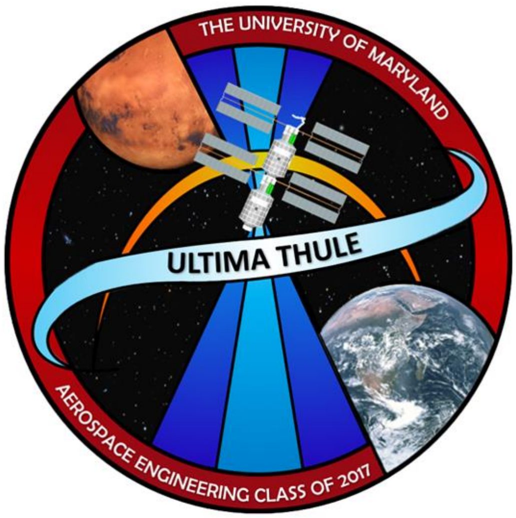
RASC-AL Technical Paper: Ultima Thule



RASC-AL Theme: Commercially Enabled LEO / Mars Habitable Module

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Introduction: Ultima Thule is Latin for the extreme limit of travel and discovery, which drives the goal of the University of Maryland's Ultima Thule program: to enable the pioneers of today to reach the extreme limit by providing a modular, multi-purpose orbital outpost and to support the pathfinders of tomorrow as humanity ventures deeper into the solar system. The mission is to design, build, and operate a modular space station which is configurable to sustain multiple commercial ventures in Earth orbit and beyond, and to support human exploration endeavors throughout the solar system.

The basic module has a minimum lifespan of 15 years and is capable of being a stand-alone commercial station which can support up to four crew members. The nominal station configuration is composed of two modules, each holding two crew members, allowing for redundancy and more space dedicated to scientific research, manufacturing operations, and technology development. Moreover, the station can be easily expanded with additional modules to support tourism, recreational activities, and various commercial ventures. Beginning launches in 2022, the Ultima Thule program plans to ultimately establish three stations in Earth orbit and one station for Mars transit. After many iterations and with feedback from a Preliminary Design Review, Critical Design Review, and interviews with experts in the field, this report represents the final design and analysis by the 41 member design team. The following describes the concept of operations, detailed habitat components, hardware testing, and business model of the Ultima Thule program.

Affected Component(s)	Load Type	Approximate Magnitude	Event	Margin of Safety
Primary Habitat	Axial Compression and Bending	972 kN and 710 kN-m	Lift Off	0
Primary Habitat	Buckling	972 kN and 710 kN-m	Lift Off	1.9
Service Module	Axial Compression and Bending	260 kN and 190 kN-m	Lift Off	0
Service Module	Buckling	260 kN and 190 kN-m	Lift Off	19.4
Endcap Longerons	Axial Compression and Bending	76 kN and 177 kN-m	Lift Off	0
Endcap Longerons	Buckling	76 kN and 177 kN-m	Lift Off	27

The main goal of Ultima Thule's program was to design a habitat that can fulfill a multitude of roles while being economically viable to support commercial demands. At the same time, the modular nature must be configurable as a transit habitat for manned Mars exploration; beyond that requirement, we envision Ultima Thule modular habitats as a basic building block for future human space exploration, whether in orbit or on the surface of an asteroid, moon, or Mars.

Specifications per Module	
Maximum Crew Size	4
Diameter	4.6 m
Length	9.7 m
Pressurized Volume	82.8 m^3
Launch Mass	28.2 MT

As represented in Table X, a single module will have room for a maximum of four astronauts with a total pressurized volume of 82.8 m^3. Each additional module will at least double the usable lab space and these stations can be expanded to accommodate space travel demands. The module is designed to fit inside the fairing of a Falcon Heavy, and launches to provide supplies and crew will use a Dragon capsule launched on a Falcon 9.

Concept of Operations

Phases 1-3: Phase 1 of the mission will begin in the quarter one of 2022 with the launch of the first Ultima Thule module (1.1) into a 51° inclination LEO orbit to dock with the International Space Station (ISS), to testbed for critical subsystems. After six months, Phase 2 will begin with the launch of four crew members to the ISS, where they will begin habitation testing. During this time period, a second module (1.2) will launch into the same orbit as the first module. Phase 3 begins in the fourth quarter of 2022, when the crewed module 1.1 undocks from ISS and rendezvous with module 1.2 to form the nominal configuration for the initial LEO station. A crew of seven will replace the original crew of four in the first quarter of 2023 and then subsequently rotated every six months.

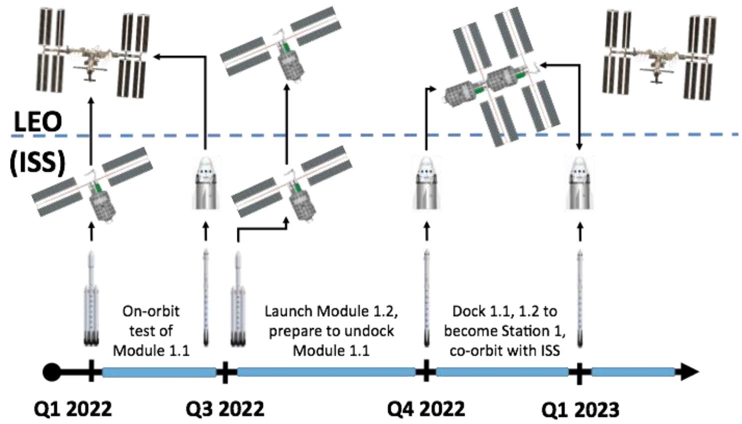


Figure X. (Station 1 CONOPS)

Phases 4-5: In order to take advantage of peak launch vehicle (LV) performance when launched from Cape Canaveral and Boca Chica, the addition of a second station in a 29° inclination orbit will start the diversification of the business profile during Phase 4 of the mission. Station 2 will follow a similar timeline, beginning with the launch of module 2.1 in the third quarter of 2024, followed by a short on orbit check-out period after which the first crew of four will inhabit the new module. The second module for Station 2 will launch and rendezvous with the first in the first quarter of 2025 and a crew of seven will then replace the original crew. The commercial expansion phase, or Phase 5 of our mission, will begin in the third quarter of 2025 with the launch of a tourism module to station 2. The tourism module will house four tourists for periods of two weeks.

