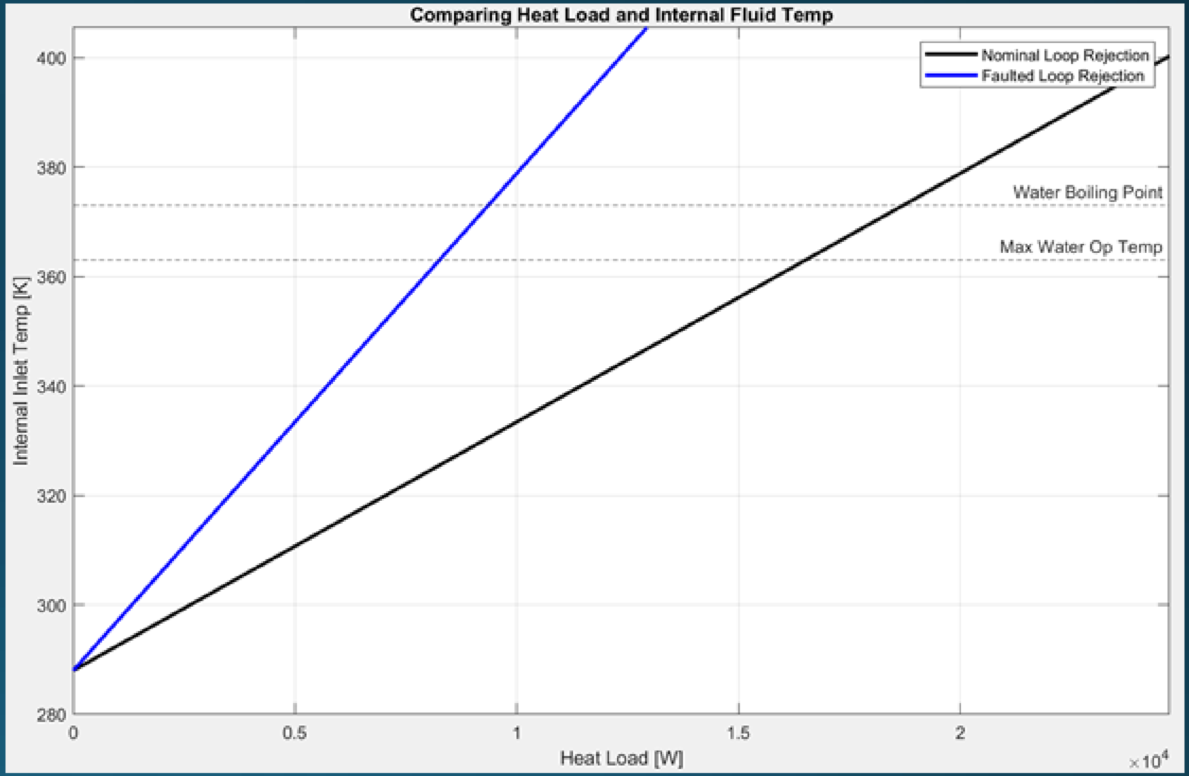


ATCS Specs

Assuming 8 modules:

- Total Mass: **1.995 Mg**
- Total Required Power: **0.494 kW**
- Contingency Power: **Up to 7.29 kW**
- Total Cost including launch: **$52.3 million**

- Total Heat Load Rejection: **~16.5 kW**
- Faulted Loop Heat Load Rejection: **~8.2 kW**



PURDUE AERONAUTICS & ASTRONAUTICS

Problem: Physical Health

- Background
  - Due to the poor conditions for human habitation on the Moon, the physical health of colonists is likely to deteriorate over the duration of a long term mission.
- Requirements:
  - Maintain physical health of colonists to the degree they are able to perform tasks around colony
  - Solution is lightweight and compact
- Assumptions:
  - ISS human spaceflight measures apply to lunar colony

Summary of Changes

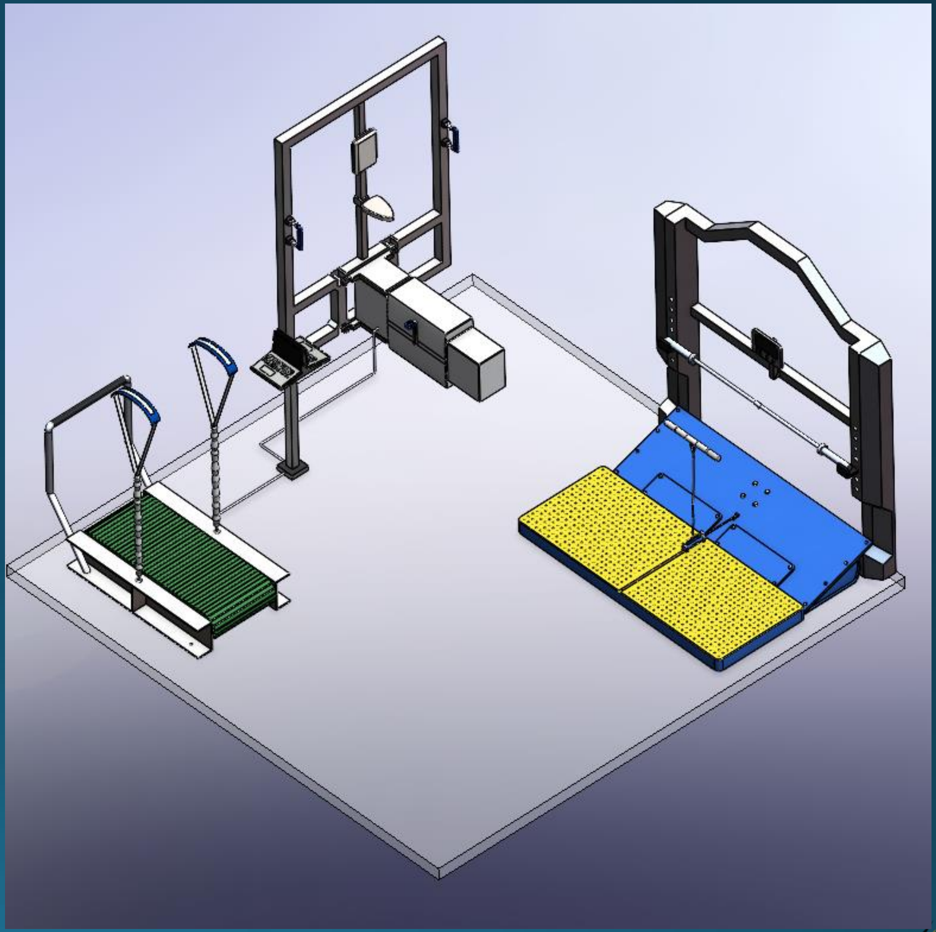
- No major changes since PDR

Solution: Crew Standard Measures

- Collection of physical, physiological, and mental measurements that encompass human spaceflight and lunar risks
  - Sleep questionnaires
  - Actigraphy
  - Metabolic panels
  - Cognition tests
  - Immune system response
  - Microbiome measurements
  - Heart ultrasounds
  - Sensorimotor tests
- Samples to analyze: blood, urine, stool, saliva, body swabs, questionnaire responses
- Measurements taken preflight, postflight, and during the mission
- Full equipment listed in Master spreadsheet

Exercise Subsystem

- The exercise equipment available to colonists includes a treadmill, squat rack, resistance machine, and cycling machine.
- Equipment is modeled after ISS exercise equipment to be effective in lower gravity.
- Recreational sports to be developed further: VR 360 treadmill, TVs for gym, small manual rovers for racing, crater skiing



CAD Models courtesy of Sam Conkle

Problem: Medical Equipment

- Background
  - The trip to the lunar surface as well as life on the colony can make the crew more susceptible to medical issues that are more difficult to treat away from Earth.
- Constraints:
  - Medical items such as pills and instruments shall be present on trips between Earth and the lunar colony.
  - There shall be an adequate stockpile of medical supplies on the lunar colony to address any medical issues that may arise for the colonists.
- Assumptions:
  - The medical supply list on the ISS is scalable to the size of the colony.

Summary of Changes

- No major changes since PDR

Solution: Medical Equipment MasterList

- Full Medical Equipment MasterList can be found under the master equipment list in the drive (over 130 medical items listed)

Medical Equipment Calculations

For 5 person crew...	
Mass (kg)	50.19747483
Vol (m^3)	0.5007565501
Vol (ft^3)	17.65733336
Cost ($)	12252.18

Per Person on Crew...	
Mass (kg)	10.03949497
Vol (m^3)	0.10015131
Vol (ft^3)	3.531466672
Cost ($)	2001.036

For 19 person crew...	
Mass (kg)	190.7504044
Vol (m^3)	1.90287489
Vol (ft^3)	67.09786677
Cost ($)	40266.684

Systems-Agriculture

AAE 450 - Spring 2021

03/23/2021

Team Lead: Nicky Masso

Kyle Alvarez, Jaxon Connolly, Wellington Froelich, Reece Hansen, Monica Viz

PURDUE AERONAUTICS & ASTRONAUTICS

Planned Design

- Aeroponics
- 24 towers per module
- 105 potatoes/bean plants per week per module
- 256 other plants per week per module
- Lights on for 16 hr/off for 8 hr
- Bring crystallized 10-10-10 NKP salt mix (0.4 kg/month)
- Total cost ~$10,000

Subsystem	Mass of System	Power (kWh / day)	Volume (m^3)
Watering	0.880 Mg	70	0.75
Lights	0.109 Mg	32	0.11
Control	-	7	-

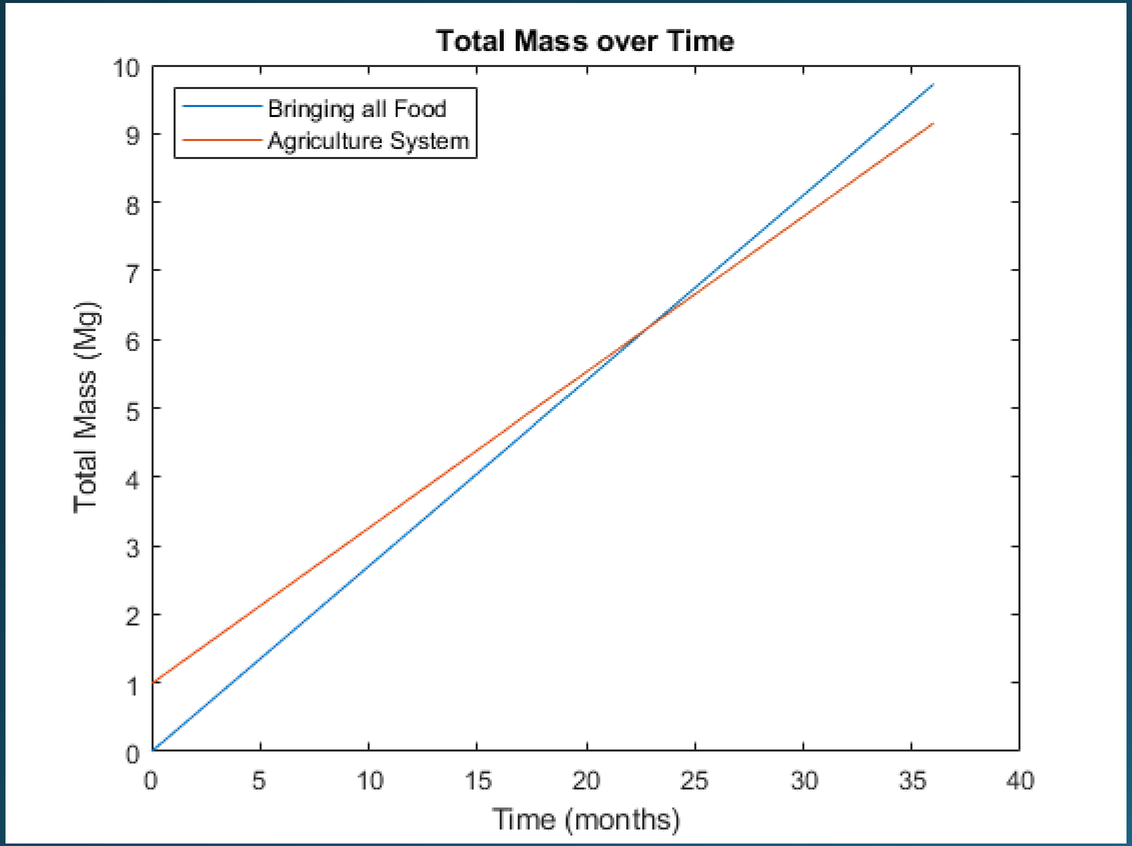
PURDUE AERONAUTICS & ASTRONAUTICS

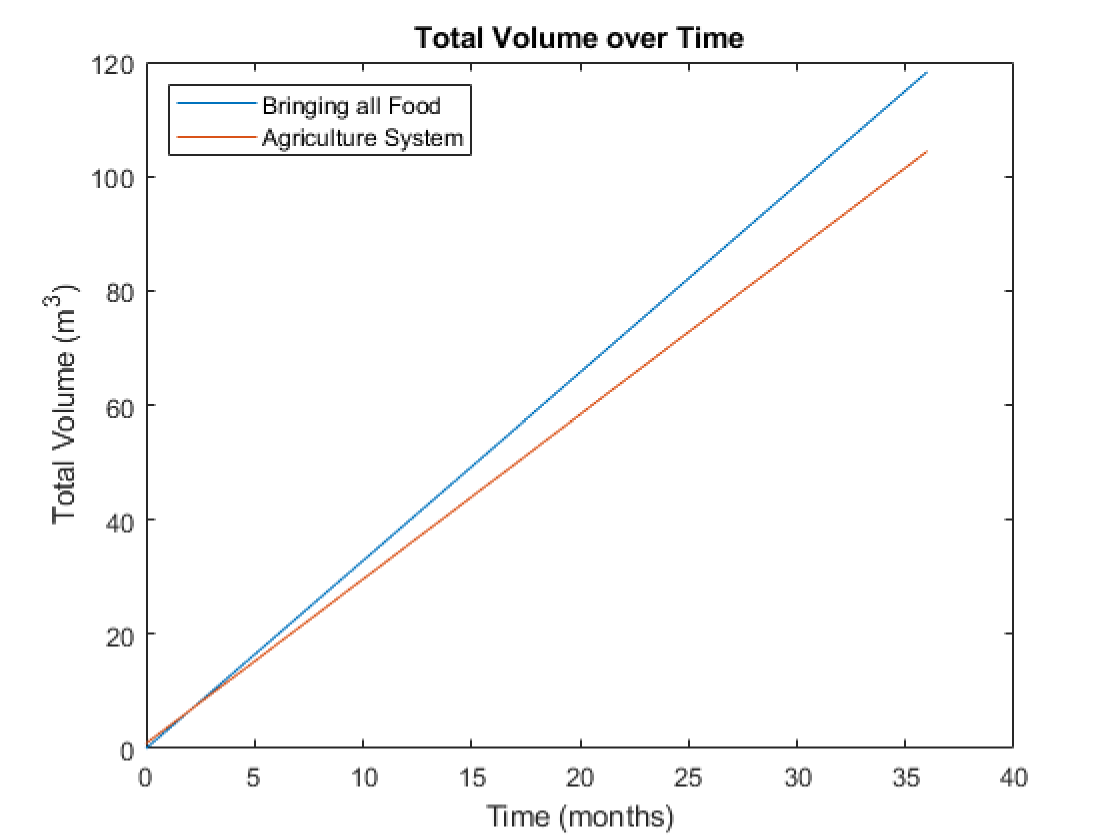
Crop Selection and Supplies

- 5 week rotating grow periods
  - Potatoes, black beans, green beans as major caloric sources
  - Lettuce, kale, chard, butternut, zucchini, tomatoes, peppers, strawberries, currents as assorted other foods
- Per-plant yields: 119 grams, 118 calories
- Supplies
  - lights, pumps, hoses, seeding area, tools
- Greywater usage
  - Residual ammonia and nitrates reduce fertilizer mass
- Thermals
  - 19 kW added to environment

