Exploration of Venus through Observations & Learning of Venus' Evolution (EVOLVE) with Tension Adjustable Network for Deploying Entry Membrane (TANDEM)

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The purpose of this paper is to propose the Exploration of Venus through Observations & Learning of Venus' Evolution (EVOLVE) mission. This is a scientific mission to Venus, intended to better understand how Venus evolved into the planet it is today, by studying its meteorology, topography, geomorphological, and strength of its magnetic field. Through its use of a tensegrity design, TANDEM can overcome unique obstacles, in the air and on interplanetary terrains, that many other rovers cannot. Thus the Entry, Descent, Landing, and Locomotion (EDLL) stages of a mission can all be achieved through the use of a specialized single system, eliminating much of the extra material and costs that traditional rovers use. This proposal highlights the development of the EVOLVE mission from conception to the Preliminary Design Review, which answers why the scientific objectives were chosen, when during the mission the objectives will be obtained, and how the selected systems will accomplish the objectives. Finally, the paper addresses future considerations for the next steps of research and development for the mission. The EVOLVE mission will prove how utilizing the advantages of TANDEM's aerial and locomotive control will expand the exploration of unknown planetary atmospheres and terrain.

Nomenclature

(Nomenclature entries should have the units identified)

A	=	amplitude of oscillation
a	=	cylinder diameter
C_p	=	pressure coefficient
Cx	=	force coefficient in the x direction
Cy	=	force coefficient in the y direction
c	=	chord
dt	=	time step
Fx	=	X component of the resultant pressure force acting on the vehicle
Fy	=	Y component of the resultant pressure force acting on the vehicle
f, g	=	generic functions
h	=	height
i	=	time index during navigation
j	=	waypoint index
K	=	trailing-edge (TE) nondimensional angular deflection rate
Θ	=	boundary-layer momentum thickness
ρ	=	density

I. Introduction

VENUS is considered to be the "Twin Planet" to Earth largely due to the similarities between the two planets, such as size, relative gravity, position in the solar system, and presence of atmosphere, however the differences between the two planets are far more interesting than their similarities. The two key difference between the two planets are their atmospheres and surface conditions. It is believed that these hazardous atmospheric and dangerous surface conditions have gradually occurred naturally over time on Venus and has led to the runaway greenhouse effect that the planet is experiencing. Due to the buildup of greenhouse gasses, the planet has become completely inhospitable for life with temperatures nearing 500 degrees Celsius, a surface pressure that is 90 times greater than earths, and the presence of sulfuric acid in the cloud layers of the atmosphere, with supercritical carbon dioxide covering the surface. These conditions make the planet one of the most uninhabitable locations in the solar system, yet modern science does not currently know why this happened to a planet so similar to our own.

In order to better understand why the planet has become so inhospitable, as well as help determine what the planet was like in the past, space missions to explore the planet are currently of high importance, as detailed in the previous decadal surveys. This paper proposes using a tensegrity frame to accomplish many of the objectives listed in the decadal surveys, including obtaining atmospheric and surface samples, as well as photography of the surface of Venus, from the air and on the surface, for scientific benefit. To better understanding the events that led to Venus's gradual evolution into the planet that is known today, specific atmospheric, mineralogy, and magnetic field experiments are planned to be conducted. The analysis of the collected data may give light to whether or not Earth is in danger of this same fate, as well as how to best combat the transformation into a far less habitable home.

II. Mission Overview

A. Mission Statement

The EVOLVE mission was tasked with obtaining readings from both the atmosphere and the soil to better understand the environment of Venus and help determine what may have caused the runaway greenhouse gasses that led to the planet's current state. Along with taking both aerial and ground images to map the unknown terrain and landscape of Venus for future endeavors onto the surface. From these mission objectives, as well as considering the harsh surface conditions of Venus, the TANDEM tensegrity framework was assigned to be further developed for the mission, based upon its unique characteristics and capabilities to overcome extreme environments.

The design of TANDEM allows for an advantageous opportunity to study the atmosphere and ground of Venus. The phases of the previously developed Entry, Descent, Landing, & Locomotion (EDLL) system and the aerial control capabilities of TANDEM [1] allow the payload in the center to conduct atmospheric tests at various altitudes within Venus' atmosphere while descending. Once the module is on the surface, the tensegrity system provides the ability to overcome the hazardous Tessera regions of Venus, which allows the payload within to conduct soil analyses in these hard to reach places. These test results aid in the understanding of different planetary atmospheres and further the identification of distinct planetary attributes that point to habitability.