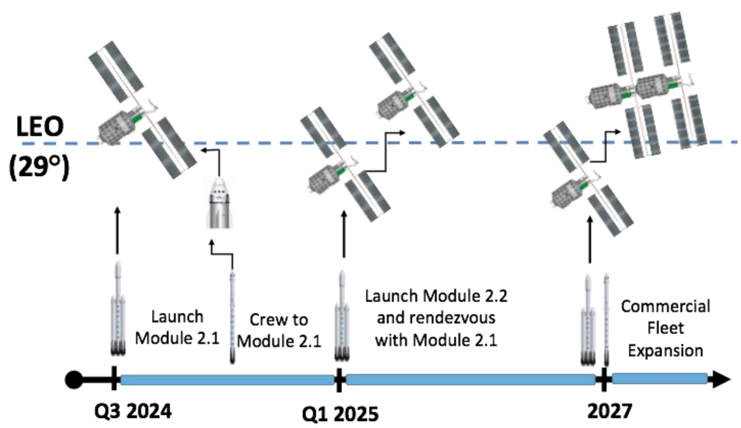


Figure X. (Station 2 CONOPS)

Phase 6: After reaching the break-even point, Ultima Thule profits will be invested back into research and the establishment of a third station in a HAEO for Phase 6. Unlike Stations 1 and 2, the HAEO station will be comprised of a single module. The HAEO module will first be launched into LEO where a booster stage will rendezvous and transfer it into HAEO. At this point, supplies and crew will be launched to the HAEO station to make it fully operational as a testbed for Mars transit technologies such as radiation shielding, rendezvous at high altitude, and booster docking.

Phases 7-8: Phase 7 of the CONOPS is the assembly of the Mars transit vehicle. Assembly will take place in LEO at an altitude of 400 km. A typical long-stay Mars mission profile has a duration of 950 days with 550 spent in Mars orbit and the remaining 400 spent in transit. Short-stay mission profiles have durations of 450 days with 30 days spent in Mars orbit and the remaining 420 days spent in transit. Short-stay missions would require one module and a Dragon capsule while long-stay missions require two modules and a Dragon capsule. A large booster is also required for propulsion. Considering a launch in 2031, this assembly would begin in 2030. Phase 8 of this mission is transit to Mars where long-stay missions optimize the use of Hohmann windows to reduce total mission ΔV and transit time.

Station	# of Modules	Location	Purpose	Date
1	2+	LEO (52˚; 435 km)	ISS testing, LEO operations	2022
2	2+	LEO (29˚; 435 km)	Commercial Expansion	2025
3	1	HAEO (29˚; 87,000 km)	Test Deep-Space Habitat	2027
4	2	LMO	Mars Transit Habitat	2031

Habitat Components

Isogrid Pressure Vessel: In order to improve load path redundancies, stiffness, and mass savings, an isogrid main pressure vessel was designed using the *Isogrid Design Handbook*. withstand launch loads with a 1.4 factor of safety (FOS). The ribs were locally stiffened such that it can withstand the interface stresses where the two Common Berthing Mechanisms (CBM) and two windows are milled out. Through finite element analysis (FEA), it was shown that the primary structure is capable of withstanding all launch loads within a margin of safety (MOS) of at least 2, and has a low mass of 910 kg. Under free vibration, the isogrid has a fundamental mode of 5.5 Hz. Compared to a rib, longeron, and shear panel structure, the isogrid offers an improved extensional and bending stiffness-to-mass ratio. An ellipsoidal endcap design was chosen in order to maximize habitable volume and minimize mass. The optimum protrusion of the endcap for this pressure vessel was found to be 0.5 meters.

Ribs and Longerons: The rib and longeron structure was designed to handle the maximum axial compression loads as well as the maximum bending moment. The nominal longeron design was boxes with sides of 11 cm and variable thickness. The thickness was varied depending on the design loads that the section experienced for optimization. The longerons of the primary habitat and service module were designed to withstand maximum launch loads, and have masses of 190 and 50 kg; whereas, the endcaps were designed to withstand Mars transit accelerations and have a mass of 19 kg. The design requires the longerons to be 11 cm wide in order to bridge the gap between the pressure vessel and the outer MMOD layers.

Micrometeoroids and Orbital Debris (MMOD): For adequate MMOD shielding, the module has a stuffed Whipple shield with a 0.17 cm thick layer of Nextel AF 62 and a 0.1 cm thick layer of Kevlar KM2 CS 705 which satisfies NASA standards for the probability of no penetration (PNP). Together with the 0.3 cm thick bumper and 0.1 cm thick rear wall made of Al 7075-T6, the uniform module shield has a PNP of 95.2% over 10 years and has a total mass of 1130 kg.

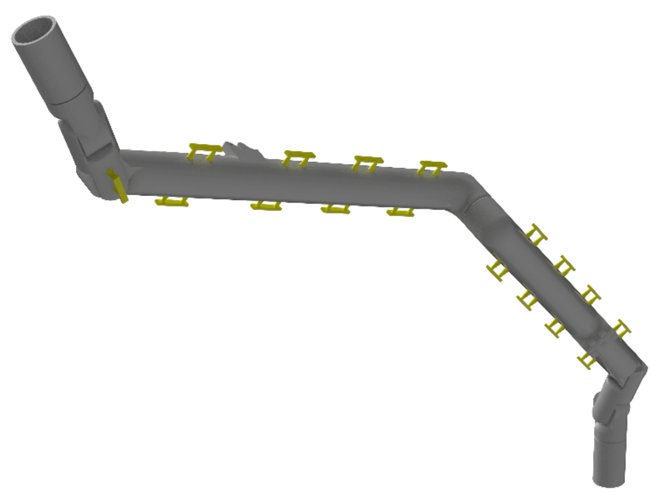
Payload Attach Fitting: Due to positioning of common berthing mechanisms, the module cannot be directly attached to the standard payload attach fitting supplied by SpaceX. A custom payload attach fitting was designed to interface with the longerons on the module. Made of titanium Ti-6Al-4V, the payload attach fitting has been designed to handle all the launch loads as well as the loads during payload integration with a mass of 467 kg.