Systems - Agriculture (Nicky Masso, Kyle Alvarez, Wellington Froelich)

Why Not Just Bring Food



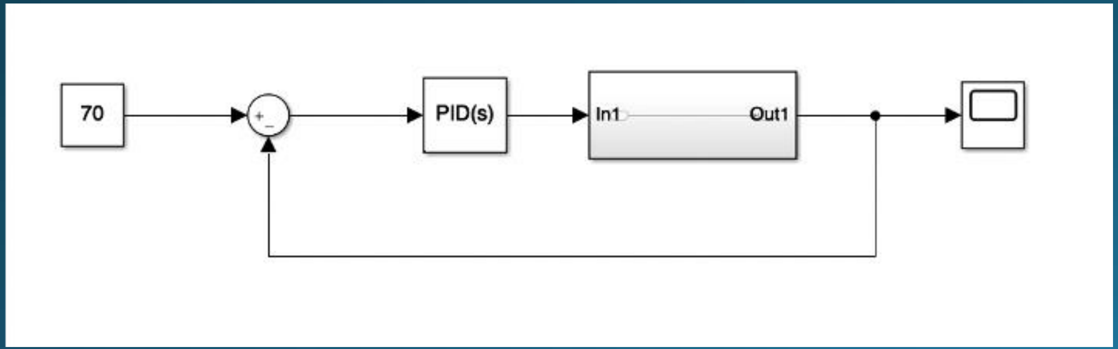


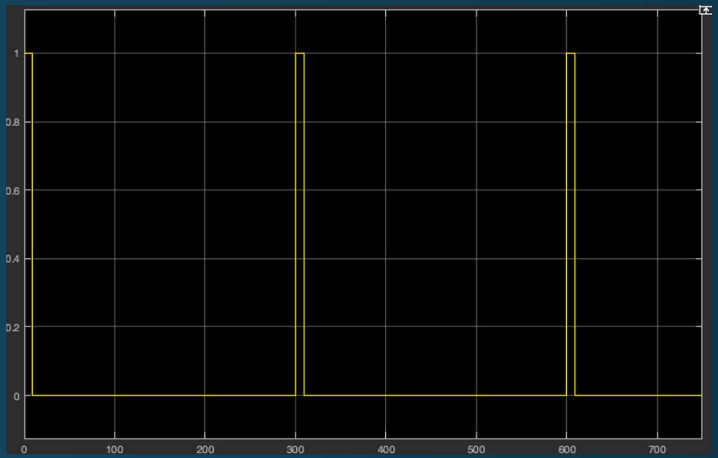
PURDUE AERONAUTICS & ASTRONAUTICS

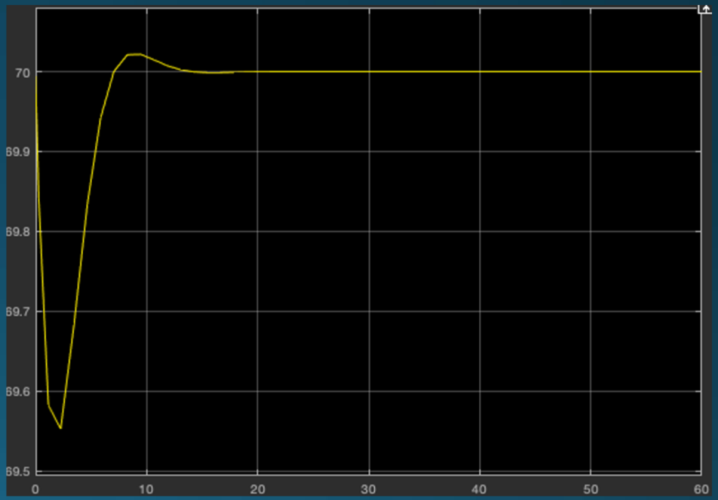
Systems - Agriculture (Reece Hansen, Monica Viz)

Control System

- Temperature
  - Integrated with hab heaters, keep 21 C
- Humidity
  - Inside towers: 90-98% humidity
  - Outside towers: reduce to habitat normal level
- Watering
  - 5 min nutrient period, 15 second spray







PURDUE AERONAUTICS & ASTRONAUTICS

Systems Research Facilities

AAE 450 - Spring 2021

03/23/2021

Critical Design Review

Team Lead: Emily Anderson

Team Members: Joong Hyun Pyo, Cody Martin, Roberto Cardano, Chad Blackwell, Riley Harwood, Jarod Utz

PURDUE AERONAUTICS & ASTRONAUTICS

Updates since PDR

- Revised totals
  - Mass: 1404.66 kg
  - Power: 2.405 kW
  - Volume: 8.077 m^3
- Updated total cost: $145,000,000
  - figure based on NASA Human Research Program
- Mining & Extraction Flowchart
- Research Lab Floor Plan

Science Objectives: Lunar Environment

- Determine global density, composition, and time variability of lunar atmosphere before it is perturbed by further human activity
  - Solution: Observation satellite mass spectrometer
- Determine the composition of the lunar surface specifically looking for water and other useful natural resources
  - Solution: Shortwave Infrared Laser Reflectometer
- Determine compositional state and distribution of the volatile component in lunar polar regions
  - Solution: Sample collection, drilling, Mini-RF & satellite imaging
- Determine the characteristics of the lunar dust environment and assess effects on lunar exploration and astronomy
  - Solution: Sample collection, drilling, Lunar Dust Analyzer

Scientific Objectives: Human Health

- Understand the short term and long term biological and physical effects of the lunar environment on the human body
  - Solution: Vital sign monitoring, crew medical sample collection
- Understand the effects of the lunar gravity on human performance
  - Solution: Bone densitometry, muscle mass measurements
- Understand the mental and cognitive effects of long-duration missions
  - Solution: Crew Standard Measures
- Determine the effects of the lunar environment on the ability of humans to reproduce
  - Solution: Animal and cell reproduction experiments

Science Traceability Matrix

PURDUE AERONAUTICS & ASTRONAUTICS

Category	Objective ID	Science Objective	Key Observations	Measurement Requirements	Source
Lunar Environment	LE-1	Determine compositional state and (lateral/vertical) distribution of the volatile component in lunar polar regions	Take rovers to explore these territories and collect samples	Collect 50-100 samples	https://drive.google.com/file/d/122aA5vyhuqTR0HdUzNo8kuO4TRsKmNk9/view
Lunar Environment	LE-2	Determine global density, composition, and time variability of lunar atmosphere before it is perturbed by further human activity	orbital and surface deployments of mass spectrometers	Take measurements daily and process data prior to human arrival	https://drive.google.com/file/d/122aA5vyhuqTR0HdUzNo8kuO4TRsKmNk9/view
Lunar Environment	LE-3	Determine the characteristics of lunar dust environment and assess effects on lunar exploration and astronomy	robotic and human surface measurements to characterise dust environment and effects on deployed systems and instruments	Exospheric dust concentrations, surface electric fields, dust mass, velocity and charge, plasma characteristics	https://drive.google.com/file/d/122aA5vyhuqTR0HdUzNo8kuO4TRsKmNk9/view
Lunar Environment	LE-4	Determine the percent composition of the lunar surface that can be used for other aspects of the mission	The Shortwave Infrared Laser Reflectometer will be utilized to determine the contents of the surface	Collect 50-100 surface samples and conduct scans throughout orbit	https://directory.eoportal.org/web/eoportal/satellite-missions/l/lunar-flashlight
Human Health	HH-1	Understand the fundamental biological and physiological effects of the lunar environment	Bone and muscle loss, diminished immune efficiency, slower wound healing, human nutrition needs, and poorer cognitive performance	Analysis of blood, urine, feces, saliva, body swabs, questionnaire responses, measure bone density and muscle mass monthly	https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=7711
Human Health	HH-2	Understand the effects of the lunar gravity on human performance to understand and promote human productivity in an off-Earth planetary environment.	Whole body coordination strategies, including balance, posture, locomotion, work capability, endurance, and speed of humans in fractional gravity, and the effect of isolation and communication lag on performance and mission coordination	Crew members must pass a series of sensorimotor tests that evaluate coordination and mobility performance	https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=7711
Human Health	HH-3	Understand the mental and cognitive effects of long-duration missions	Memory levels, cognitive and spatial awareness, grammatical reasoning, critical thinking	Each test shall measure mental and cognitive levels, performed by each crew member bi-weekly within 2 hours of going to bed	https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=1125
Human Health(Water)	HH-4	Determine the amount of ice on the surface of the Moon and how that can be used when humans land on the Moon	Use spectrometer to determine ice content and take surface samples using rovers	Collect 50-100 surface samples and conduct scans throughout orbit	https://drive.google.com/file/d/122aA5vyhuqTR0HdUzNo8kuO4TRsKmNk9/view
Human Health(Water)	HH-5	Determine if water harvested from lunar ice is safe for human use and consumption.	Use activated charcoal and ion-exchang-ing resins, similar to "Bios-3"experiments (Gitelson et al.,2003). pH test strips, multimeter for testing conductivity.	Collect 25-50 samples from different locations	https://pubmed.ncbi.nlm.nih.gov/11540303/
Human Health	HH-6	Determine and measure the ammount of radiation the base will be subjected to	use irradiation monitors and irradiance monitors to measure daily ultraviolet radiation	UV radiation exposure levels must be measured monthly for each crew member	https://drive.google.com/file/d/122aA5vyhuqTR0HdUzNo8kuO4TRsKmNk9/view
Human Health	HH-7	Determine the theoretical effects of the lunar environment on the ability of humans to reproduce.	Conduct scientific research on animals or cells and determine whether critical periods of exposure to gravity exist for normal development, effects from space radiation, and toxicity levels due to expose to lunar dust	8 freeze-dried mouse spermatoza will be exposed to the lunar environment for 6-24 months and returned to Earth for fertilization	https://www.lpi.usra.edu/lunar/strategies/objectives/ex_ob_2006.pdf

Timeline

Pre-Launch → **Years 1-2** → **Year 3** → **Year 4** → **Year 5+**

Pre-Launch Crew Measurements
Take health measurements according to Standard Measures for each selected crew member prior to their launch to the lunar base

Lunar Atmosphere Measurements
Once observation satellite is built, mass spectrometer will begin atmospheric measurements prior to human arrival
No Crew

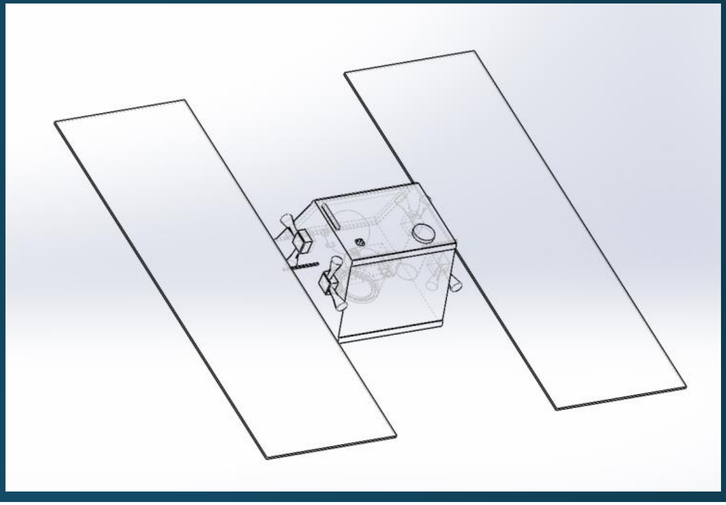
Begin Crew Standard Measures
As humans arrive, scientific objectives are focused on gathering health data and beginning lunar gravity research
Crew: 5 people

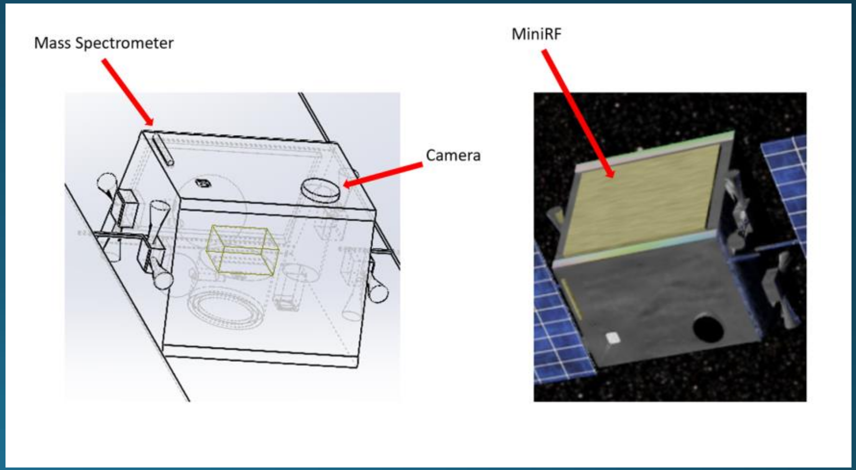
Research Lab Habitat
Once the lab habitat is finished, begin geological sample analysis and lunar surface exploration missions. Continue and refine human health research with additional lab space
Crew: 13 people

Science Objective Adjustment and Refinement
Long-term health effects of crew, development of new science objectives, refining previous goals based on new data
Crew: 19 people

Instruments: Satellites

	Mass [kg]	Power [Watts]	Volume[m^3]
Mass Spectrometer	8	10	0.002
Mini-RF	14	25-50	0.0396
Camera	8.2	6.4	0.189
Total	30.2	51.4	0.2306