B. Scientific Objectives

There are many scientific reasons to observe and analyze Venus's evolution. In this section, those reasons are focused on and the specific applications of each piece of equipment is further discussed in the Technical Overview sections. There is little to no information on numerous qualities of Venus and this mission focuses on accomplishing 4 primary objectives that aim to answer key scientific questions about Venus, in studies such as its meteorology, topography, geomorphological, and strength of its magnetic field. Table 1 summarizes the scientific objectives, the methods and the instruments that will be used to meet these objectives, along with the potential scientific gains.

Table 1: EVOLVE Science Objectives Summary

Science Objectives	Method	Instrument	Potential Scientific Gain
Assess the geomorphological surface processes present on Venus.	Gather images of Venus's surface in the near-infrared (550 – 1000 nm) and optical ranges during descent and on the surface.	Navigation Cameras (NAVs), Hazard Avoidance Cameras (HAZs), and Venus Descent Imager (VENDI)	Scientists can study how the Tessera & volcanic regions were formed.
			Map the topography of the unknown Venusian terrain
Characterize the surface-atmosphere interactions as well as overall atmosphere evolution.	Analysis of 1.71 mm^3 samples of atmospheric fluid collected during the descent phase.	Tunable Laser Spectrometer (TLS)	Aids in determining the cause of Venus's runaway climate change
Characterize mineralogy and major elemental chemistry of Venus's Tessera regions.	Analysis of 25 surface soil samples of 3 cm^3	Chemistry and Camera (ChemCam)	Composition analysis of millions of years worth of Venusian terrain via the Maxwell Montes
Determine if the current theory of a preexisting active Venus dynamo is true.	Measure magnetic field strength at various points on the Venusian surface.	MAG-3 Magnetometer (MAG3)	Even if << magnetism is detected this can be proof of a pre-existing Venusian dynamo

Gaining data assessing the geomorphological surface processes present on Venus allows for scientists to study how the waterless planet formed its Tessera and volcanic regions. The near-infrared and optical images obtained primarily by the DISR, with some assistance from the Navigation (NAVs) and Hazard Avoidance (HAZs) cameras, during descent can be used to gather the needed geomorphological data and to map the topography of the unknown Venusian terrain. These images also help target an ideal landing area for TANDEM and gains pertinent information for future exploratory missions of Venus.

The atmospheric conditions of Venus are major scientific focuses of the EVOLVE mission. The Tunable Laser Spectrometer (TLS) will be used to analyze the atmospheric fluid and determines the composition. Characterizing the atmospheric composition aids in determining the cause of Venus's runaway climate change. This information may be applied to Earth and possibly provide valuable insight on deterring climate change here.

The characterizing of Venus's soil will be accomplished by analyzing multiple soil samples from different areas around the Maxwell Montes. This Tessera regions exposes various layers of the tectonic plate, which allows for the ChemCam to determine soil composition over millions of years on Venus. This can uncover many unknown Venusian traits, such as a possibility of once present water, and further explain the Venusian evolution.

Venus is known not to have a planetary magnetic field, but the reason for this is still unknown. The MAG3 will be utilized to conduct geophysical surveys around the Maxwell Montes which will detect magnetic anomalies of various types. Even if a small amount of magnetism is discovered in this Tessera region, this can be proof of a preexisting Venusian dynamo and possibly even the evidence of water being on the surface.

III. System Requirements Review

A. Mission Concept Development

Based upon scientific objectives, the team began to identify important stages of the mission to develop. This assisted the team to better understand the mission parameters and potential roadblocks, as well as brainstorm potential solutions. The EVOLVE mission was divided into 5 categories: Interplanetary Travel, Entry, Descent, Landing, and Locomotion and Exploration. After brainstorming concepts for each stage of the mission, the selections were narrowed down to a final mission selection, which would take into account key systems and subsystems needed to achieve each of the scientific objectives of the mission. The following are the EVOLVE concept development team's initial mission phase concepts which mainly focused on identifying the most scientifically beneficial surface target location and the sample collection/testing procedures.

1. Interplanetary Travel Phase

The TANDEM module and its payload will travel from Earth to Venus via a launch system such as the Falcon 9 rocket from SpaceX. It will either launch as a joint mission with additional projects such as the BREEZE mission, or if needed launch alone. For this section, the launch phase is beyond its scope and is assumed to be successful. This phase will be revisited in more detail in later sections.

2. Entry Phase

The entry phase will use a system similar to the initial TANDEM design developed by Schroeder, Samareh, and Bayandor [1]. The design uses a heat shield made of carbon fiber-reinforced carbon to protect the tensegrity robotics and the payload stored within from the high entry pressure and temperature.