Airlock: An inflatable design was chosen for the airlock so that it could be stowed within the trunk of the Dragon Crew Capsule, thus saving on launch volume. During pressurization, the airlock expands axially to its full length of 2.71 m, yielding an internal volume of 7.26 m^3 which is sufficient to accommodate two astronauts at a time. The airlock is composed of five major components: the bulkhead, hatch, shell, support structure, and a passive CBM.

Configuration	Diameter [m]	Length [m]	External Volume [m^3]
Stowed	2.15	1.09	3.96
Expanded	2.15	2.71	9.84

A major design point for the airlock was a method of keeping it rigid when was fully depressurized. In order to accomplish this, a rib and longeron support structure was designed in which four ribs are woven into the inner scruff layer of the shell. After initial pressurization, the longerons are snapped into the ribs and complete the structure. The design load for the support structure was based on the maximum force an astronaut could generate while pulling from a standing position, which was found from NASA's *Human Integration Design Handbook*.

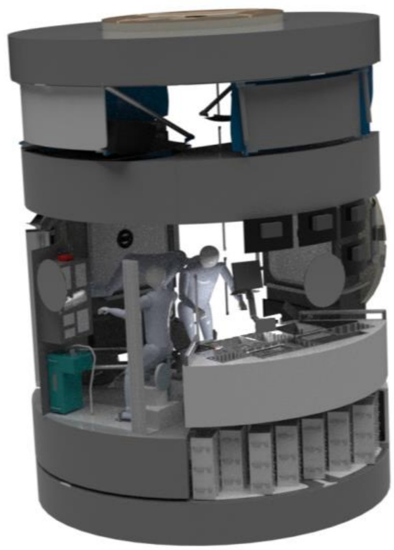
Robotic Arm: Ultima Thule stations will be equipped with a relocatable, seven degree-of-freedom, 10.7 m long arm capable of berthing additional Ultima Thule modules and most current commercial cargo spacecraft. To deploy itself from its launch configuration, the robotic arm will actuate its joints, including two single-use joints that move with the severing of frangible bolts and are then permanently stiffened with locking collar mechanisms. By assuming that the arm will have a loaded speed similar to Canadarm2 and that the Ultima Thule arm will be made of black aluminum, structural analysis, including bending, buckling, and torsional analysis, determined an optimum inner and outer diameter of 0.33 and 0.34 m, respectively.



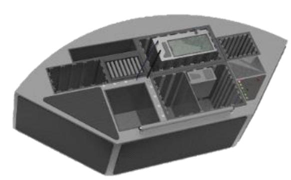
Internal Layout: The interior of a module contains all the necessary equipment for life support, health monitoring, exercise, scientific experiments, dining, storage and personal sleeping for four astronauts. The interior layout design comprises of quarter circle sections, called alcoves. The alcoves were designed to provide a simple method to modify the interior layout without sacrificing habitable volume and mounting space.

Inner Diameter [m]	1.5
Outer Diameter [m]	4.3
Height [m]	5.03
Habitable Volume [m^3]	48
Total Volume [m^3]	73

The crew group area will be in the middle of the habitable volume. This area, sectioned by function, is the space where the crew will conduct group meetings, recreational activities, commanding of the spacecraft, video communication, and additional science. Dedicated space for the crew to interact both socially and professionally is critical for any manned vehicle. Next to the crew group area will be a commanding station where the crew will be able to monitor and access all spacecraft subsystems. This station will be equipped with both a rotational and translational hand controller to control spacecraft subsystems as well as robotic assets in the case of a necessary manual override. The personal alcove is equipped with a sleeping bag, storage, retractable privacy curtain, and a computer on a flexible arm.



The health of the astronauts must be monitored on board. For LEO, the capabilities of the medical alcove have been based off of the International Space Station Medical Operations Requirements Documents. The medical alcove will be able to cover first aid, routine medical care, basic life support, advanced life support, and in-flight health status evaluations. Additionally, to keep astronauts healthy and physically fit during spaceflight, exercise equipment is included. Multiple types of cycle ergometers, treadmills, and resistive exercise options were compared and after evaluation, the Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS), the Treadmill with Vibration Isolation and Stabilization System (TVIS), and resistance bands were chosen as the exercise equipment for reasons including lower mass, power, etc. The CEVIS, TVIS, and resistance bands were modified and combined into one system to conserve volume. Virtual reality goggles will be an option for the crewmember to use when exercising to simulate running or biking through a scenery of choice.



Each module of Ultima Thule shall be capable of housing four astronauts for six months without the need for resupply barring extenuating circumstances. The atmosphere composition in LEO will be 18.8 kPa pPO_2 & 81.8 kPa pPN_2 and 18.8 kPa pPO_2 & 51.2 kPa pPN_2 for EVAs/outside LEO. Pumps and pressure vessels will be used to reduce the cabin pressure prior to scheduled EVAs. Electrolysis of water will supply the crew's oxygen. The two-month backup O_2 and EVA oxygen supply will be provided by LOx stored in the service module. Liquid N_2 is stored in the service module and will last six months. A four bed molecular sieve will remove the CO_2 from the atmosphere. The backup CO_2 removal system will last fourteen days and consists of LiOH canisters. The CO_2 re-generator will be a sabatier reactor with an efficiency of 49% using a microlith substrate to be tested on the first module sent to the ISS.\cite{CSAC_MicrolithSab} Should the microlith system fail, the monolith system will replace the microlith substrate. Additionally, Ultima Thule will be equipped with a water reclamation system (WRS) to reduce the demand of water per resupply mission. The WRS (89% efficiency) will consist of a Urine Processor Assembly (UPA), Water Processor Assembly (WPA), and an ionomer-membrane water processor (IWP), developed by Paragon Space Development Corporation. The IWP will remove any water that remains in the brine from distillation. For a crew of four people with resupply missions every three months, the estimated resupply mass is 810 kg. There will be a three-month reserve onboard, which increases the mass to 1620 kg.