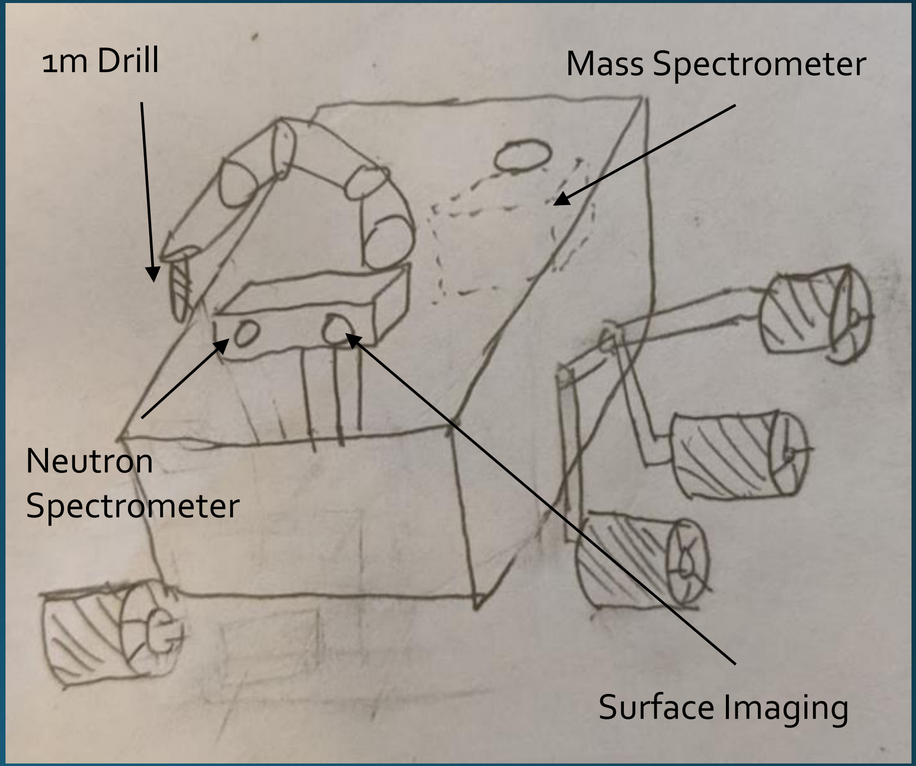


Observation Satellite with Science Equipment[1]
courtesy of CAD & Satellites team

[1] https://docs.google.com/document/d/1rfVBpIYdP_-7yh2ezPM9q3KJm5tyVBpbaSMm5IDAUSs/edit#

Instruments: Rovers

	Mass [kg]	Power [Watts]	Volume[m3]
Mass Spectrometer	10	8	0.043
Neutron Spectrometer	0.5	1.8	0.00129
Drill for Sample collection	41	30-40	0.25 (for 1m Drill)
Surface Imaging	0.8	8.5	0.00383
Base Scouting Rover	502.9	783.6	5
Total	555.2	836.9	5.29812



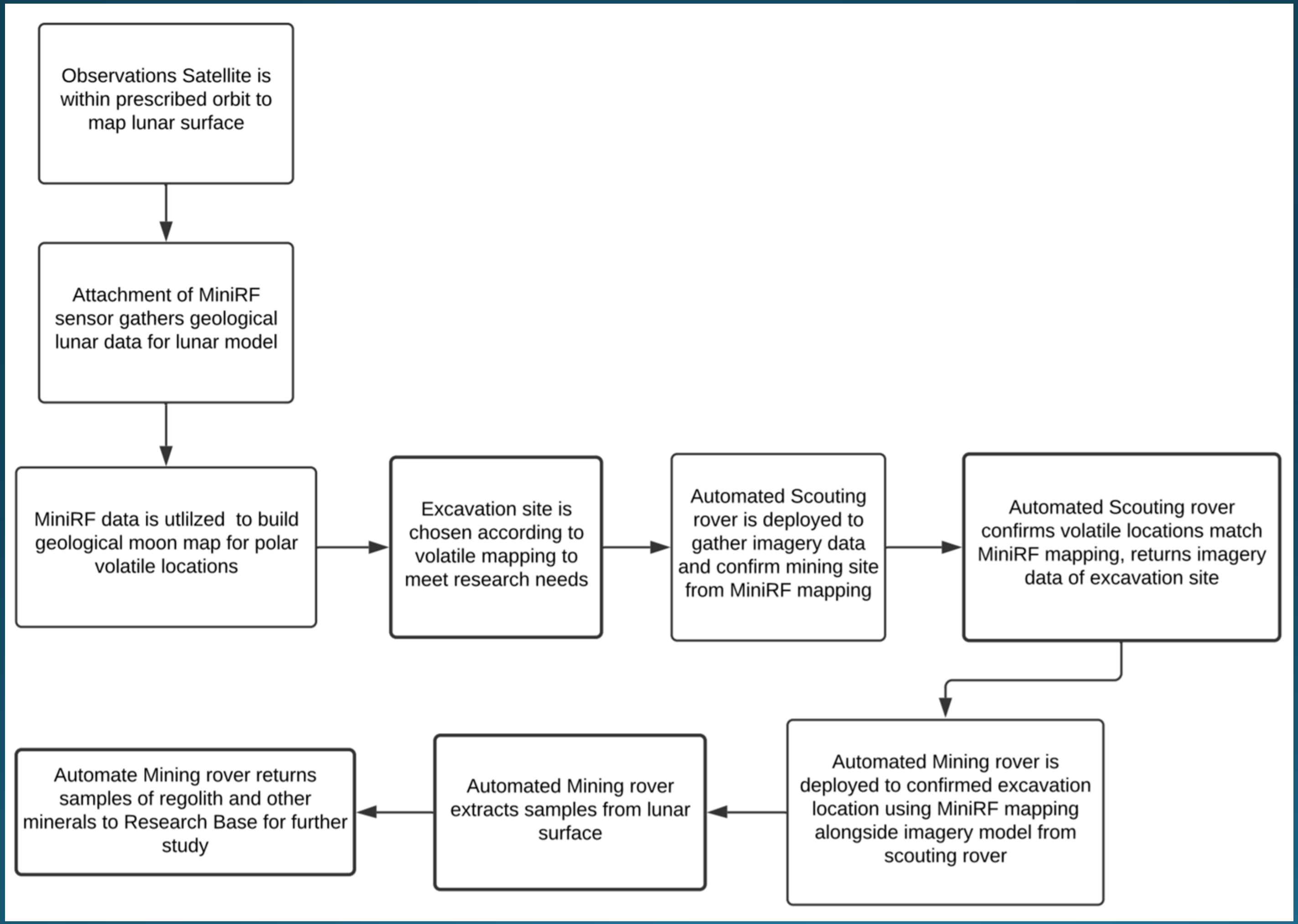
Scouting Rover with Science Equipment
courtesy of Rovers team

- CAD request was made, still in progress for design
- Satisfies Science Objectives 2a, 3b, 4a, 8a[2]

[2] https://docs.google.com/document/d/1TnrmhgXlclkvfyMUgMGnGu1Y6HJg9QtD26mFSYWr6MA/edit

PURDUE AERONAUTICS & ASTRONAUTICS

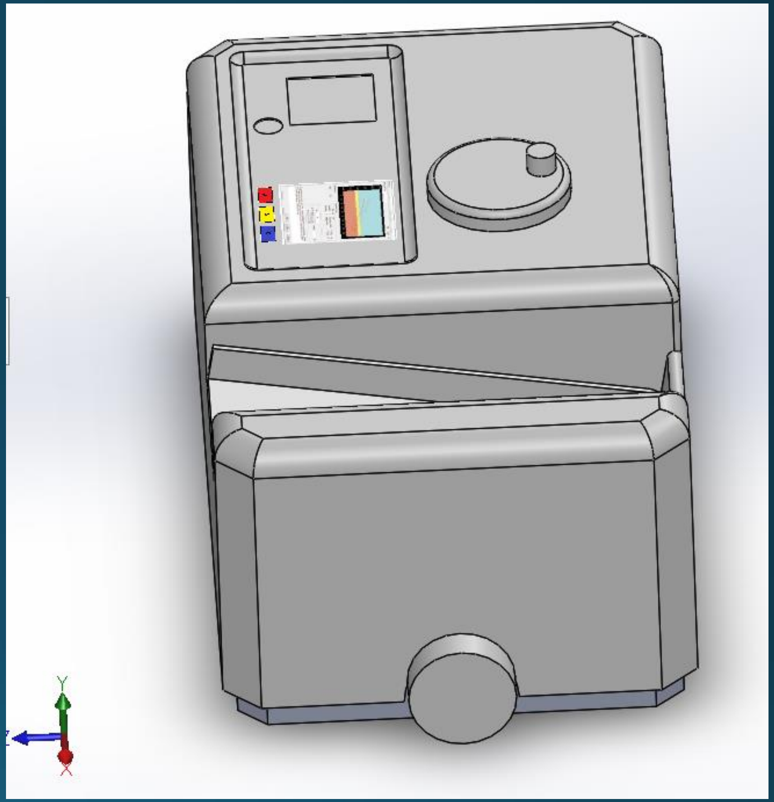
Mining & Extraction Flowchart



Flowchart by Roberto Cardano

Instruments: Habitat

	Mass (kg)	Power (Watts)	Volume (m^3)
Bone Densitometer	10	66	0.03255
Centrifuges	16	100	0.0438
Cardiac Ultrasound	7.3	265-636	0.0126
Actigraphy Watches	0.589	9.3	0.00051
Blood sample equipment	45.39	N/A	0.406
High speed camera	4.5	9	0.004997
Laptop	1.75	57	0.00173
Mammal reproduction equipment	3.9	100	0.013
Laboratory Freezer	729.83	550-900	2.035
Total	819.26	1516.8	2.549



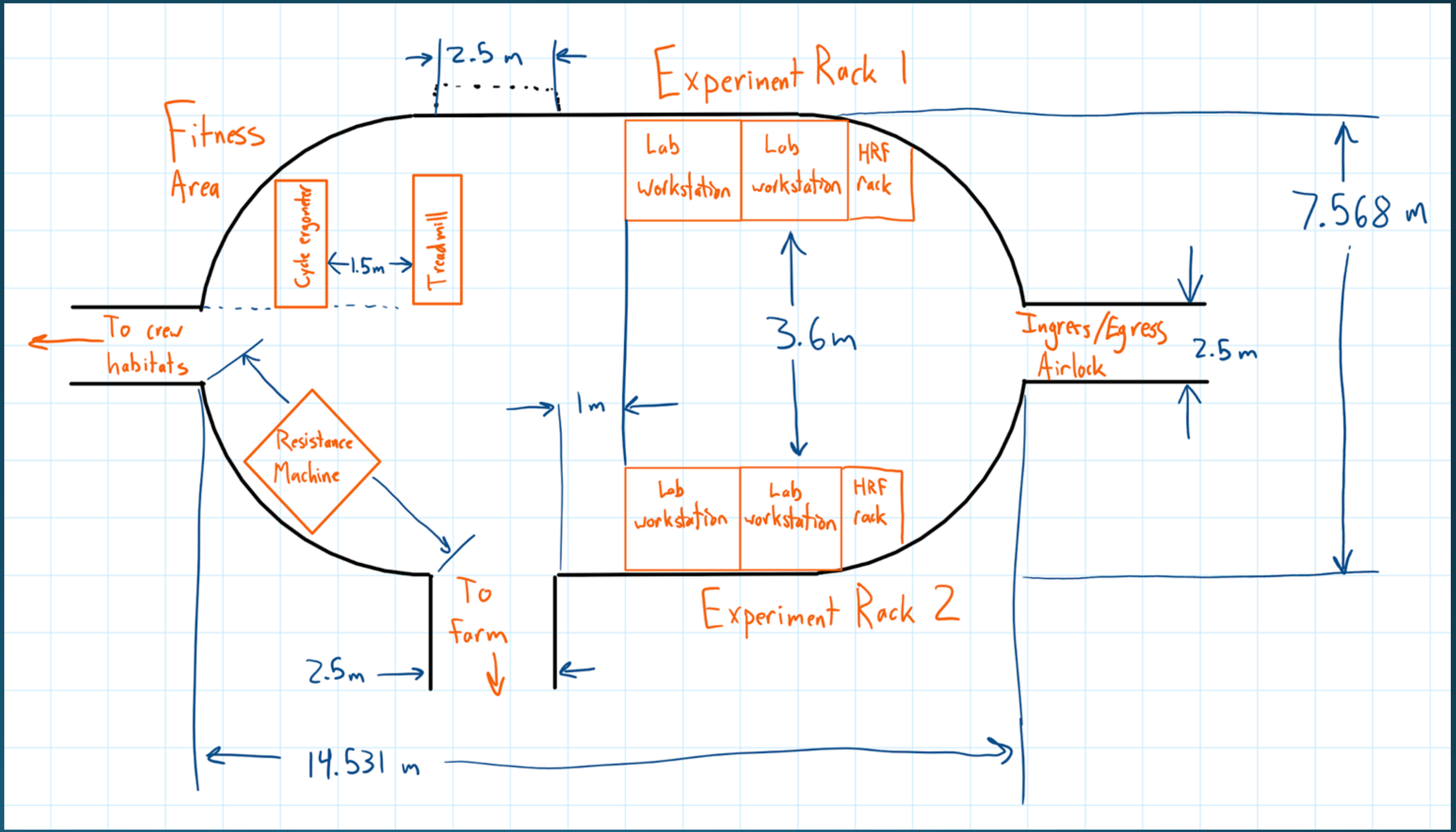
Bone Densitometer - CAD Model by Vishank Battar

- More CAD models in progress

PURDUE AERONAUTICS & ASTRONAUTICS

Research Lab Habitat Floor Plan

- Combined with fitness area for maximum usage of space
- Incorporates 2 experiment racks
  - ER1: Lunar environment research
  - ER2: Human health research



Research Habitat Schematic by Chad Blackwell

Final Steps

- Finalize risk/fault analysis
- Receive CAD models for experiment racks

Vehicles - Satellites

AAE 450 - Spring 2021

10 March 2021

Lead: Sammy Dickmann

Team Members and Contributors:

Lorin Nugent
Jaxon Connolly
Monica Viz
Stephen Grabowski
Matt Popplewell
Greg Fretti
Alan Gelman
Nicky Masso
Ethan Woller
Anna Cismaru
Dale Williams
Roberto Cardano
Sanjana Singh

PURDUE AERONAUTICS & ASTRONAUTICS

PDR Action Items

#	Action Item Description	Action Item Status
1	Resolve discrepancies in satellite timeline and launch schedule	Completed
2	Finalize mass and power numbers	Nearly Finished
3	Add more detail to CAD models	Nearly Finished
4	Name satellites	In Progress