3. Descent Phase

The descent phase of the EVOLVE mission uses the initial TANDEM design [1] once again. Once the entry process is complete, the heat shield will be discarded, while an adjustable drag plate will remain attached to the back of the system. This design allows for changing both the velocity and position mid descent. The inner payload will be able to collect and analyze atmospheric samples, during the descent and also use the onboard camera equipment to gather imaging data. The payload design will allow the atmospheric fluids to flow through the atmospheric analyzer during descent, using the drag plate to allow for a varied descent rate to acquire detailed data of the atmosphere (dependent on module's current altitude, next desired altitude ranges to take sample, and other drivers). This will allow the rover to analyze Venus's atmosphere while simultaneously transmitting the collected data to Earth.

4. Landing Phase

[redacted]

[redacted]

[redacted]

[redacted]

B. General System Requirements

After the mission concepts was selected, the team created criteria to gauge the success of the mission, which would help put each goal of the mission into focus for further development. These goals included the functional goals required for the mission, as well as the constraints on the mission based upon the environment and the tensegrity frame itself.

1. Functional Requirements

In order for the EVOLVE mission to be functionally successful the system must be able to meet the following criteria:

i. Trajectory Phase – The orbiter spacecraft and the TANDEM payload must travel from Earth to Venus around the predicted trajectory speed and time range. An example of a scheduled time created [redacted]

ii. Entry Phase – TANDEM must be successfully deployed into the atmosphere of Venus without enduring system malfunction, such as [redacted]

iii. Descent Phase – As the module passes through the atmosphere of Venus, the aerial control capabilities must [redacted], in order to allow the [redacted] enough time to complete its analysis and record [redacted] data, [redacted]

iv. Landing Phase – TANDEM should be able to endure the [redacted] as it lands on Venus and moves through the rough, hazardous terrain. The location of landing must be within the [redacted]

v. Locomotion & Exploration – The tensegrity frame should be able to accurately [redacted]. Cameras will aid in the guidance of the module. The method of using [redacted] The data received from the soil sample testing must be able to be recorded or relayed back to Earth via communications system.

Coverage: The main focus is to explore the Tessera region terrain. Since Earth is Venus's twin planet, it can be mirrored after Earth Coverage which is a spacecraft instrument used to track a specific region. Using the spacecraft that launches TANDEM as communications center, [3] Area Coverage Rate (ACR) would help identify the terrain and map out the area.

Responsiveness: [redacted]

Secondary Mission: [redacted]

2. *Performance Requirements*

In order for the EVOLVE mission to be operate successfully it must be able to complete the following tasks:

i. Descent Phase Objectives

a. Gather and transmit near-infrared imaging data below cloud and above surface level during TANDEM descent. The purpose is to allow the study, along with potentially mapping, of the terrain and atmosphere of Venus.

b. Collect atmospheric fluid during TANDEM's descent once the drone reaches 16 km above the Venusian surface and transmit results [redacted]

Because of the descent objectives, a slow descent is preferable for the EVOLVE mission to allow for TANDEM to obtain as many images and atmospheric samples as possible. This is because the goal of gathering of images and atmospheric samples of the Venusian atmosphere can also only be accomplished once because of the single descent TANDEM will have. During this descent, TANDEM must be able to endure the strong wind, corrosive acids, high temperatures while analyzing atmospheric particles and obtaining near-infrared images simultaneously. Because of this, the structure of TANDEM must also have architecture that completely protects the camera, signals, and atmospheric analyzer within the payload. However, TANDEM will have user-control options to control the position and speed of the descent, which will assist in accomplishing the mission goals. Despite this, TANDEM will still be required to have some type of self-autonomy to complete the descent phase, in the event of losing communication with the module, due to interference or distance.

ii. <u>Exploratory & Locomotion Phase Objectives</u>

a. Obtain 25 soil samples [redacted]

b. Measure the current (if any) magnetic field strength of Venus at different locations throughout the planet, and [redacted]

During this phase the testing of [redacted]

[redacted]

[redacted]

3. Constraints

i. Extreme surface temperature – Due to the intensive greenhouse effect of the planet, the surface of Venus has been measured at 465 ^{o}C on average, which is nearly double the temperature ranges of conventional ovens in normal use, with only self-cleaning ovens reaching temperatures of the scale [4].

ii. High surface pressure – The dense atmosphere of Venus has created extreme pressure along the surface of the planet as well as the extreme greenhouse effect present. This surface pressure is currently estimated to be 92 bar, which is 90 times greater than the atmospheric pressures on earth, and is similar to pressures found 3000 feet underwater [5].