The astronauts aboard the Ultima Thule will use disposable wash towels and wipes to stay clean. All cleaning will take place in the bathroom, which has a toilet and a privacy curtain. For all missions until the Mars transfer, materials will be disposable. All clothing will be sealed in Cargo Transfer Bags (CTBs) and will be worn out according to NASA's baseline standards. The mass and volume estimates needed for a four-month period are shown in the table above**.** In order to save on mass, a simple washing machine will be used to extend the usability of clothing for the Mars mission. The design of the washing machine is based on the winning concept of NASA's "Simple Microgravity Laundry System" design challenge. The specifications of the machine are given in the table above**.**

	Mass: Crew of 4 for 3 Months (kg)	**Volume Crew of 4 for 3 Months (m^3)**
Clothing	57.9	2.045
Dry and Wet Wipes	134.1	0.567
Miscellaneous	136.7	0.093
Total Values	**328.7**	**2.71**

In order to test the interior layout of a module, a preliminary mockup of the interior module and two of the alcoves were built. These mockups were tested in the Neutral Buoyancy Research Facility (NBRF) at the University of Maryland, which is utilized for simulating microgravity. Multiple tests were performed with the mockup in the NBRF and the data collected was used to modify the design for improved astronaut operation. The habitable volume of each alcove received positive feedback for solo and dual person usage. Also, Radial and axial storage access was deemed acceptable by the test subjects with the modification of staggering alcoves to allow easier accessibility for mounting around the interior. The final designs of the alcoves feature a personal alcove, common alcove utilized for storage, scientific experiments, food prep and medical space.

EVA Suit Selection & Storage:
The Z-3 suit was selected. Factors such as communication systems, operating pressure, donning/doffing, etc. were considered when deciding between the Z-2/Z-3 suit (Z-3 will have most of the same features as the Z-2) and the EMU.

The estimated total volume for two space suits, extra suit components, and the standard EVA tool suite is ~3.51 m^3, so two alcoves will be needed for EVA suit and tool storage.

LEO Radiation: LEO radiation shielding will consist of a 4cm thick polyethylene wall. The reason for choosing polyethylene is because it is cheap, readily available, less massive than other materials, and is an effective shield against GCRs. The estimated total mass is approximately 3500 kg and the estimated total volume is approximately 3.60 m^3. 4 cm of polyethylene shielding was chosen because it was a good balance between mass, volume, and dosage amounts for a six-month crew rotation for male and female astronauts ranging from 25-45 years of age.

Storage Essentials: Storage analysis began with expanding the NASA consumption rates[1] per person over varying crew and the mission duration. A 15-day buffer was added for 90 and 500 days, while a 300-day buffer was added for the 1000-day trip. This analysis incorporates an 89% and 70% reclamation rates for water and oxygen respectively. The storage available comes from the alcoves, CTBs, and the CBM. CBM storage refers to the excess volume surrounding the common berthing mechanism that the door does not occupy.

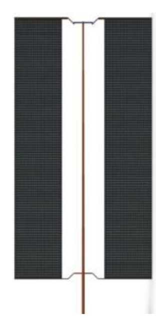
Storage Location	Volume [m^3]
CBM Storage (x2)	3.04
Alcove (x2)	4.3
Single-Sized CTBs (x163)	8.6
Total	**15.9**

Storage Item [m^3]	90 Days, 7 Crew
Food	2.85
Water	1.9
Liquid Oxygen	0.077
Total	**4.86**

Power Generation and Storage: The power station on each module shall be capable of supporting nominal and emergency operations and shall last the full lifecycle of each station. The power budget baseline of 15.6 kW includes the total power consumed by the station (13 kW) and a 20% margin to account for solar panel shading. Solar panel shading is also mitigated by rotating alpha joints on the solar array assembly. Then the power needed to charge the batteries during sunlit times in each orbit was also calculated to be 9.4 kW for LEO and 4.4 kW for HAEO, leading to a total power budget of 25 kW to support each module. Photovoltaic arrays were chosen as the best source to generate this power. The Spectrolab XTJ cell was selected since it was found to be the most cost effective option. These cells have a BOL efficiency of 29.8% and require that the solar arrays be 88 m^2 to generate the 25 kW.

To store this energy, two factors were considered: the energy required to operate each module at peak power while eclipsed and the contingency energy to operate the module for eight hours at peak power. Calculating the contingency energy using the peak power allows the module to operate in critical power module (5.05 kW) for 26 hours. It was determined the best option for an energy storage system in LEO is combination system with lithium thionyl chloride primary batteries and lithium cobalt oxide secondary batteries.

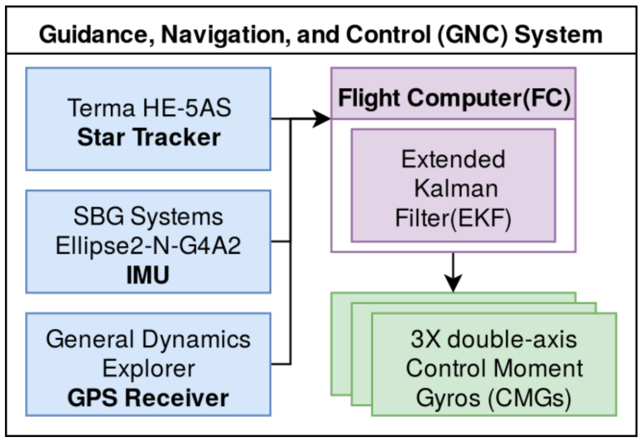
Battery Type	Primary LEO ($Li\text{-}SOCl_2$)	Secondary LEO ($LiCoO_2$)	Primary HAEO ($Li\text{-}SOCl_2$)	Secondary HAEO ($LiCoO_2$)
Battery Mass [kg]	248	245	248	172
Energy Requirement [kW-hr]	9.28	124	26.05	124



Propulsion: The reaction control system (RCS) shall be capable of fulfilling all rotational and translational maneuvers required with a fully decoupled 6-DOF RCS system. It shall also be reliable enough to survive the full lifespan of the station and support each module in LEO and HAEO. There are four maneuver types required for the station while in LEO: atmospheric drag compensation, debris avoidance, CMG detorquing, and docking. To ensure high performance and high TRL, an MMH/NTO bipropellant mixture was chosen. The summation of ΔV's over a six-month period (providing redundancy in case of missed resupply) is 37.82 m/s. There are four thruster quads placed symmetrically around the module. To mitigate risk, the nozzles are canted to avoid plume impingement, there are redundant valves, and the quads can be replaced. The system mass for the HAEO mission is 242.8 kg while the LEO system mass is 550 kg.