PDR Action Item #1

- Discrepancy in satellite timeline and launch schedule discovered in PDR
  - Ready to launch in Year 3 vs Year 1
- Schedule now consistent among teams
  - Year 1: development, manufacturing, and test
  - Year 2: begin launching satellites
- Updated schedule and budget/costs on Slides 9-10

PDR Action Item #2

- PDR contingency: 20%
- Now: 0% (not adding any more payload)
- Additional delta-V for communications satellites maneuvering into orbit: ~1 km/s
- Updated sizing chart on Slide 11

PDR Action Item #3

- Most components modeled in detail
  - Thrusters need commercial example
- Changes to solar panel and propellant tank sizes applied
- Updated CAD models on Slides 12-13

PDR Action Item #4

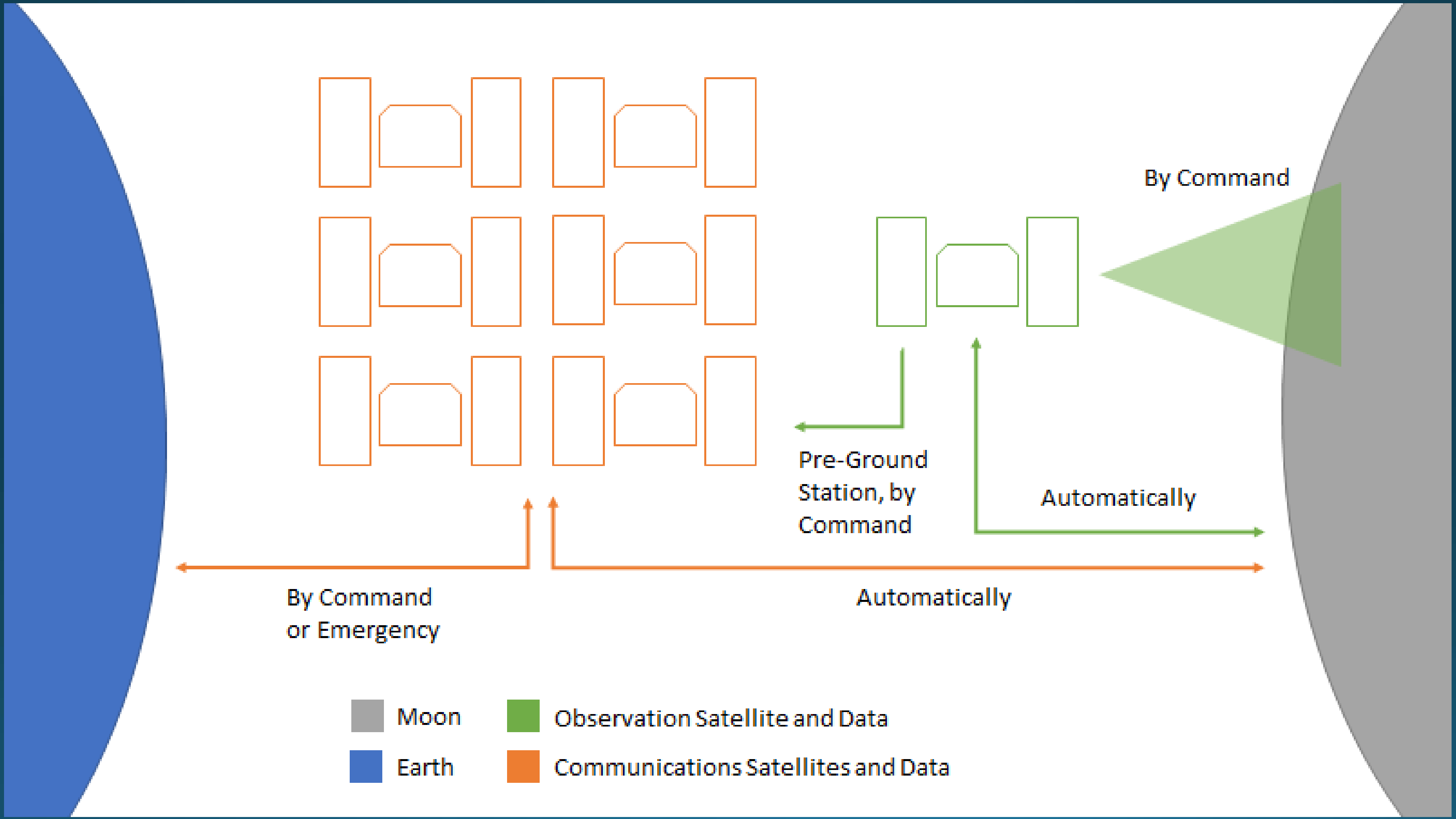
- Communications constellation: Circumlunar High-altitude Extraterrestrial Lunar Link (CHELL)
- Ideas for observation satellite:
  - FirstStep Orbiter
  - Send us your ideas!

Objectives

- Communications satellites:
  - Enable communication between the Moon and the Earth
  - Enable communication among the Lunar colony
  - Enable communication between the observation satellite and the Earth

- Observation satellite:
  - Take optical images of the colony and other areas of interest
  - Complete research objectives
    - Collect RF data to map lunar volatiles for research
    - Collect and analyze atmospheric samples

Concept of Operations



Schedule

Year 1 → **Year 2** → **Year 3** → **Years 4-10**

Year 1
Develop, manufacture, and test satellites concurrently

Year 2
Q1: First comm sats launch (2/rocket)
Q2: Observation sat launched
Q3: Second comm sats launch (2/rocket)

Year 3
Q1: Final comm sats launch (2/rocket)

Years 4-10
Nominal operations
Designed satellite lifetime: 15 years

Budget and Costs

- Costs related to satellites change throughout mission timeline
    - Development, manufacture, and test costs vs operations costs

Year 1 | Year 2 | Year 3 | Years 4-10

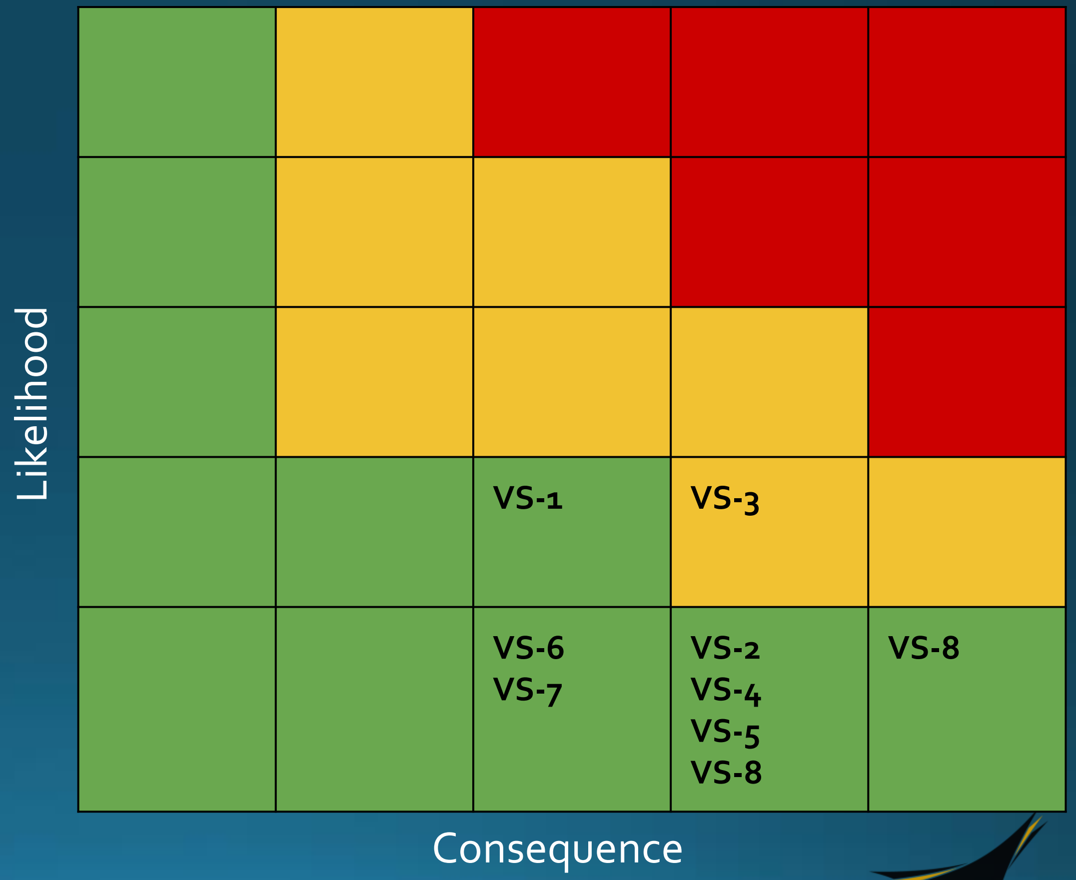
Communications:	$225 million	$12 million + launch costs each year	$12 million per year
Observation:	$45 million	Launch costs each year	Included
Total:	$270 million	$12 million + launch costs each year	$12 million per year

PURDUE AERONAUTICS & ASTRONAUTICS

Risk and Fault Analysis

- 9 major, unique/relevant faults analyzed

ID	Description
VS-1	No contact with communications satellite
VS-2	No contact with observation satellite
VS-3	Solar panels do not provide power
VS-4	Camera images are unusable (ie blurry, corrupted)
VS-5	Sensor data are unusable (ie unusual, corrupted)
VS-6	Satellite does not successfully transmit data
VS-7	Satellite has incorrect attitude
VS-8	Battery failure
VS-9	Off-nominal orbit

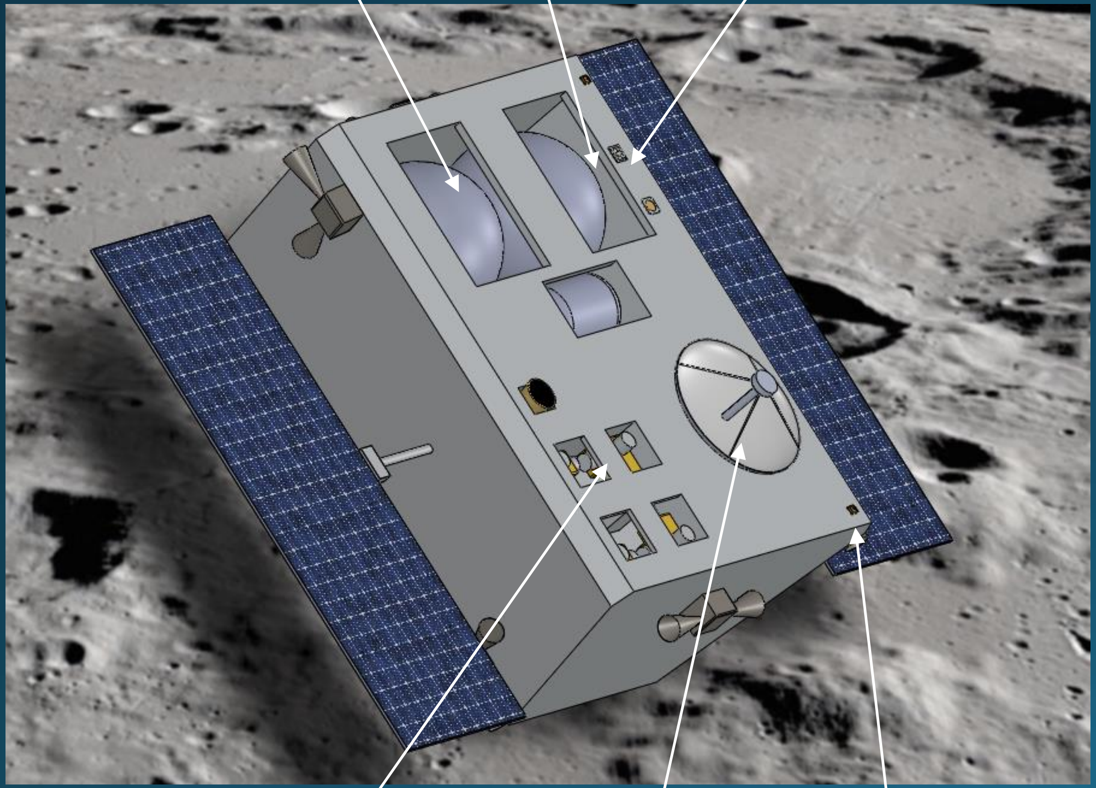


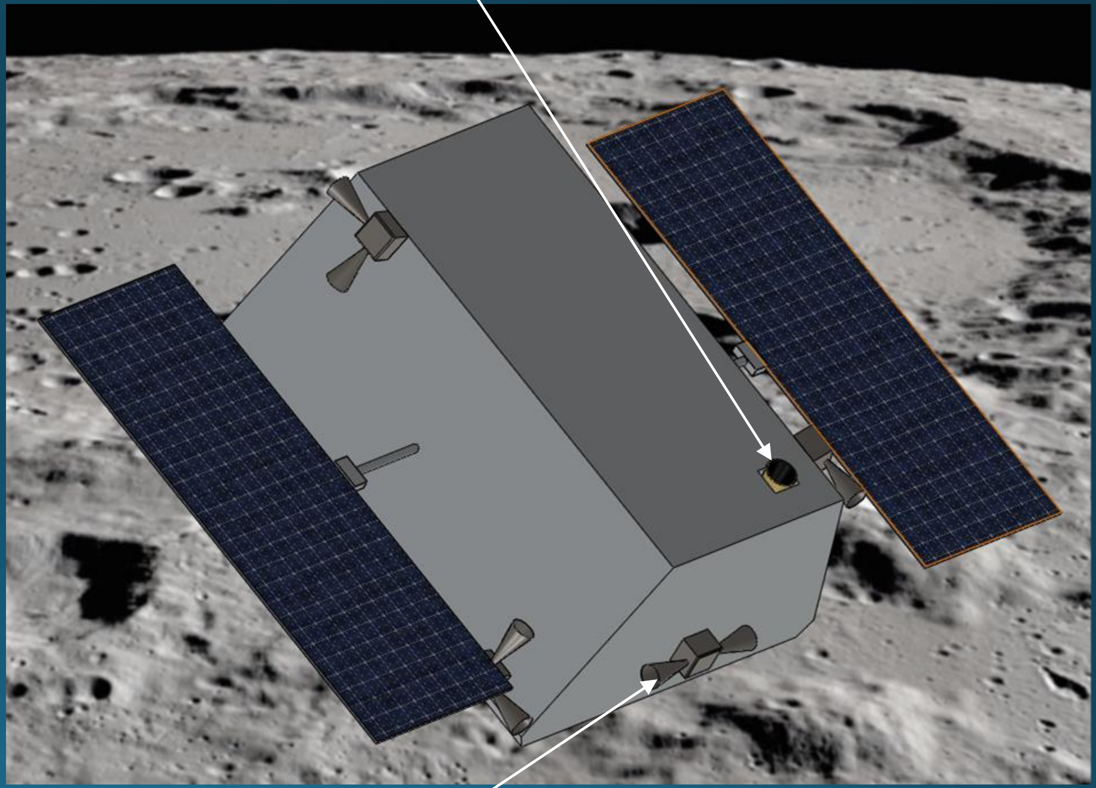
Dimensions and Sizing

	Communications	Observation
Dry Mass (kg)	577	287
Wet Mass (kg)	1350	371
Power (W)	973	2991