iii. Highly corrosive atmosphere – Venus has multiple layers of sulfuric acid in its atmosphere, causing sulfuric acid clouds from 100 km to 50 km, and a sulfuric acid haze from 50 to 25 km above the surface. Though there is not sulfuric acid present on the surface, the surface atmosphere is composed almost entirely of carbon dioxide in a supercritical state, which is highly corrosive.

iv. Lack of terrain resolution – Due to the dense cloud coverage, much of the landscape of Venus is not visible to telescopes or orbiting vessels and is largely unknown. Though topological maps of the surface exist, additional imaging, scanning, and interpreting of the Venusian landscape is required to better guide the mission's exploration path.

v. Limited time frame – Due to the combinations of the heat, pressure, possibility of extreme Venusian weather, and the supercritical levels of carbon dioxide on the surface, the total lifespan of the rover, and consequently the entire mission, becomes limited. The life of the mission is constrained by the ability of the mission's equipment to withstand the environmental conditions and is expected to be short-lived, before components and/or hardware begin to fail.

C. System Acceptance Criteria

The final step of the concept development phase was to establish the mission success criteria. This helped to gauge what aspects of the mission would be seen as acceptable to omit or only partly complete due to aspects such as damage to the system or other unforeseen problems. To best determine the success of EVOLVE and its systems operation, the team developed criteria to judge the requirements of each system. These scales were broken into Minimum requirements to be deemed a successful mission and criteria for a highly successful mission.

1. Minimum Success Criteria

i. Having a successful rocket launch and reaching a Venusian orbit successfully

ii. Having the TANDEM module successfully engage and deploy its EDLL sequence through Venus's atmosphere without damaging the tensegrity frame beyond movement.

iii. Successfully protecting the central payload and its internal components from impact forces during the landing phase of the mission.

iv. Have the rover remain active and in communication long enough to retrieve sufficient data about the surface conditions of Venus, primarily through surface and/or atmospheric sample testing data.

2. Full Success Criteria

[redacted]

[redacted]

3. *Structure Acceptance Criteria*

To meet the above mission criteria, a system acceptance criteria list was created to aid in understanding and planning for the mission architecture and equipment being brought to the surface of Venus. The completed system must be able to meet the below criteria to be deemed capable of completing the mission objectives.

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IV. System Design Review

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3. Materials for Compressive and Tension Members

When researching the material requirements, factors such as material strength, heat resistance, thermal expansion rate, corrosion rate, and density were investigated. These criteria gave a framework to establish potentially viable materials.

Steels and Aluminums were first researched, however the high density and weak corrosion resistance of steel and the low thermal resistance of aluminum, quickly eliminated the two options from further research.

Titanium was found to have many desirable qualities for the exploration of Venus. Titanium boasts high thermal resistance and has the highest strength to weight ratio of any other metal [7], with Ti-6AL-4V retaining a tensile strength of around 900MPa at Venus' surface temperature. The material also boasts low expansion and elongation rates, and very high corrosion resistances, with alloys [8] or annealing [9] further boosting resistances. These properties made titanium alloys very desirable material for the Venus mission.

Carbon Fiber was also researched, and was found to have impressive structural qualities, such as high tensile strengths with low densities. By using unique weaving and threading patterns, the strength could be optimized in lateral directions, which would be superb for a tensegrity system [10]. The largest current drawbacks to the system are the thermal resistances. Even when combined with phenolic resins to boost its resistance, carbon fiber melts shortly after being exposed to temperatures of 500 Celsius [11] [12]. If advances are made in the thermal resistance of the material, it could prove useful for the mission.

4. Bar Dimensions

[redacted]

5. Wire Routing Subsystem

From studying the tensegrity frames utilized on Superball it was seen that a wire routing mechanism was needed for the proper spooling in and out of wire for the actuation of each leg. Further research found that without properly

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2. Ballistic Coefficient

Researching the ballistic coefficient helped to understand how the speed and heating of the system occurs during the entry processes. Both low and high coefficients were researched.

Having a high ballistic coefficient promotes a faster entry process, once again allowing the bypass of Venus' corrosive atmosphere. However, a high ballistic coefficient will slow the system less, while lead to a higher heating rate on the sides of the heat shield, potentially damaging the system [14].

Using a low ballistic coefficient will result in the system slowing more rapidly, while also dispelling much of the frictional heating. This method would also cause unwanted exposure to Venus' atmosphere, which could harm the system [14].