Thermal Control: The Thermal Control System consists of active and passive systems designed to maintain livable crew environment at nominal temperature of 293 K and to dissipate the maximum heat load of 37 kW. The Active Thermal Control System (ATCS) will consist of an internal water coolant loop and an anhydrous ammonia coolant loop located outside of the pressurized volume to minimize risk of ammonia exposure to crew. The Passive Thermal Control System will consist of 19 m^2 radiators, thermal coatings, and a 33 layer MLI blanket.

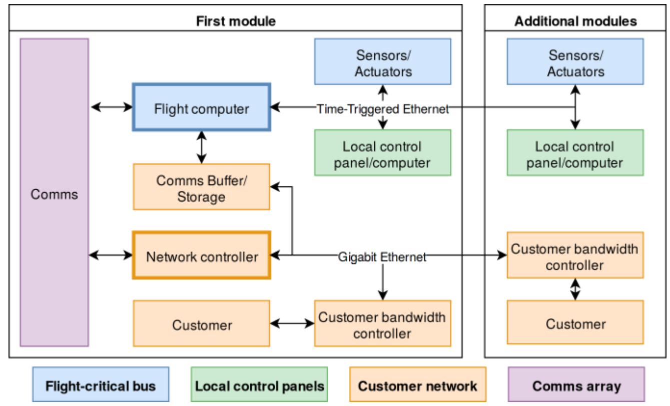
GNC: The GNC system is designed to facilitate attitude and orbit determination, and control, with high reliability and accuracy. The star tracker provides accurate attitude measurements and the GPS provides position and velocity measurements. The Ellipse2 is an enhanced IMU that can take attitude and position measurements using accelerometers, gyroscopes, magnetometers, and GPS. Measurements are combined using an Extended Kalman Filter (EKF) to create high confidence estimates that will remain even if one sensor fails. The control system consists of 3 double axis CMGs, each is 0.5m in diameter, has an angular momentum capacity of 700 N-m-s, a torque capacity of 100N-m, and consumes about 200 W.



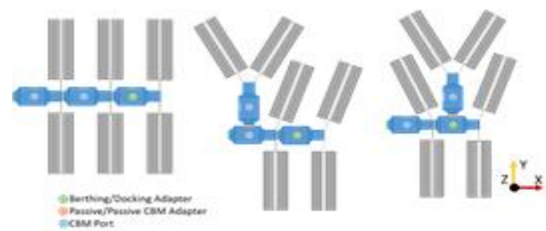
Communications: As an orbital space station supporting commercial customers, we must be able to communicate with all on-orbit and ground sources, ensure a constant link with Earth while in LEO, and provide bandwidth for science and commercial data. Inmarsat L band at 1 Mbps will be used for telemetry and the 800 Mbps O3b Ka network for commercial data. A 15% surcharge on data downlink makes communications cost neutral, so a higher rate will be negotiated with the customers to bring in revenue. O3B coverage is not continuous, so commercial data is cached outside those 10- to 20-minute access windows. Each module has a pointed Ka/X band single access dish, phased arrays controlled by software defined radio for communication over S/L/X bands, and a UHF pointed dipole antenna for approaching spacecraft. A lasercom system with ground stations may achieve speeds of up to 10 Gbps in LEO. If laser and relay infrastructure is delayed until the year of profitability, development would cost less than $20B USD in under 5 years, enabling an order of magnitude increase in bandwidth. This increase could give the public the overview effect and shift their cognitive perspective to one that is more science centric through live 3D or VR views of the Earth.

The on-board network moves data between the flight computer, communications array, sensors, and the customer. The network is split into the flight network and the customer network. Separation enables reliability, redundancy, and real-time compliance of the flight network. The flight network consists of Time-Triggered Ethernet, developed circa 2007 by TTETech. This network adds a scheduled layer over standard ethernet, allowing real-time message passing to be planned. The bus uses 10Mb/s hardware to achieve a margin greater than 100%. This network runs in triplicate, ensuring two-fault tolerance. The customer network consists of COTS gigabit ethernet. The paid-tier Network Attached Storage (NAS) doubles as a downlink cache for the station during 03B blackout.

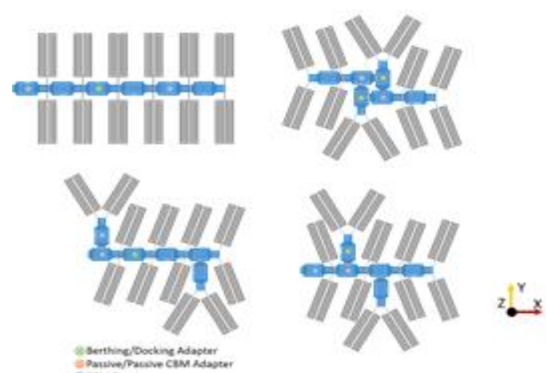
	Raw data rate [kB/s]	TCP overhead [kB/s]	Total [kB/s]
First module	22.8	19.0	41.8
Additional modules	7.7	16.8	24.5
6 module Total	**61.3**	**103**	**164.3**



The on-board flight computers (FCs) were designed to operate the module as a single unit or support a multi module configuration. The FCs will be commercial off-the-shelf (COTS) BAE RAD750's 6U-220 units. Having already flown in space, these units have a TRL of 9, which reduces development and deployment costs. At all times, there will be 3 FCs active. A voting system will cross-check the outputs of each, ensuring that a failure of a single unit does not affect the station. The voting system will utilize a hybrid voting scheme to prevent it from being a single point of failure. A fourth FC, running different software, will be kept on-line but out of the loop. This separate FC will take over in event that all 3 main FCs malfunction. The flight data recorders are Airbus solid-state data recorders (DRs). There will be two on-line simultaneously along with a third as a hot spare. Typically, additional units for both the FCs and DRs will come up as part of additional station modules. When the new module is docked to the station, the FCs and DRs onboard the new module will be shut off and kept as on-orbit spares.