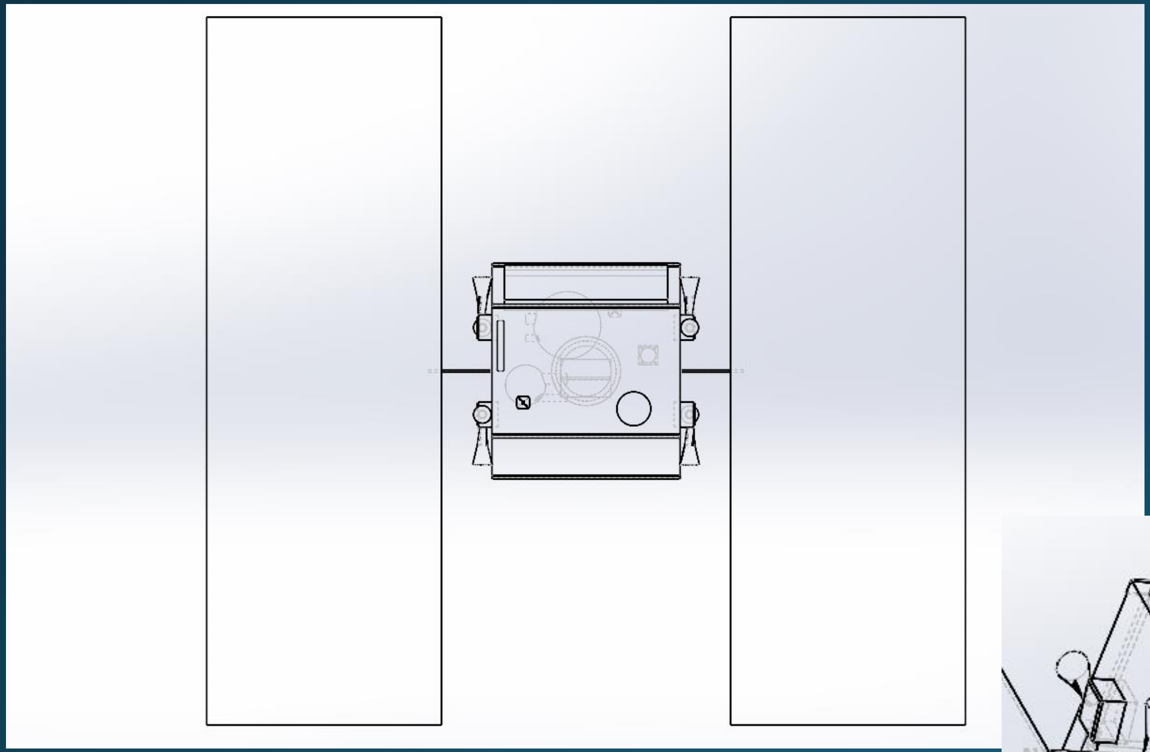
	Communications	Observation
Bus (m)	3.1 x 2.4 x 1.5	1.7 x 1.5 x 1.1
Solar Panels (m)	1.11 x 3.32	1.96 x 5.87

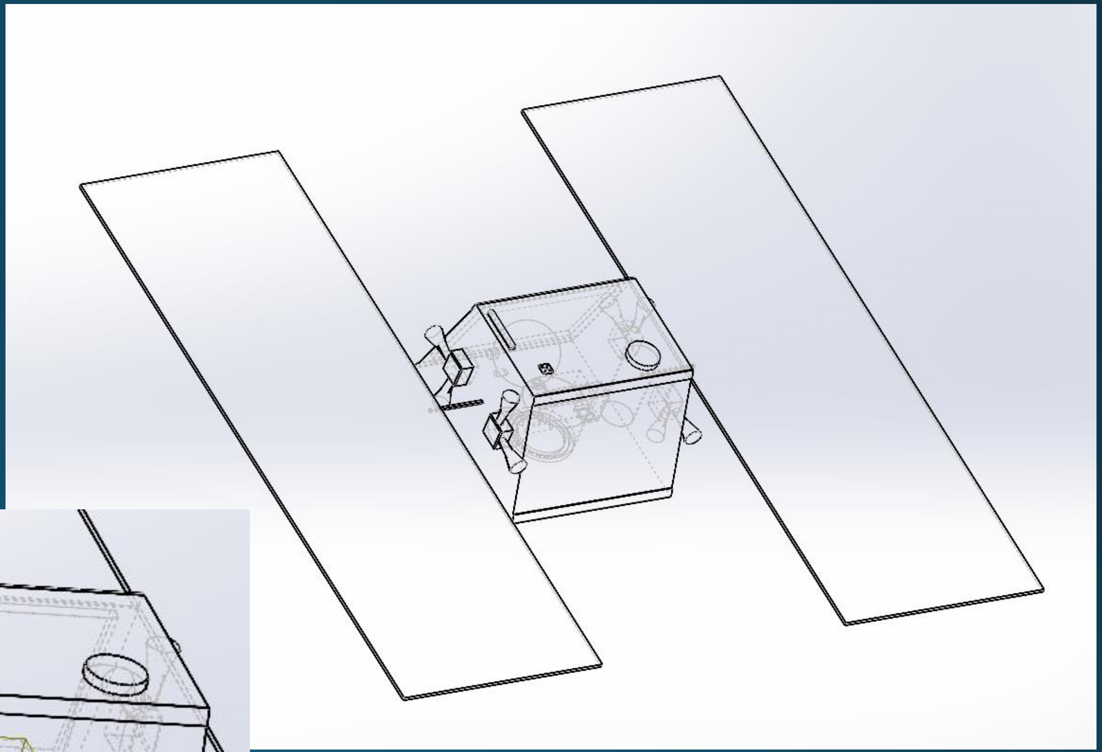
CAD Model - Communications

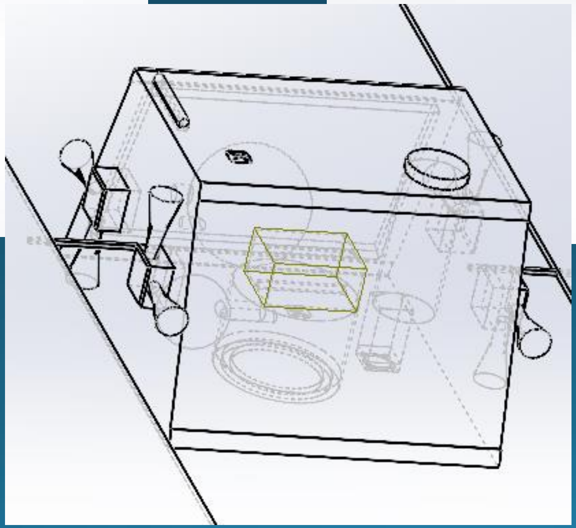




CAD Model - Observation







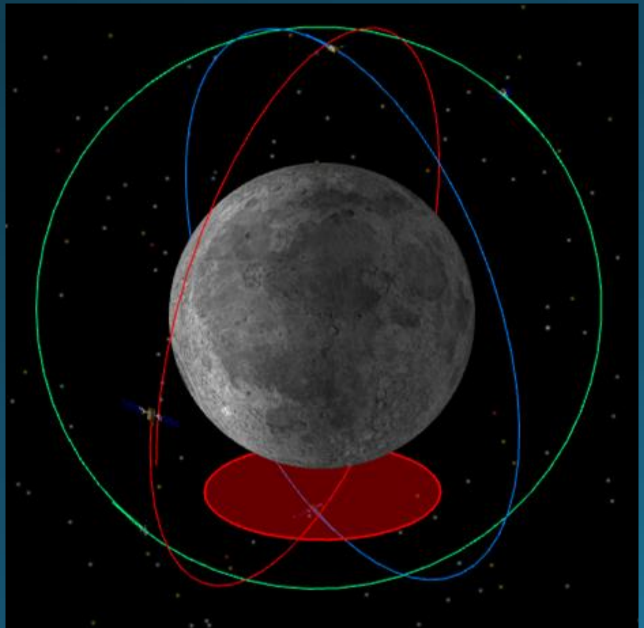
Summary of

Subsytems

Mission Design

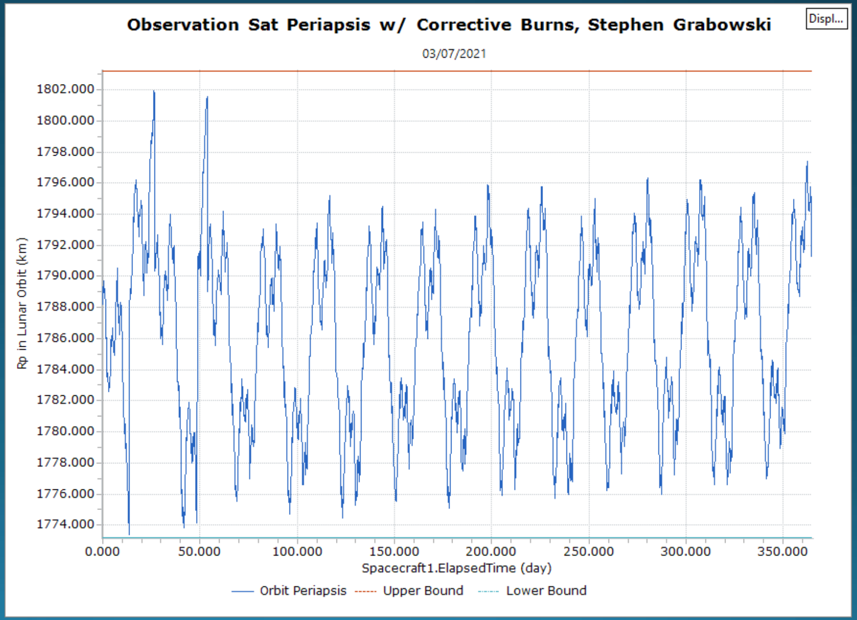
Communications

- Walker constellation configuration for stability, consistent coverage, and potential for expansion
- 6 satellites in 3 orbital planes (2/plane)
    - ~100 m/s/year for stationkeeping
- 1500 km circular orbits



Observation

- Quasi-frozen 50 km x 216 km orbit chosen
    - Variations naturally bounded and won't impact Moon
- Target burns no more than once every 13.5 days to stay within +/- 15 km when observing
- Delta-V budget: ~137 m/s/year



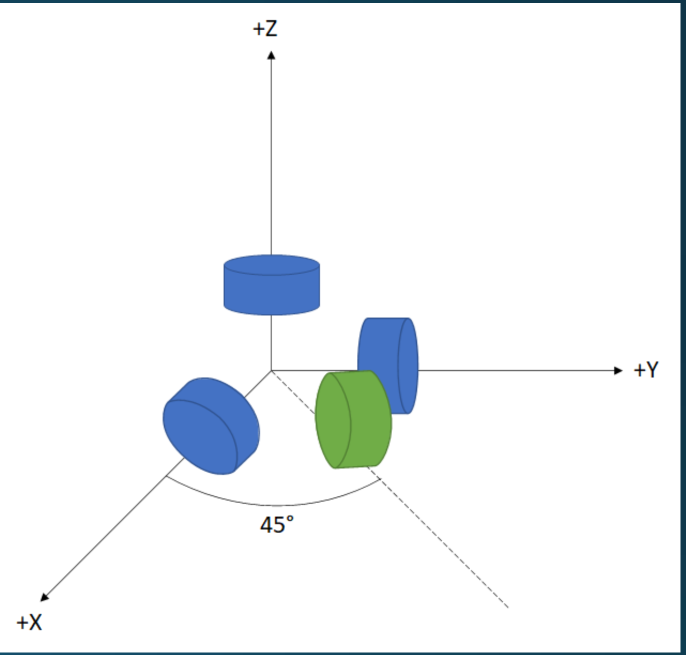
PURDUE AERONAUTICS & ASTRONAUTICS

Communication Infrastructure

- 3 Frequency bands enabled
  - Ka Band:
    - For transmission of "dead" data to Earth
    - 0.97 m dish antenna, 444 W transmitter power, 32 Mbps max data rate
  - S band
    - For crosslink with observation satellite, uplink from Earth/Moon
    - Patch antenna
  - X band
    - For downlink to Earth/Moon
    - Patch antenna
- Allowing the communication satellites to have S and X band capability enables voice communication with Earth before ground station is set up
  - After the ground station is set up, live voice and video will be relegated to that, and satellites will only be used for voice and video comms in emergencies

Attitude Control System

- Reaction Wheel Assembly comprised of 4 reaction wheels
- Mass/Power/Volume is based upon the required torque, momentum storage, and power requirements