3. Shielding Methods

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[redacted]

4. Drag Shielding

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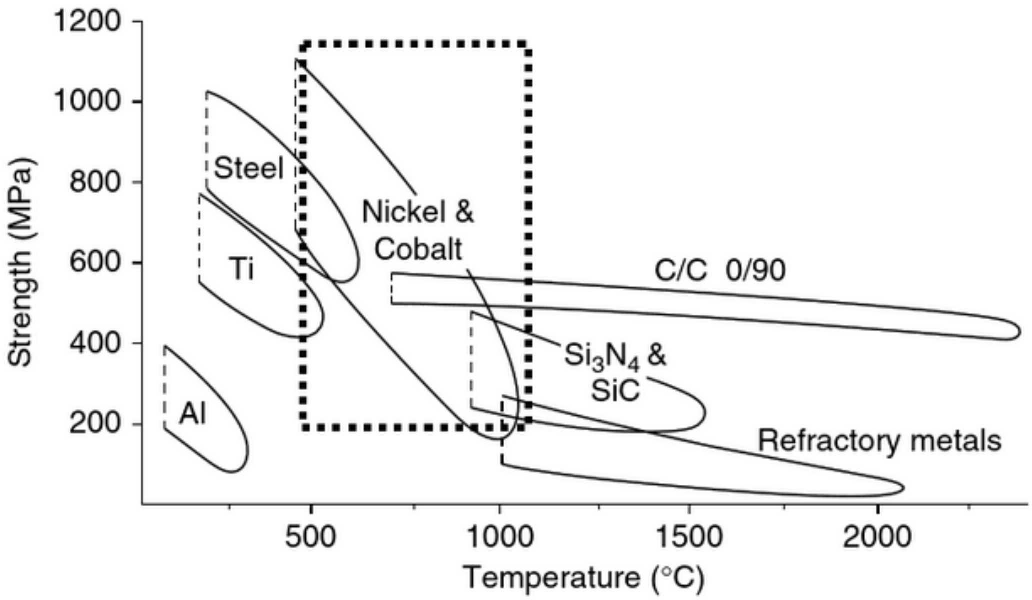

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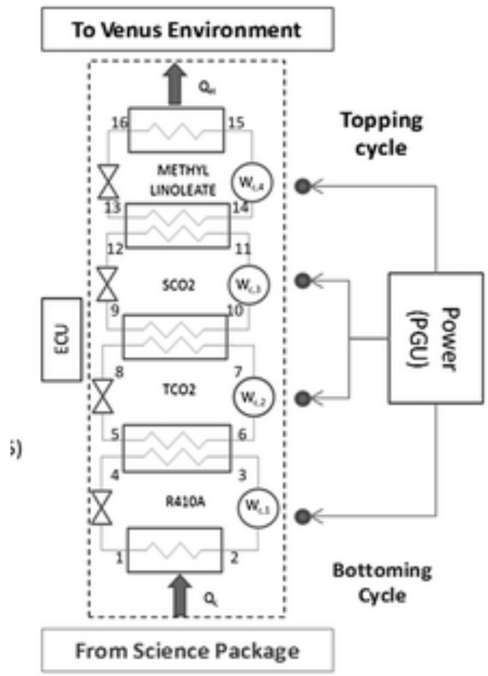

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[redacted]l layout and equipment for the system.

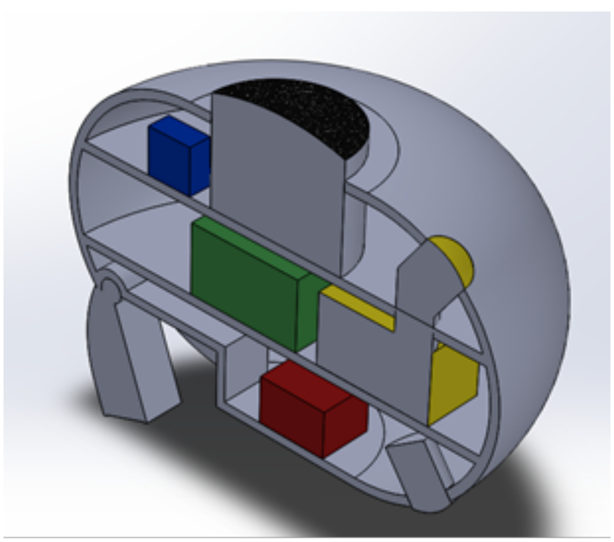

Fig. 3: Cut view showing the communication equipment (black), magnetometer (blue), (green), atmospheric analyzer (yellow), and Raman LIBS processor (red)