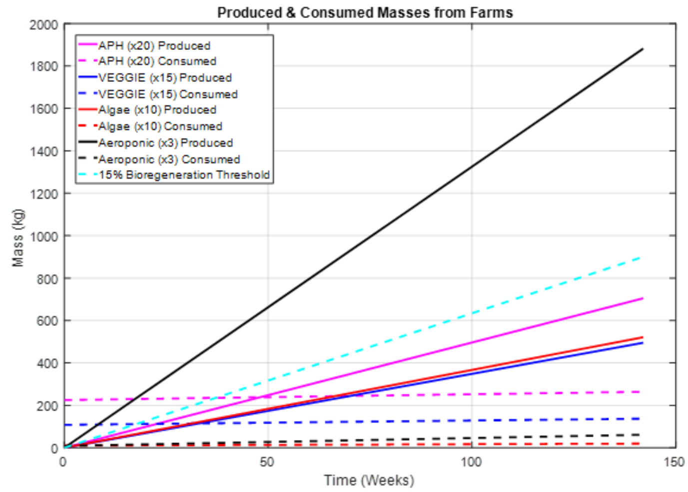
Future Growth: The modularity of these modules allows for many potential options for future growth and expandability at current station locations as well as expanding to other locations. Preliminary analysis showed that the station could exist within a Low Lunar Orbit with minimal changes, opening the door for other locations as well, such as orbiting Phobos or Deimos. Another area for growth is expanding stations in current locations which allows for more capacity to accommodate tourism, science, and additional commercial ventures. Each station in LEO can expand to six modules. Because each module has solar arrays attached to fixed locations for stand-alone capabilities, the optimal configuration is for the modules and solar arrays to be on the same plane picture to the right depicts low fidelity schematics of possible three module and six module configurations.



Changes for Mars

The Mars transit habitat station will consist of two modules. Given the two options of either a long stay or short stay mission, the station was designed for a maximum mission duration of 1000 days. Some of the biggest changes between the LEO/HAEO modules and the Mars modules are accommodations for sustaining the crew without regular resupplies.

Nutrients: By starting with NASA's recommended nutritional constraints and long term mission food requirements, a combination of supplements and farming are employed for Mars. Research shows the potency reduction in vitamins does not occur rapidly enough to become obsolete during the designed Mars mission timeframe. However, a long term Vitamin D study shows that taking higher dosages than the daily recommended amount is required to maintain a healthy level of Vitamin D over long durations without exposure to sunlight. Additionally, the lack of farmable foods containing vitamin B12 demands onboard supplements of Vitamin B12 and D. But even with supplements, NASA still recommends a fresh vegetable production unit for long duration missions similar to our project. **Table** displays the trade study between various space-rated plant systems. **Graph** illustrates the increased performance of an aeroponics farming system over the available plant systems on the ISS. With 3 aeroponic systems, 13.25 kg of food can be produced each week, cutting the food storage needed by 30%. For Mars, the aeroponics system provides the highest food mass with the lowest mass consumption. Soybeans, turnip greens, potatoes, chlorella and red sweet peppers were chosen as crops for the food mass calculations. One red pepper provides almost all of the average female's daily nutritional requirements while the other crops all contain the proper proportions of all nine essential amino acids for proper protein health. Due to the increased food supplies the long term storage will increase for Mars as shown in **Table.** A .47 kg per day reduction consumed is applied to food to account for the mass produced by the aeroponics lab.



Storage Item [m^3]	1000 Days, 4 Crew
Food	12.5
Water	12
Liquid Oxygen	0.5
Total	**25**

The Water Reclamation System (WRS) for Mars transit will not change, but a washing machine system will be used to reduce the clothing mass, which contributes 17 kg of wastewater per day. Since there is no resupply during Mars transit, all of the water will be onboard during transit. For the maximum mission duration, a water wall will be used for radiation and will supply water for the last 340 days. A long stay mission will require an extra 6700 kg of water on top of the 5100 kg required for the short stay option. Additionally, the need for surgical capabilities and shelf life of intravenous fluids in medical kits will increase for the Mars mission. The module will be outfitted with an Aqueous Immersion Surgical System (AISS), and the Intravenous Fluid Generation (IVGEN), which will be on-board to produce intravenous fluid and normal saline.

Radiation Shielding: The radiation environment outside of Earth's magnetosphere is very intense and presents a major health risk for astronauts on missions to Mars. The Mars configuration of the module contains four primary layers of passive radiation shielding to protect. The first is the module structure consisting of the MMOD shielding and the aluminum structure. 4 cm of polyethylene shielding lines the inside of the habitat. This layer is identical to the LEO radiation shielding. The third layer is a 4 cm thick waterwall enclosed in double redundant polyethylene bladder. This waterwall will be launched empty filled with ~3500 kg of water during in-orbit assembly. Finally, the sleeping alcoves are surrounded with 12 cm blocks of polyethylene. The shielded sleeping alcoves can serve as a "storm shelter" during a Solar Particle Event (SPE).