Communications Satellites		
Mass (kg)	Power (W)	Volume (m^3)
27.8	360	0.0110

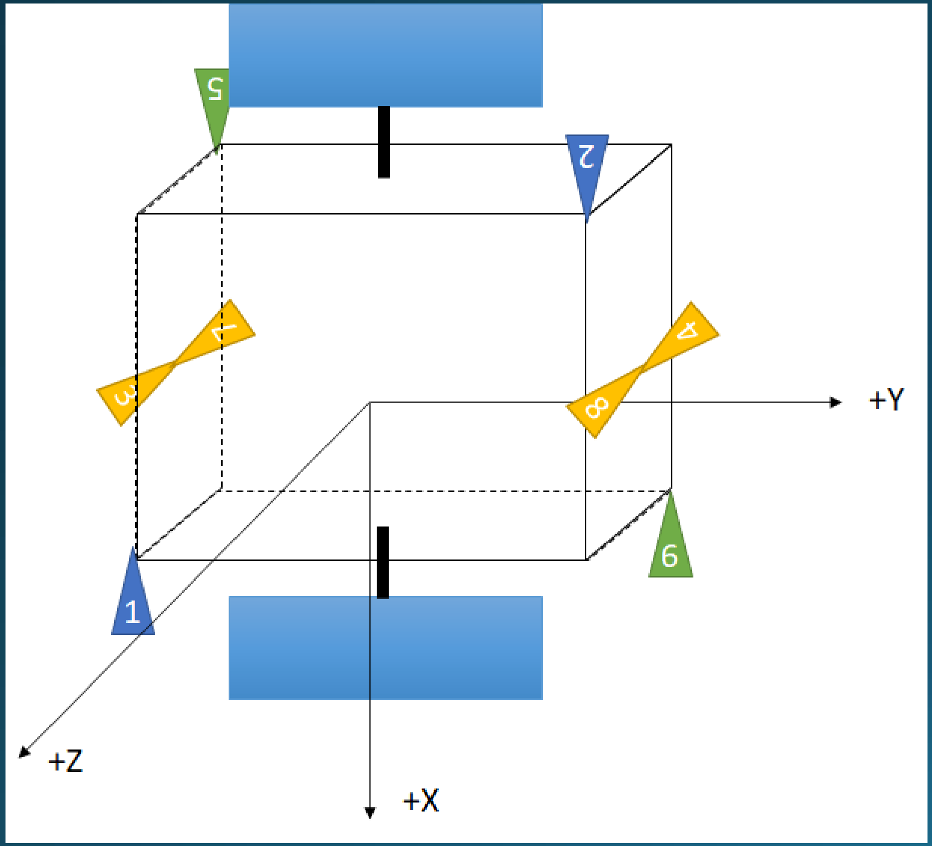
Based on Collins' RDR 23-0 RWA

Observation Satellites		
Mass (kg)	Power (W)	Volume (m^3)
52.8	500	0.1001

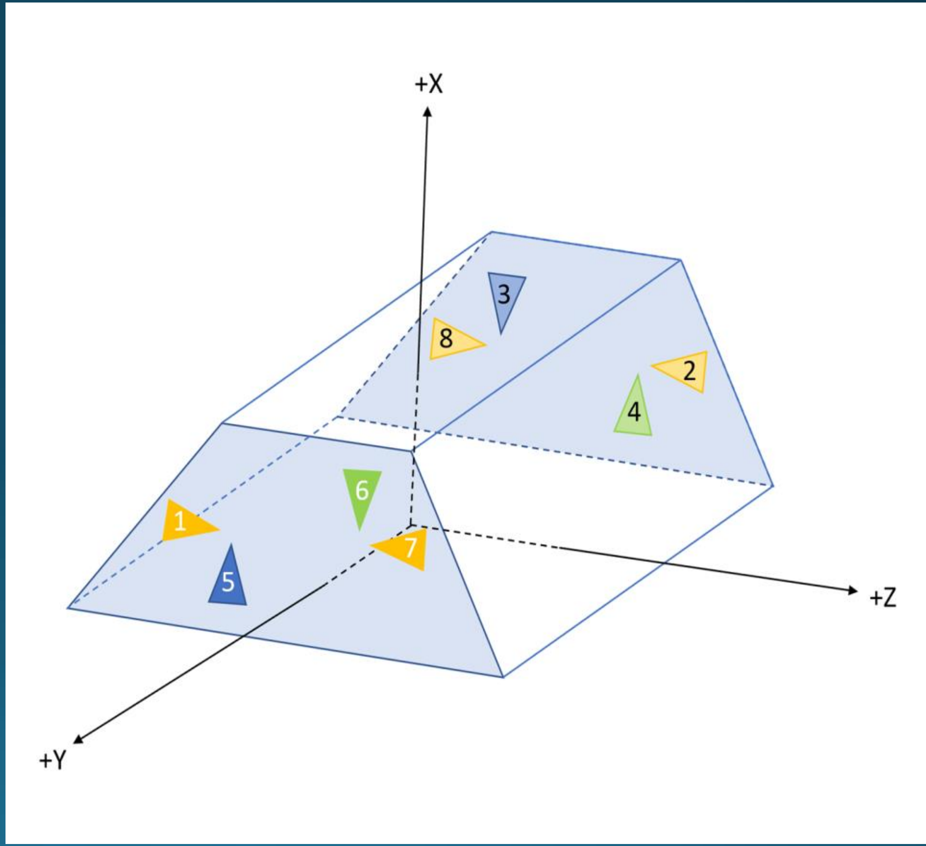
Based on LRO's RWA designed by NASA Goddard

ACS Thruster Layouts

- 8 thrusters on each satellite for momentum dumping



Communications Satellite



Observation Satellite

Observation Payload

- **Camera**
  - Use: observation and documentation of colony health and progress
  - Near Angle Camera with 0.5 m resolution
- **MiniRF**
  - Science objective: map lunar topology for exploration and mining
  - Technology demonstration on LRO (failed relatively soon into lifetime)
- **Mass Spectrometer**
  - Science objective: determine atmospheric composition and effect of human habitation
  - Based off MASPEX on Europa Clipper

	Camera	MiniRF	Mass Spectrometer
Mass (kg)	15	13.8	8
Power (W)	20	25	25

Power Systems

- Solar arrays used are DSS Roll-Out Solar Arrays (ROSA)
    - Following a 3:1 ratio of length to width
- BOL power requirements were calculated based on degradation and correction factor
    - Correction factor of 2.1 used for eclipse
    - 0.5% performance degradation per year
    - 7.24% reduction in performance over 15 years

Satellite	EOL Power Requirement (kW)	BOL Power Requirement (kW)	Dimensions of Solar Arrays (m)
Communications	2.0441	2.2038	1.11 x 3.32
Observation	5.8768	6.3023	1.953 x 5.868

Thermal Systems

- Satellite will primarily utilize a passive thermal system
  - Silver teflon coating for protection from solar radiation
  - Excess heat radiated from plate coated with SG121FD white paint
  - Excess heat conducted to passive radiator (plate) via thermal straps
- Some components may require targeted systems
- Power reqs: ~11 W for both satellites

Propulsion Systems

- Communications satellite: fully chemical propulsion for stationkeeping, attitude control and momentum unloading
  - Hydrazine monopropellant and Helium as pressurant
  - 2 propellant storage tanks of 0.94 m diameter, composite overwrapped pressure vessels (COPV)
  - 773 kg of propellant

- Observation satellite: electric propulsion for orbit changes and chemical propulsion for attitude control/momentum wheel dumping
  - Electric propulsion uses a system based on the NSTAR xenon thruster
  - Hydrazine used for ACS
  - 20 kg Xenon supercritical liquid, 64 kg Hydrazine

Action Items

- Launch vehicle selection for both types of satellite
- More detailed thermal control system, especially regarding hydrazine storage and instrument requirements
- + in progress PDR action items

Detailed

Backup

Requirements

Requirement ID	Requirement Description	Measurement
CTRL-1	The satellite optical camera shall have a nominal GSD of 0.5 m.	GSD
CTRL-2, COM-1	The observation satellite shall be capable of downlinking 4 2.5 km x 2.5 km images per pass.	Bps
CTRL-3	The optical camera shall have a swath of 2.5 km.	Pixels*GSD
CTRL-4	The observation satellite altitude variation while taking images shall not exceed +/- 15 km.	km
CTRL-5	The pointing accuracy for the observation satellite shall be 60 arcsec.	arcsec
CTRL-6	All satellites shall have a minimum expected lifetime of 15 years.	years
CTRL-7	The MiniRF shall probe lunar regolith on S and X Band frequencies at 2380 Mhz (±10 Mhz) and 7140 Mhz (±10 MHz), respectively.	MHz
CTRL-8	The MiniRF shall have a swath of 6 km for S band and 4 km for X band	km
CTRL-9	The MiniRF shall have a zoom capability of 15 m x 30 m	m
CTRL-10	The mass spectrometer shall be capable of storing 100,000 ions.	ions
CTRL-11	The mass spectrometer shall extract ions at a rate of 2kHz	kHz
CTRL-12	The mass spectrometer shall have a mass resolving power of m/Δm = 46,000 (FWHM)	Full width at half maximum (FWHM)

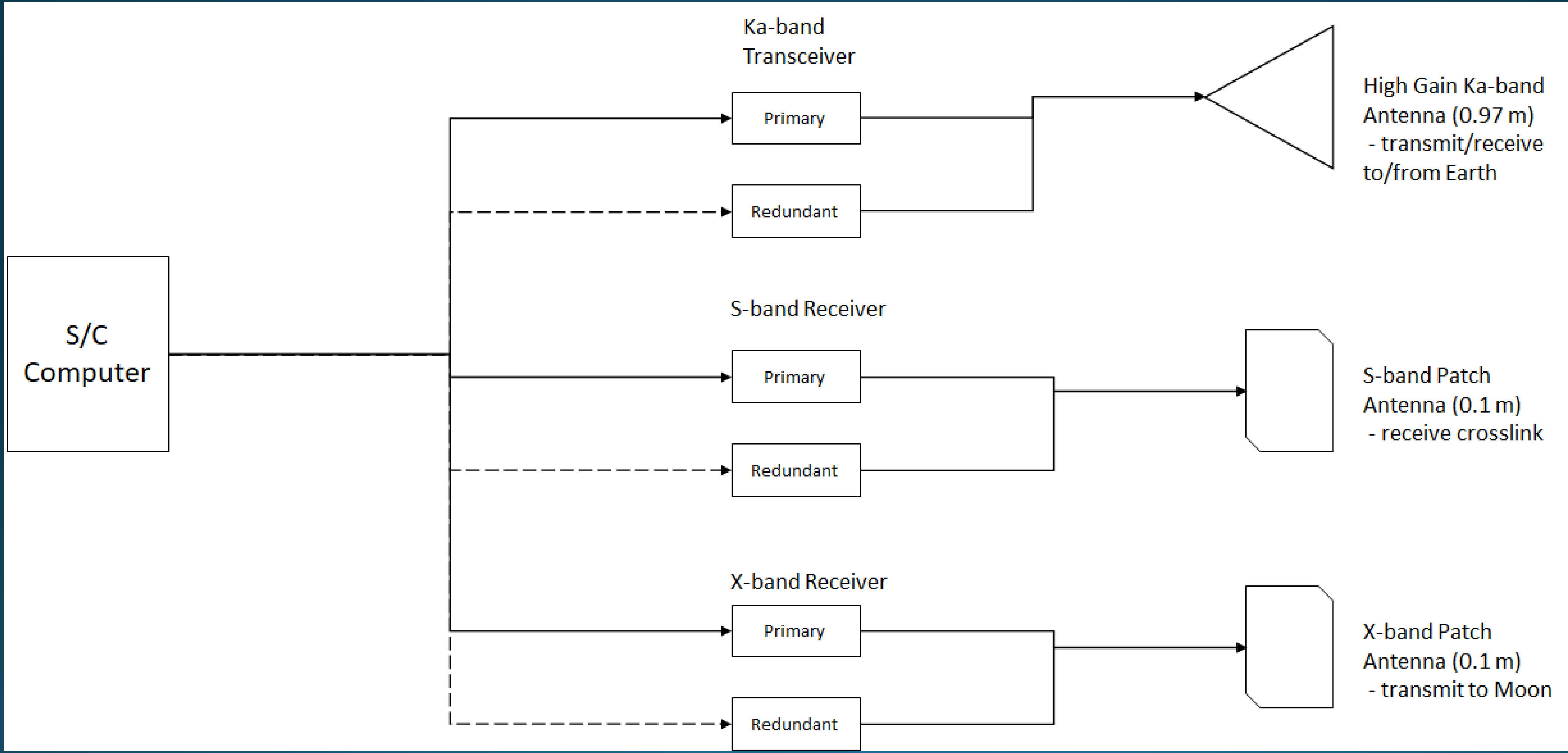
+additional linked research requirements

PURDUE AERONAUTICS & ASTRONAUTICS

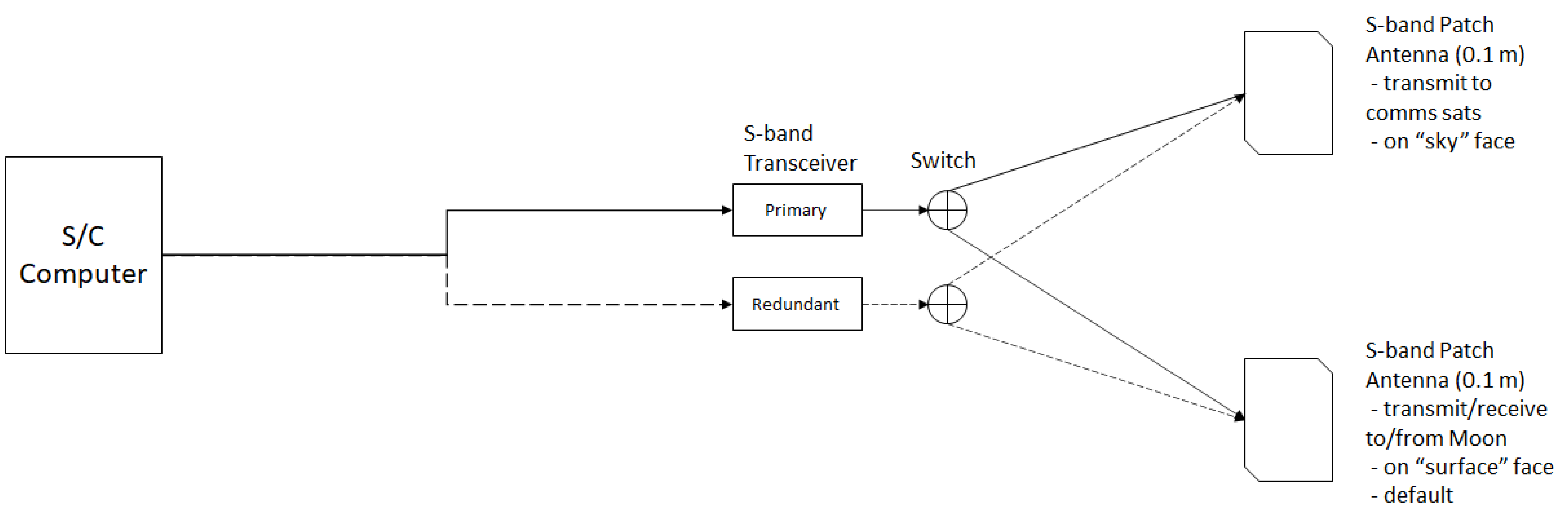
Assumptions

- Possible to develop and manufacture all satellites simultaneously
- Accelerated development, manufacture, and test timeline of 2 years
- Largest design assumption: components are compatible
    - No interference
    - No field-of-view keep-out zones
    - Same communications protocol
    - Thruster impingement negligible
- Operations costs during launch year are not prorated

Communication System - Communications



Communication System - Observation



Team Lead: Vishank Battar

Team Members: Cody Zrelak, Ajay Chandra, Alan Gelman, Nick Johnson, Omtej Vallabhapuram, Joseph Seiter, Chase Neff

CDR - Rover Systems

Problem & Solution

Problem	Solution
Area Preparation	Clearing Rover
Resource Collection	Mining Rover
Gathering Regolith for Habitat Shielding	Collection Rover
Location Searching/ Observation	Scouting Rover
Method for Constructing Habitat/ Other Structures	Construction Rover

Action Items from PDR

- Finalize mining and scouting rover design
- Provide justifications for design choices per feedback from PDR
- Cost estimation
- Risk/ fault analysis
- Develop launch schedule for mission design (mass/ fiscal year estimates)

Design Justifications from PDR

Regolith 3D Printing Rover

- Power requirement too high for 3D printing to be beneficial

Faster Travelling Speed

- Tasks completed before humans arrive do not require faster speeds
- Requiring faster speeds unnecessarily adds more power.