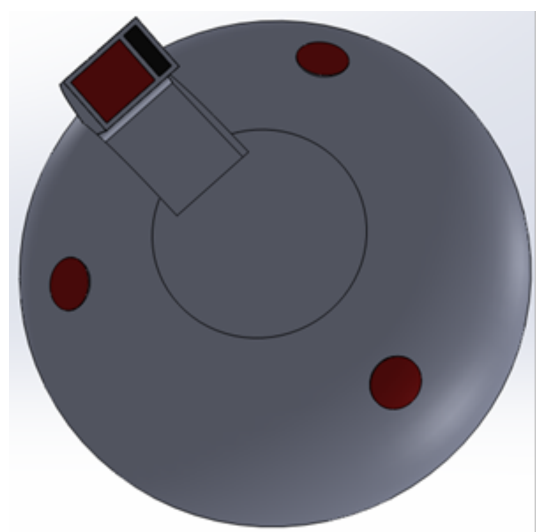

Fig. 4: Underside of payload showing retractable camera (black) and Raman LIBS scanner (red), as well as the three positioning cameras (red)

V. Preliminary Design Review

The next stage of the mission design was narrowing down the subsystem choices until a single cohesive mission was formed, to do this, calculations were performed and additional research was done for each subsystem to justify each choice made for the mission. Through this process, the final mission design was solidified, and each aspect of the mission subsystems was thoroughly fleshed out.

The EVOLVE mission is divided into 5 categories: Interplanetary Travel, Entry, Descent, Landing, and Locomotion & Exploration. Each phase concept and when objectives are targeted over the mission timeline are explained in the following sections.

A. Preliminary Mission Overview

Below is the Proposed Preliminary Mission Overview Flowchart that summarizes each of the 5 EVOLVE with TANDEM mission phases in Fig. 5.

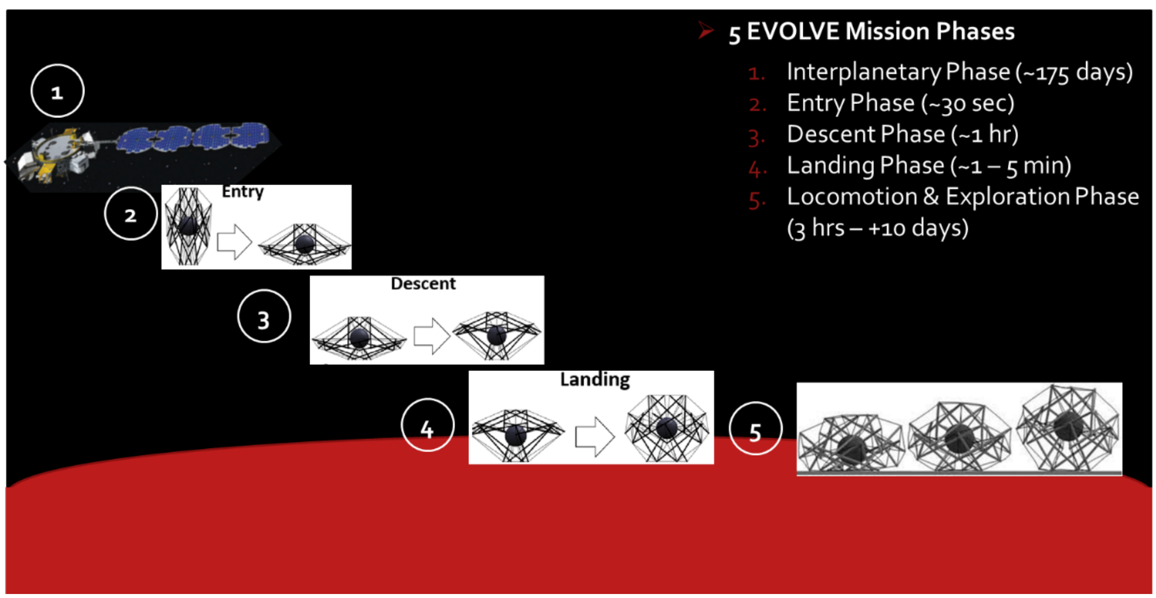

Fig.5 EVOLVE with TANDEM Mission Overview Diagram

1. Interplanetary Travel Phase

The TANDEM module and the ESPAStar orbiter will travel from Earth to Venus via the Falcon 9 launch vehicle manufactured by SpaceX. The Falcon 9 rocket uses nine Merlin engines, which have the highest thrust to weight ratio of any competing rockets manufacturers and depending on the final mass of TANDEM, Appendix A can estimate payload capability for the integrated Falcon 9. Appendix B is the current best estimate and predicted mass of the TANDEM module payload that was developed by EVOLVE with TANDEM mission development team. The initially predicted overall mass for the TANDEM payload was approximately 1,400 kg [1] which, even with the EVOLVE team's design alterations, which ended up resulting in a predicted mass of about 3,850 kg, over the expected value of the team. Even though the predicted mass was over our expected values, its current predicted mass, combined with the incredible packing factor of about 0.27 (calculated below using Equation 1) shows that the proposed system can be manufactured to below the maximum payload capabilities of the Falcon 9 rockets, but with minor modifications and advances in technology the overall mass could be decreased substantially.