Power and Propulsion: For transit to Mars the power system is limited by the decreased solar irradiance of 590 W/m^2 and the eclipsed time in a Mars orbit, and because of this the solar arrays will need to increase in size to 158 m to generate the required 25 kW. Additionally, battery mass will increase to allow for longer contingency power operations up to 40 hrs. In order to make the transit from LEO to a Mars orbit, a separate booster propulsion stage that is capable of achieving the required ΔV's for a long stay mission (8.75 km/s) and a short stay mission (18.4 km/s) must be used. The RCS system at Mars will be the same as in LEO and HAEO except due to the lack of atmospheric drag, propellant and pressurizing tanks will only have a system mass of 550 kg. Also for a Mars mission additional heaters and insulation will be added to maintain crew and component temperatures and to prevent freezing of fuel lines.

Risk

A Failure Modes and Effects Analysis (FMEA) and Probabilistic Risk Assessment (PRA) were used to analyze the risk to the habitat in LEO and drive risk averse design decisions. The FMEA identified 12 critical failure modes. The PRA made use of fault tree analysis to quantify risk of Loss of Mission (LOM). The table below shows the risk contributions from key subsystems. Further analysis will be needed to assess reliability of the Mars transit configuration. Nevertheless, a second independent module in Mars transit allows for a fourfold increase in the failure rate of one module, which exceeds our estimates, without increasing the risk of LOM.

Subsystem	Probability of LOM due to Failure
Life Support	0.0207
Propulsion	0.0005
Power Generation	0.0107
Thermal Control	0.0038
Avionics	0.0104
MMOD Strike	0.0109
Total LOM Risk	**0.0569**

Business Model: Ultima Thule's mission architecture was designed to rely on a variety of revenue streams which capitalize on the most promising emerging markets in space, such as tourism, additive manufacturing, and advertising. Most importantly, each station will host between three and six sovereign astronauts to continue the scientific research that has been the driving focus on the soon-to-be-deorbited ISS including biology/biotechnology, materials science, fundamental physics, and Earth science. Analysis assumes that NASA will act as Ultima Thule's anchor tenant, and will provide funding for initial research and development amounting to $1,400 USM across five years in exchange for priority access to Ultima Thule's services for the entire 15-year operational lifespan. Pricing for station services was designed to remain as low as possible to maintain an edge in a competitive climate while still covering costs from other major areas of expenditure including production, launches, and operations. NASA's initial funding along with revenue from sources mentioned above are sufficient to generate net positive margin between 2025-2026 assuming on demand for services. Figure **X** depicts two scenarios of the business outlook: the left conservatively portrays Ultima Thule's anticipated costs/revenue based on expected demand for maintaining astronauts in LEO. The right portrays anticipated costs/revenue in the event that demand is higher than expected, in which case overall mission expenses and margins will be scaled as shown. The figure depicts all anticipated costs and revenue sources as they pertain to mission CONOPs, including the launch of the first station in 2022, launch of the second station in 2024, and module sales made in 2027 and 2031 for Mars transit testing and Mars transit itself.

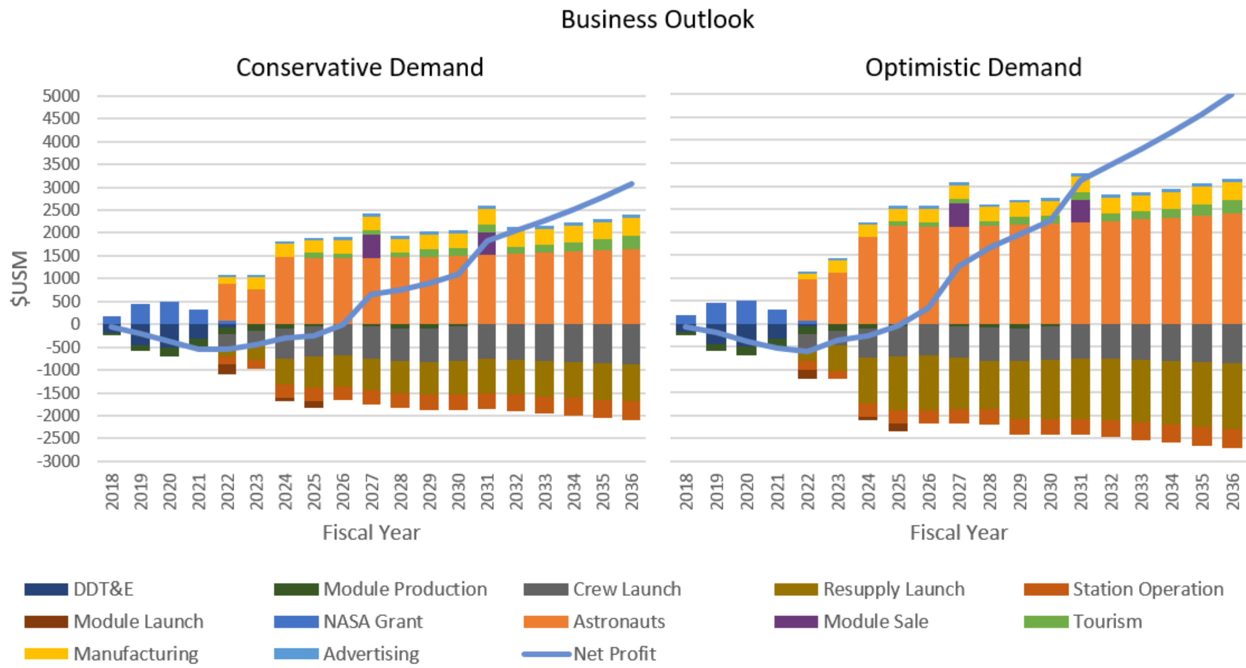


Figure X. Business Outlook for Ultima Thule (ASK JORDAN FOR A BETTER VERSION OF THIS PICTURE AFTER YOU CONVERT TO WORD)

(PUT COSTING HERE)

Costs for Ultima Thule were determined largely by the use of parametric cost estimating relationships (CER) and data from analogous systems. Design, development, test, and evaluation (DDT&E) costs were determined by a CER developed from NASA/Air Force Cost Model (NAFCOM) and adapted to a commercial approach based on a NASA study of SpaceX's commercial approach. The total DDT&E cost is distributed over the first 5 years of development based on a 60:40 spread given the technical complexity of and human factors within the program. Module production costs were also determined using a CER and an 80% learning curve was applied to production costs due to the modular nature of the design. Each module's production costs are distributed over a three-year production period. Station operation costs were based upon analogous data for the ISS which showed that over the first 10 years of life, operations cost each year were approximately 11% of the total DDT&E costs. Module launch costs are driven by the price of the Falcon Heavy while resupply and crew launch costs are based on the cost of a Dragon and Falcon 9.