Rover Longevity

- Life span is currently undefined. Similar to past rovers, will most likely last longer than 10 years .
- Once humans arrive, manual upgrading of rovers is possible to perform other tasks.

Functionality Delegation

- Limited power and size constraints for individual rovers
- Delegating tasks to specialized rovers limits complexity of individual rovers
    - Decreases failure points

Complexity

- Added complexity increases number of failure points, gets expensive, and is unnecessary because simple tasks can be accomplished with simple mechanisms

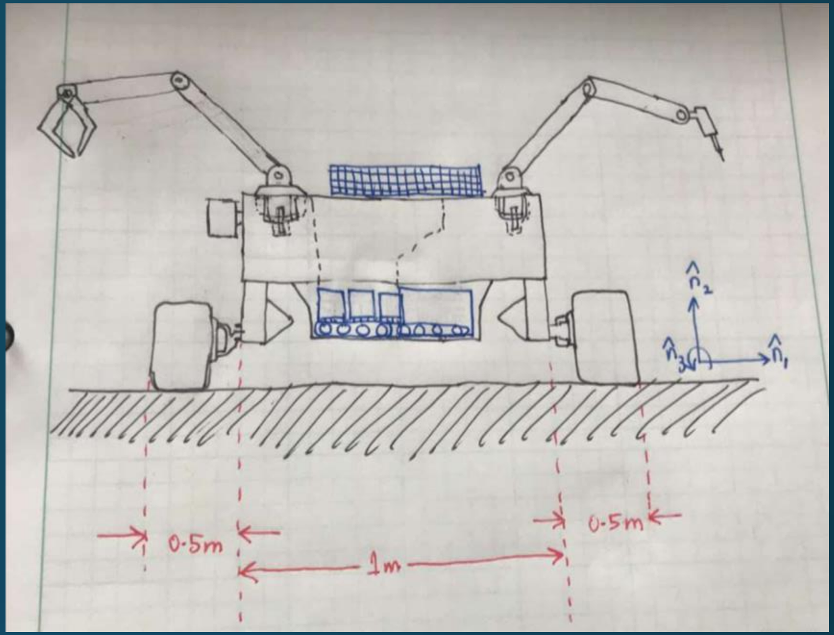
Mining Rover

Mass (kg)	Power (kW)	Volume (m³)	Gather Rate (min/core)	Est. Cost (USD)
963.3	885.4	12.5	22.7	200,168,788.20

Ref ID	Intermediate Event	Ref ID	Basic Event	Likelihood	Consequence	Overall
MINING ROVER						
VRM-1	Drive-train Failure	VRM-1.1	broken steering linkage	3	5	15
		VRM-1.2	dust in motor	1	5	5
		VRM-1.3	loss of motor power	2	5	10
VRM-2	Drill failure	VRM-2.1	DC motor voltage spike	1	1	1
		VRM-2.2	Dust jams drill drive gears	2	5	10
		VRM-2.3	Drill breaks from overuse	3	3.5	10.5
		VRM-2.4	Drill overheats and melts	1	3.5	3.5
VRM-3	Storage failure	VRM-3.1	Blockage in storage bay prevents further loading	3	2	6
		VRM-3.2	ERAs fail to maneuver core into bay	2	1	2
		VRM-3.3	storage bay is overfilled	2	1	2
		VRM-3.4	storage bay is compromised by impact	1	4	4
VRM-4	Instrumentation failure	VRM-4.1	Imaging/camera failure	1	2.5	2.5
		VRM-4.2	Loss of attitude knowledge	1	2	2
		VRM-4.4	Loss of position knowledge	2	2	4
VRM-5	Battery Failure	VRM-5.1	Voltage surge due to solar flare	3	3.5	10.5
		VRM-5.2	Battery overheats	1		0
		VRM-5.3	Battery discharges completely	2	2.8	5.6
		VRM-5.4	Electrical connection loss	1	3	3
		VRM-5.5				0
VRM-6	Structural Failure	VRM-6.1	Failure of floor of storage bay	1	3.8	3.8
		VRM-6.2	Suspension failure due to overload	2	2.6	5.2
		VRM-6.3	Wheel failure due to overload	2	2.2	4.4
		VRM-6.4	ERA failure due to overload	2	3.4	6.8
VRM-7	Suspension Failure	VRM-7.1	Jammed suspension	4	2	8
VRM-8	Loss of Stability	VRM-8.1	Tipping/falling	3	4	12
		VRM-8.2	Loss of ERA attitude knowledge	2	1.2	2.4
		VRM-8.3	Loss of vehicle attitude knowledge	2	1.2	2.4

Scouting Rover

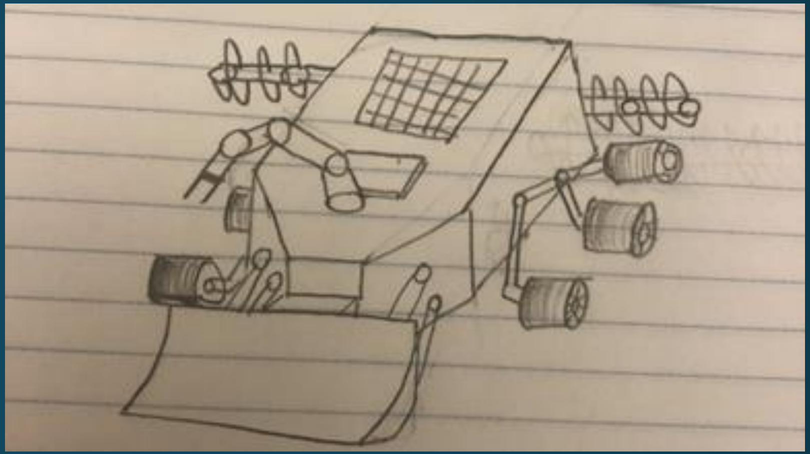
Mass (kg)	Power (kW)	Volume (m^3)	Est. Cost (USD)
502.9	0.7836	10	64,919,023.2



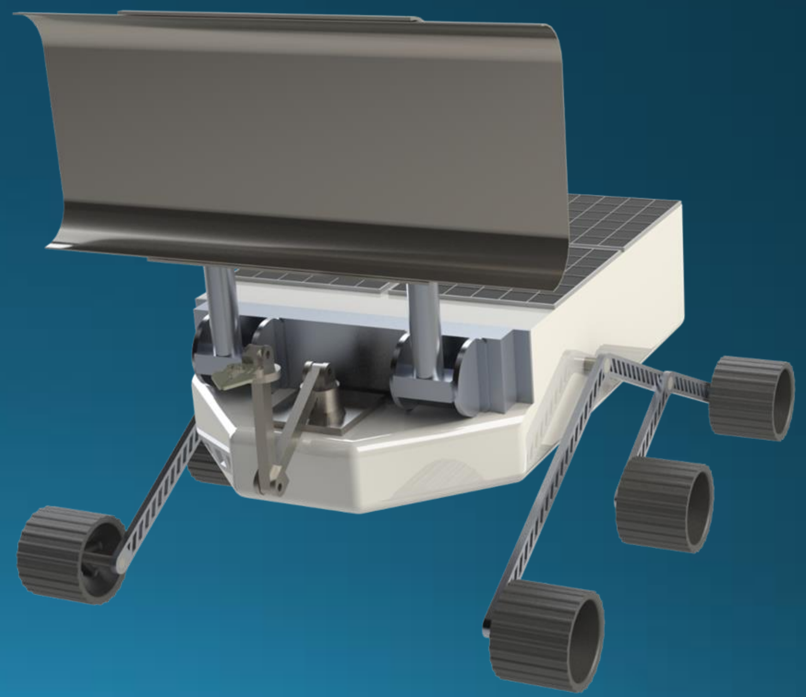
Ref ID	Intermediate Event	Ref ID	Basic Event	Likelihood	Consequence	Overall
SCOUTING ROVER						
VRS-1	Drive-train Failure	VRS-1.1	Dust jams DC motor	1	5	5
		VRS-1.2	DC motor overheat	2	3	6
VRS-2	Instrumentation Failure	VRS-2.1	Loss of position knowledge	2	2	4
		VRS-2.2	Imaging/camera failure	2	2.5	5
		VRS-2.3	Radiation damage	1	3	3
VRS-3	Battery failure	VRS-3.1	Battery death	2	3	6
		VRS-3.2	Battery Overheat	1	2	2
VRS-4	Structural failure	VRS-4.4	Impact damage	2	3	6
		VRS-4.5	Wheel nut failure	1	3	3
VRS-5	Suspension failure	VRS-5.1	Tipping/falling	2	3	6
		VRS-5.2	Suspension breakage	1	3	3

Clearing Rover

Mass (kg)	Power (kW)	Volume (m^3)	Clearing Rate (m^3/min)	Habitat Clearing Time (hr)	Est. Cost (USD)
585	1.079	10	0.0688	~6	64,900,289.2

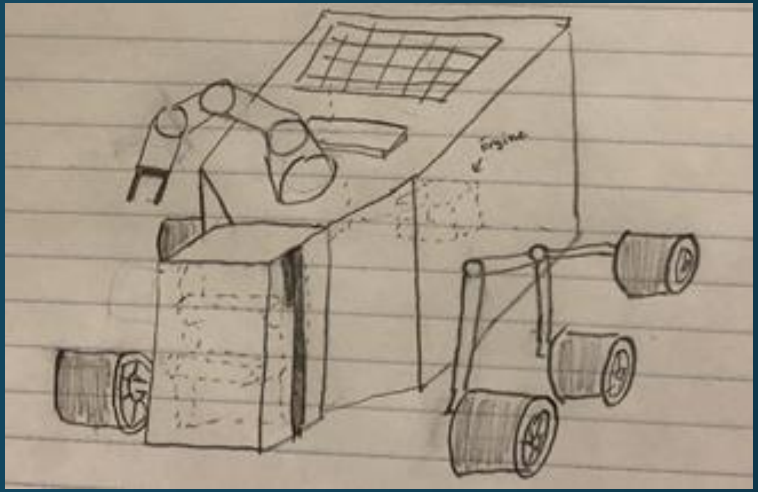


Ref ID	Intermediate Event	Ref ID	Basic Event	Likelihood	Consequence	Overall
CLEARING ROVER						
VRC-1	Drive Train Failure	VRC-1.1	Broken Steering Linkage	3	4	12
		VRC-1.2	Dust in Motor	1	1	1
		VRC-1.3	Loss of Motor Power	2	5	10
VRC-2	Body Failure	VRC-2.1	Body Buckles	1	4	4
		VRC-2.2	Micrometeoroid Impacts	4	2	8
VRC-3	Instrument Failure	VRC-3.1	GPS Position Loss	2	2	4
		VRC-3.2	Solar Flare Interference	1	3	3
		VRC-3.3	Solar Wind Circuit Ionization	2	3	6
VRC-4	Battery Failure	VRC-4.1	Battery Explosion	1	5	5
		VRC-4.2	Battery Recharge Failure	2	4	8
VRC-5	Suspension Failure	VRC-5.1	Fatigue Failure	2	4	8
VRC-6	Robotic Arm Failure	VRC-6.1	Robotic Arm Jam	2	4	8
		VRC-6.2	Robotic Arm Claw Failure	1	3	3
VRC-7	Wheel Failure	VRC-7.1	Wheel Bearing Jam	2	3	6
		VRC-7.2	Wheel Fatigue Failure	1	4	4
		VRC-7.3	Spoke Failure	1	4	4
VRC-8	Axle Failure	VRC-8.1	Fatigue Failure	1	5	5
VRC-9	Plow Failure	VRC-9.1	Plow Hydraulics Failure	2	5	10
VRC-10	Auger Failure	VRC-10.1	Augur Jam	3	3	9



Collecting Rover

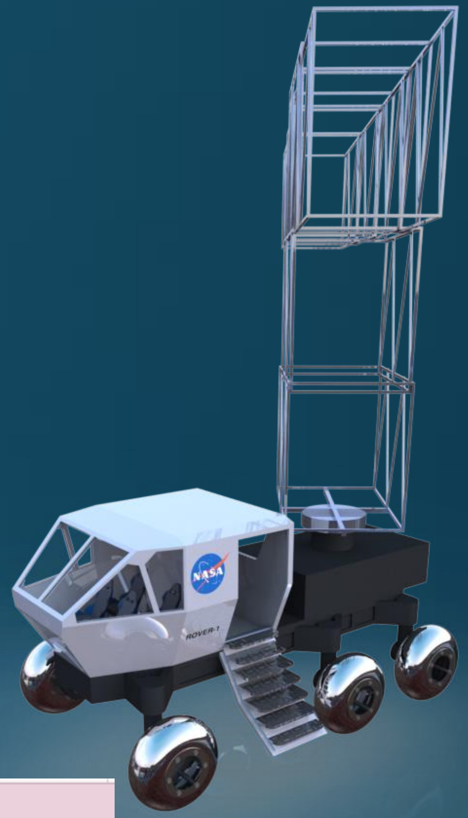
Mass (kg)	Power (kW)	Volume (m^3)	Clearing Rate (m^3/min)	Habitat Clearing Time (hr)	Est. Cost (USD)
585	1.079	10	0.0688	~6	69,420,904.2



Ref ID	Intermediate Event	Ref ID	Basic Event	Likelihood	Consequence	Overall
COLLECTION ROVER						
VRL-1	Drive Train Failure	VRL-1.1	Broken Steering Linkage	3	4	12
		VRL-1.2	Dust in Motor	5	1	5
		VRL-1.3	Loss of Motor Power	2	5	10
VRL-2	Body Failure	VRL-2.1	Body Buckles	1	4	4
		VRL-2.2	Micrometeoroid Impacts	4	2	8
VRL-3	Instrument Failure	VRL-3.1	GPS Position Loss	2	2	4
		VRL-3.2	Solar Flare Interference	1	3	3
		VRL-3.3	Solar Wind Circuit Ionization	2	3	6
VRL-4	Battery Failure	VRL-4.1	Battery Explosion	1	5	5
		VRL-4.2	Battery Recharge Failure	2	4	8
VRL-5	Suspension Failure	VRL-5.1	Fatigue Failure	2	4	8
VRL-6	Robotic Arm Failure	VRL-6.1	Robotic Arm Jam	2	4	8
		VRL-6.2	Robotic Arm Claw Failure	1	3	3
VRL-7	Wheel Failure	VRL-7.1	Wheel Bearing Jam	2	3	6
		VRL-7.2	Wheel Fatigue Failure	1	4	4
		VRL-7.3	Spoke Failure	1	4	4
VRL-8	Axle Failure	VRL-8.1	Fatigue Failure	1	5	5
VRL-9	Storage Failure	VRL-9.1	Bay Door Jamming	2	5	10
		VRL-9.2	Storage Enterence Bloackage	2	4	8