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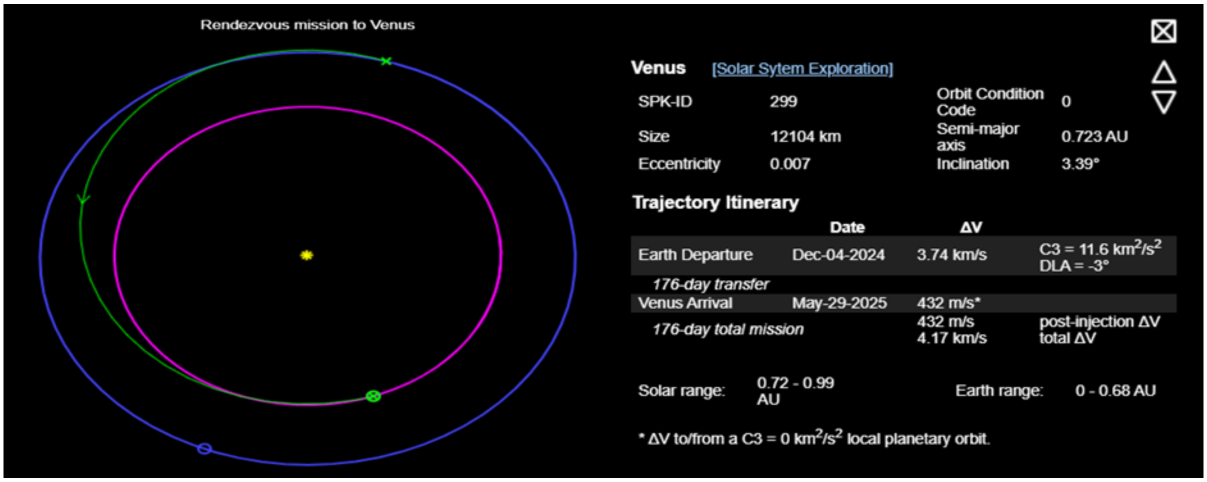

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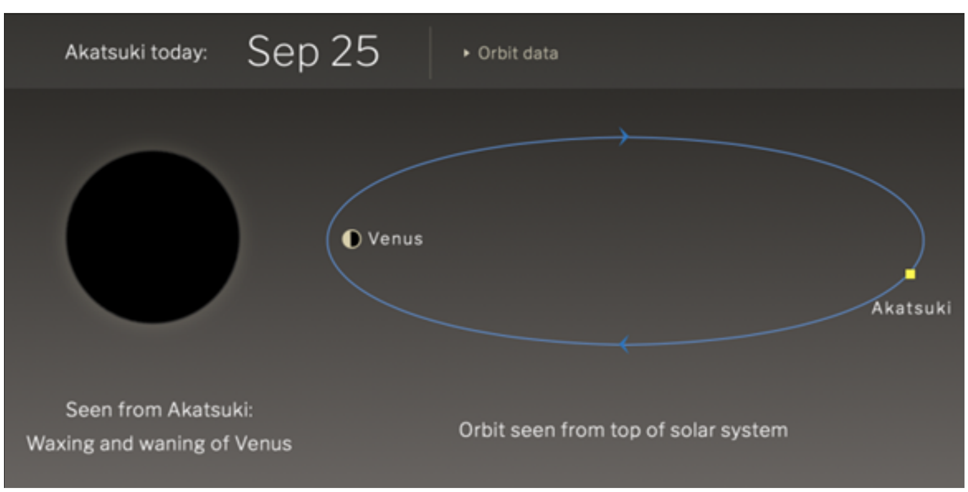

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2. *Entry Phase*

The entry phase will initiate in the mesosphere of Venus at a point ranging between 130 – 100 km above the Venusian surface. Doing trade studies of Venus Climate Mission (VCM) [47] and Venus High Temperature Atmospheric Dropsonde and Extreme-Environment Seismometer (HADES) [48], a middle point was reached for the entry altitude. It may not be optimal to separate at a higher altitude like 150 – 200 km as this will increase the time TANDEM pummels through the thick Venusian atmosphere. This could result in unwanted overheating and degradation of the heat shield and drag plate even before TANDEM could reach the surface. It is also not preferred to have a shallow entry altitude, for example below 100 km, as this will result in less time for atmospheric data collection and even less time to slow down the descent speed.