NASA currently spends almost $4,000 USM per year to maintain between two and three astronauts on the ISS This price is derived from the high operations, launch, and maintenance costs associated with the ISS in particular. To maintain three astronauts in space for one year, by contrast, Ultima Thule offers a total cost to the consumer of $270 USM per year per astronaut -- or $810M total -- which accounts for all launch, resupply, and ground operations costs. Furthermore, Ultima Thule offers the capability of hosting six astronauts aboard a single station at a reduced rate of $200 USM/year per astronaut -- or $1,200 USM total. These prices are expected to drop by as much as 30% over the first 10 years of operation resulting from improvements to infrastructure and operational efficiency. The number of astronauts that Ultima Thule will host on each station is dependent on global demand for astronauts in LEO. If demand is high enough, Ultima Thule will benefit from operating at maximum capacity of six astronauts; but if not, a healthy business profile can be maintained with only three astronauts per station. Additionally, these price points allow for one Ultima Thule astronaut to be permanently stationed onboard in order to conduct station maintenance and operate equipment that supports Ultima Thule's other ventures. If customers desire more research space, additional modules can be added to the station at the expense of the customer. The customer will cover module production and launch costs ($200-$250 USM) and pay a recurring fee of $50 USM annually to cover the costs of additional station maintenance and ground operations, plus an added fee for the increase in capability.

To determine market demand for a human LEO habitat, Ultima Thule considered the budgets and previous spending history on manned space flight of the world's most developed space organizations. The top four markets exist in the USA (NASA), Russia (Roscosmos), China (CNSA), and Europe (ESA), but not all of these can be considered reachable markets. Both Russia and China have demonstrated interest in developing their own space habitats in LEO, meaning their interest in Ultima Thule will be limited. NASA and ESA, however, have shown a continual interest in manned spaceflight over the past two decades and are highly likely to invest in Ultima Thule's services [MPA5]. Based on this, it is expected that NASA will wish to maintain at least three astronauts in orbit between 2022 and 2030, continuing operations similar to those conducted aboard the ISS and gearing up for missions to Mars starting in 2031. ESA, Japan, and India all currently have sufficiently large space budgets ($5,000 USM, $2,600 USM, $910 USM respectively) *and* interest to maintain at least one astronaut in orbit, while Israel and Canada's budgets ($370 USM, $48 USM) are projected to grow sufficiently in coming years. Among these nations, it was assumed that between three and six astronauts per year would launch to Ultima Thule to conduct scientific research and represent their nation's space program. Towards the end of the mission's 15-year nominal lifespan, if global demand for habitable LEO stations diminishes, Ultima Thule will be poised to shift away from astronaut-based revenue and become entirely dependent on other revenue streams.

Ultima Thule will begin space tourism operations in 2025 with the launch of a dedicated tourism module that will dock with a LEO station. The starting price per tourist for a two-week stay aboard the station, accounting for all launch, supplies, and training costs, will be $27 USM (in 2025 dollars). This price is set by the high cost of launch vehicles, which accounts for $22 USM (81%) of the price per ticket -- the other $5 USM is profit for Ultima Thule. While this price point remains in the $20-$30 USM range it is expected that only between four and seven individuals will be willing to take the trip per year. A decrease in launch prices with the advent of improved launch vehicle technology will be the only way that tourist prices can drop significantly. Once prices do decrease, and the price per ticket reaches $5-$7.5 USM, a market study by Futron Inc. indicates that demand will grow to 40-86 tourists. At the start of tourism operations in 2025, Ultima Thule can expect to earn $20 USM annually in profit, which will increase to approximately $50 USM by 2030. If a new launch vehicle emerges by that time with 50% more launch capacity at 50% the cost, the price per ticket for tourists could reach the $5 USM mark and Ultima Thule could expect to earn up to $300 USM in profit annually.

By 2022, Ultima Thule anticipates that some of the additive manufacturing techniques that are currently the focus of research and development will be ready for large scale production and distribution. The focus of Ultima Thule's manufacturing ventures will be ZBLAN (an exotic, high-quality fiber optic cable) and silicon carbide wafers (high-grade computer chips) as they show promise of generating annual profits of $260 USM and $30 USM respectively. Other areas including protein crystallization and tissue growth were considered but believed to be too undeveloped at this time to be relied upon as a stable revenue stream.

Advertisements, naming rights, sponsorships, and film production account for the minor revenue streams that Ultima Thule anticipates, generating approximately $40-$60 USM per year based off extrapolation from appropriate Earth analogues.

In 2027 and 2031, Ultima Thule plans to sell modules to NASA and collaborating international partners in the pursuit of Mars transit. These sponsors will pay for production and launch costs in addition to a fee equivalent to 2.5 times production costs ($300-$400 USM) for permanent ownership of each station. The station sold in 2027 will operate in a high altitude orbit as a testbed for Mars transit, and the station sold in 2031 will be the operational transit vehicle.

Other ventures that this analysis considered but did not include in the final business model included satellite assembly, space mining, and entertainment. These ventures were either deemed infeasible for Ultima Thule's current design or too immature for pursuit within a 15-year timeline.

Conclusion

UMD's Ultima Thule program aims to enable the pioneers of today with a station of tomorrow that can support a variety of commercial endeavors. The station has the capability to support several different economic ventures, ranging from a low Earth orbital space station to a Mars transit habitat. The station will provide multi-purpose orbital outpost and test bed to support the pathfinders of the future. While the nominal station configuration consists of two crew members per module, up to four crew members per module can be supported to allow for greater modularity in the function of the station. With this program, UMD hopes to accomplish the goals set forth by the meaning of Ultima Thule: to strive for and achieve the extreme limit of travel and discovery.

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