Construction Rover

Mass (kg)	Power (kW)	Volume (m³)	Est. Cost (USD)
14574.96	25.62	79.743	229,745,660.5



CONSTRUCTION/MODULAR ROVER						
VRD-1	Drivetrain failure	VRD-1.1	Dust in DC motor	1	4	4
		VRD-1.2	Broken Steering Linkage	3	1	3
		VRD-1.3	Loss of motor power	2	5	10
VRD-2	Body Failure	VRD-2.1	Body Buckles	1	4	4
		VRD-2.2	Micrometeroid impacts	2	2	4
VRD-3	Instrumentation Failure	VRD-3.1	GPS Position Loss	2	2	4
		VRD-3.2	Solar Flare Interference	2	3.5	7
		VRD-3.3	Solar Wind Circuit Ionization	2	2	4
VRD-4	Battery Failure	VRD-4.1	Battery Explosion	1	4	4
		VRD-4.2	Battery Recharge Failure	1	3	3
VRD-5	Suspension Failure	VRD-5.1	Fatigue Failure	2	3	6
		VRD-5.2	Shock/Impact Failure	1	2	2
		VRD-5.3	Detachment	1	1	1
VRD-6	Wheel Failure	VRD-6.1	Impact Damage	1	5	5

Launch Schedule

Rover	Launch Period
Collection	Y1, Q4
Clearing	Y1, Q4
Scouting	Y1, Q4
Mining	Y1, Q4
Construction	With Humans

Cody Zrelak, Section 3

Rovers Team Timeline

Send Collection Rover
Autonomous Rover sent to collect regolith for habitat shielding

Send Clearing Rover
Autonomous Rover sent to clear and flatten space for the habitats and solar farm

Send Scouting Rover
Autonomous Rover sent to find locations of needed resources and lands

Preparation Phase
Year 1

Send Construction Rover
Human driven rover designed to do heavy lifting and construction. Has numerous modules that can be attached

Send Mining Rover
Autonomous Rover sent to collect resources that will be needed by the colony and raw resources to be processed by the colony

Groundbreaking Phase
Year 2

Tasks Completed
Clear land for habitats
Clear land for solar farm
Collect Regolith for Shielding
Find Ice and Start Mining it

Completion Phase
Year 3

Sustain Tasks
Collect Regolith for water processing
Collect needed and usable resources
Clear land for projects
Scout for various needs
Construct the colony

Sustain Phase
Years 4-10

PURDUE AERONAUTICS & ASTRONAUTICS

Action Items Before Configuration Freeze

- Finish CAD for scouting rover
- Mass for construction rover - currently estimated
- Power requirements

Vehicles - Interior
AAE 450 - Spring 2021

03/10/2021
Complete Design Review

Team Member: Joong Hyun Pyo, Sanjidah Hossain, Mackenzie Marks

Overall Changes/Additions

- Robotic Arm
  - Updated power and volume requirements
  - Uses other than storage and inventory
  - Cost estimation
- Assistant Robot
  - External Activity considerations
- Mechanical Surgical Arms
  - New Addition for dedicated medical operations

Purpose

After the initial phase of colonizing the Moon(Post 10yr Project), we want to provide the colonist with addition non-human support from research/medical purposes to trivial maintenance of the habitat for an extended period of time. Experimental study of the use of autonomous robotics/vehicles in a limited, hostile environment.

- Requirements
  - Heavy load lifting
    - Average load bearing: 2.5-3x Human body weight
  - Precision Control
    - Medical Procedure
    - Replacing Components, Electrical work
  - Additional Habitat Control/Maintenance
    - Autonomous Experiments
    - Cleaning
- Assumptions
  - Fully established colony with proper power, life support, and temperature control

Problem: Heavy Load Maneuvering

- Background
  - Despite low gravity conditions, heavy loads will be difficult to move without the assistance of a machine
  - Space conservation requires stacking, thus the ability to reach heavy resources stacked on top of each other safely is necessary
- Constraints
  - Limited space for operation within habitat
  - Limited power available
- Assumptions
  - Resource storage facilities concentrated in one section of the habitat
  - Resources organized and labeled in a systematic manner to allow for automation

Solution:Heavyload Robotic Arm

	Mass (kg)	Power (kW)	Volume (m^3)	Speed (m/s)
Body	100	200	2	0.8
Arm	250	150	0.8	10

- Features
  - 8 degrees of freedom on arm, 3 degrees of freedom on wheels, 2 degrees of freedom on forklift
  - Automated storage and retrieval - can maintain and update inventory
  - Capable to lifting up to 230 kg, able to reach max height of 3.5 meters
  - Capable of navigating the whole habitat and can be used to lift any heavy object on request

Heavyload Robot CAD Model

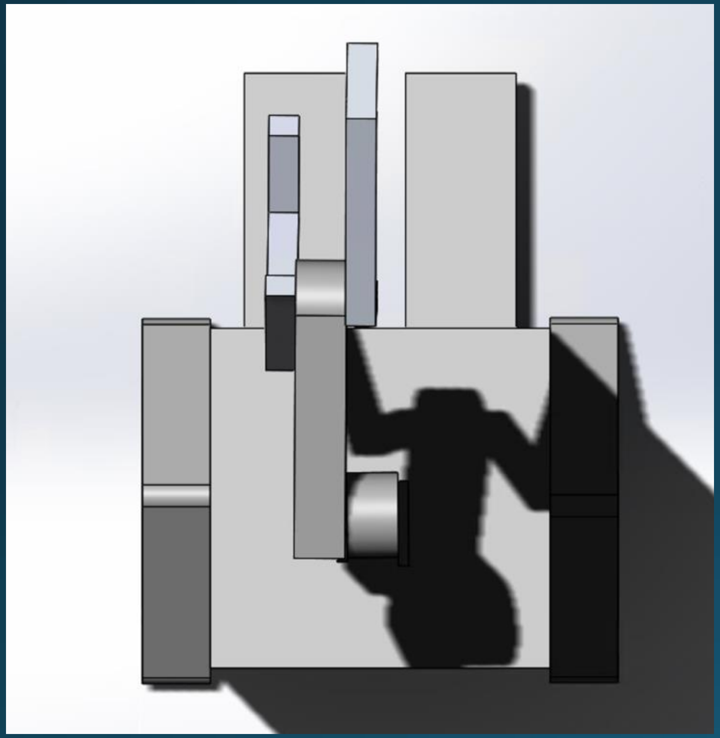


Figure 1: Top View

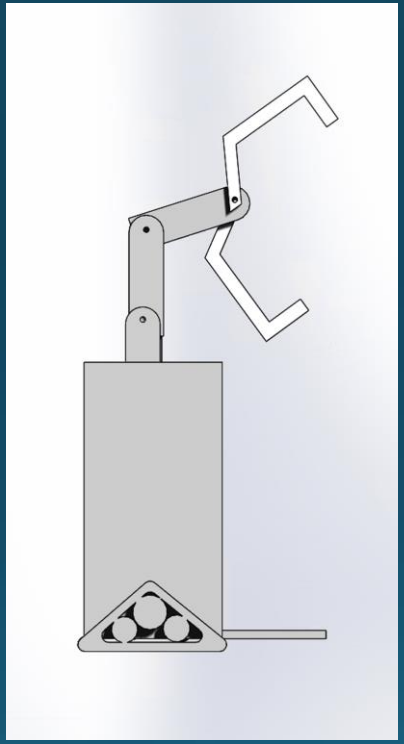


Figure 2: Side View

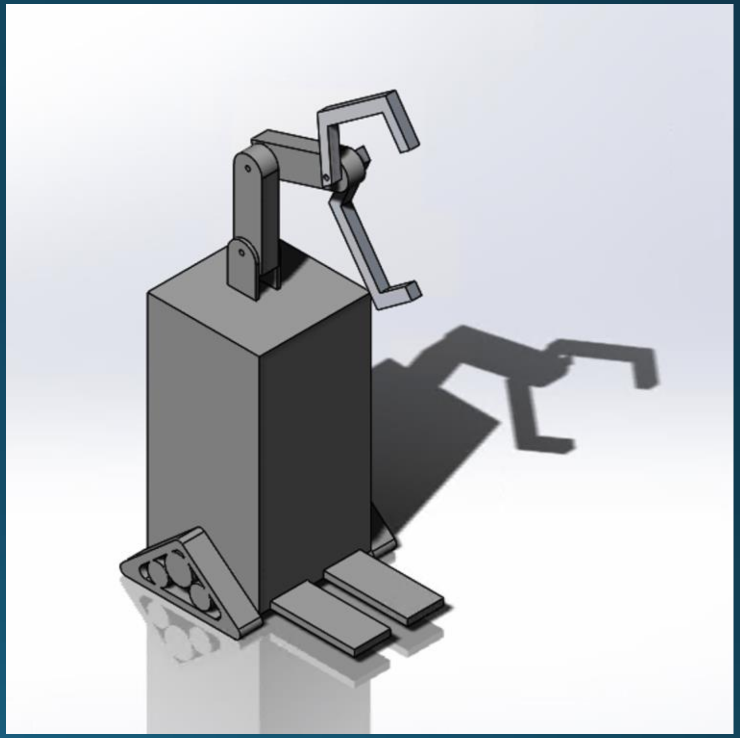


Figure 3: 3D View

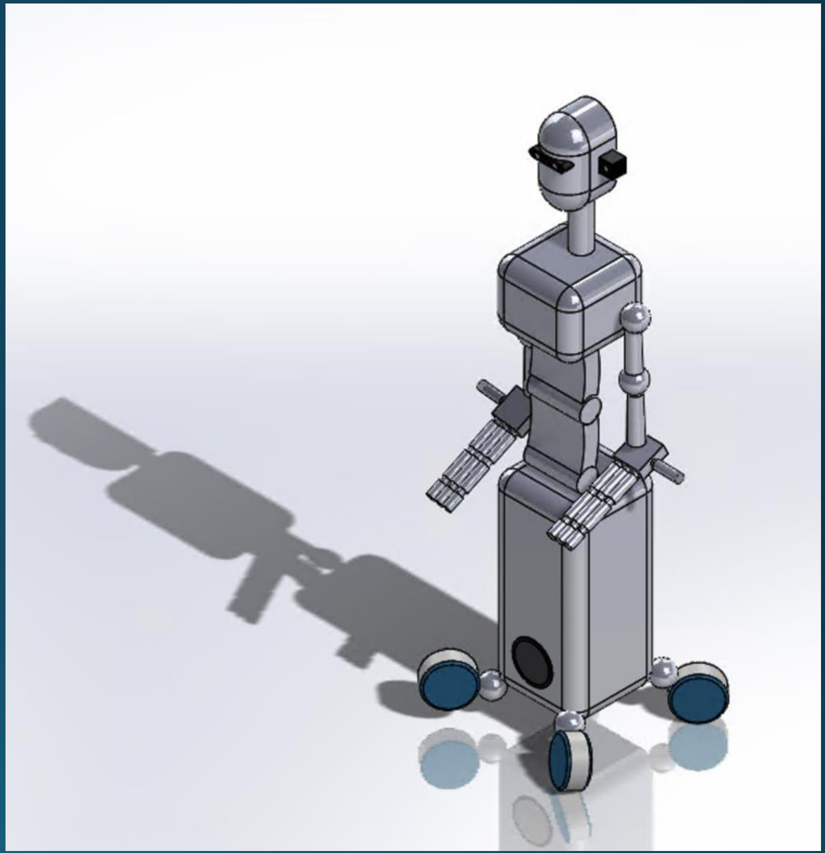
Problem: Mobility & Dexterity

- Background
  - Given the size of the habitat, the inside will be crowded with human activity and materials. Therefore, the robot requires minimal space while being able to perform both trivial and complicated tasks.
- Constraints:
  - Limited space in interior of habitat
  - Unexpected activity/collisions during maneuvers between stations.
  - Low operational Temperatures of the Moon
- Assumptions
  - Habitat has reflective tape/lines along the floor
  - A.I. Capable Technology
    - Object identification and basic problem solving
  - All areas of materials are organized

Solution: Assistant Robot

	Mass [kg]	Power [kW]	Volume[m^3]
Assistant Robot	204	120	1.31
Thermal Electronic Housing Unit	3 - 4	0	0.14
Radioisotope Heating Unit (Per unit)	0.0396	Output: 1 Watt	0.000017

- Features
  - Medical Procedures
  - Autonomous Experiments
  - Habitat Maintenance
  - External Activities (Equipped with Thermals/Shielding)
    - Maintenance of habitat
    - Equipment repair
      - Solar Panels
      - Radio Equipment



Model By:
Mackenzie Marks (CAD Team)

Problem: Major Medical Operations

- Background
  - Given the status of the Moon colony, unexpected accidents will occur. Whether that is from external activity, or within the habitat. Therefore, for major medical operations a dedicated mechanical surgical arms are required.
- Constraints:
  - Limited space in interior of habitat
- Assumptions
  - All areas of materials are organized
  - Medical/Government approved
  - Habitat is clear for open surgery
  - Medical module for colony is constructed (Optional)

Solution: Mechanical Surgical Arms

	Mass [kg]	Power [Watts]	Volume[m^3]
Surgical Arm(3)	30.3	36	1.485
Remote Operating Hub	264	69	2.02
Total	294.3	99	3.51

- Possible Operations
  - General surgery(hernia, gallbladder, bariatric)
  - Cardiac Surgery
  - Colorectal
  - Head and Neck Surgery
  - Urology Surgery

Total Estimated Time/Cost

- Manufacturing
  - Robotic Arm: $200,000
  - Assistant Robot: $500,000
  - Surgical Arm: up to $1.3 million
- Testing
  - Robotic Arm: $50,000-$75,000
  - Assistant Robot: $300,000
- Maintenance
  - Robotic Arm: $10,000-$30,000 annually
  - Assistant Robot:$35,000- $55,000
  - Surgical Arm: $140,000

Timeline

- Post 10 year project for Lunar Colonization
- The robots will serve as a study for the feasibility of autonomous humanoids in different environments and how people interact with it when it is present inside the habitat. Both for remote and on-site operations, we want to test its capabilities and usefulness for future missions.