[redacted]

3. *Descent Phase*

Understanding the climate of Venus is one of the top priorities that came up in the Planetary Decadal Survey [49], and Venus Exploration Analysis Group's (VEXAG) [50] goals. Analyzing Venus's bulk composition and interior composition includes the critical characterization of the noble gas molecular and isotopic composition of Venus. High resolution panoramic imaging of Venus's topography has also been amongst the goals found from researching both these sources. Half of the science objectives are fulfilled during the descent phase. They can only happen once in the entire mission life of TANDEM, and that is during this phase

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Schematic of EDL sequence as a chronological list:

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x. TANDEM landing

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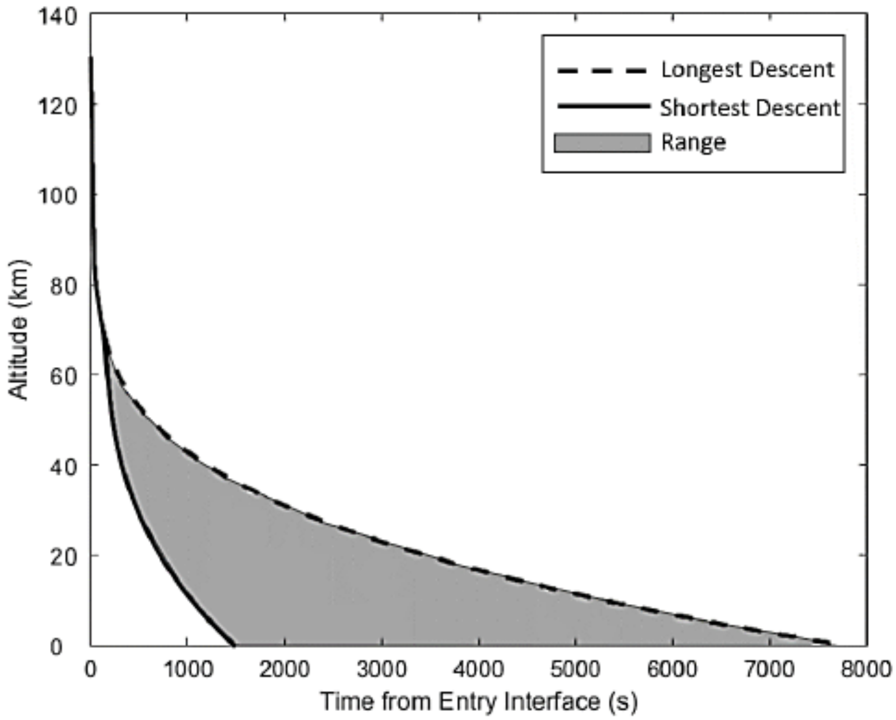

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4. *Landing Phase*

The EVOLVE mission will aim to meet the below landing criteria:

a. Land near a Tessera mountainous range.

b. Land in an area where there is abundance of rocks and soil.

c. Land near the northern pole of Venus.

The Maxwell Montes region was found to satisfy all three of the above stated criteria, allowing for adequate data collection of a magnetic field, as well as soil composition. Landing at the base of the mountain, ideally in/near a valley, to collect both data from the Tessera mountain itself, as well as from the soil around it. The idea is that the rocks in this region would be less exposed to the high winds and extreme weather, hopefully retaining more of their unique attributes.

When landing on Venus, the structure and payload must be able to withstand the impact force/pressure to ensure the success of the EVOLVE mission. Ideally this means that a slow descent is ideal during this phase of the mission. The speed of which TANDEM descent is controllable via the drag plate. This is done by having the drag plate deploy after the heat shield is separated. The drag plate functions by expanding its area to allow drag force to slow the descent. The drag plate essentially functions by acting similarly to a parachute. However, after a certain height from the surface of Venus, the drag plate will dis-attach from TANDEM causing freefall. The reason for dis-attaching the drag plate from TANDEM during landing phase, is so the drag plate does not potentially interfere with TANDEM's locomotion once on the ground. In addition to that, due to the small payload and tensegrity bar size, it is difficult to include propellants to control the landing. It is because of this reason, EVOLVE is proposing that TANDEM be dropped freely from the atmosphere onto the ground.

At this particular height, the instrumentations and overall TANDEM structure must be able to withstand the impact it will take on the ground in order for mission success. FEA simulations to obtain ideal drop height was conducted. However, these simulations did not take into account the hardness of the ground. Despite the Maxwell Montes having soil, it is still unknown how the soft or hard the area of impact will be.

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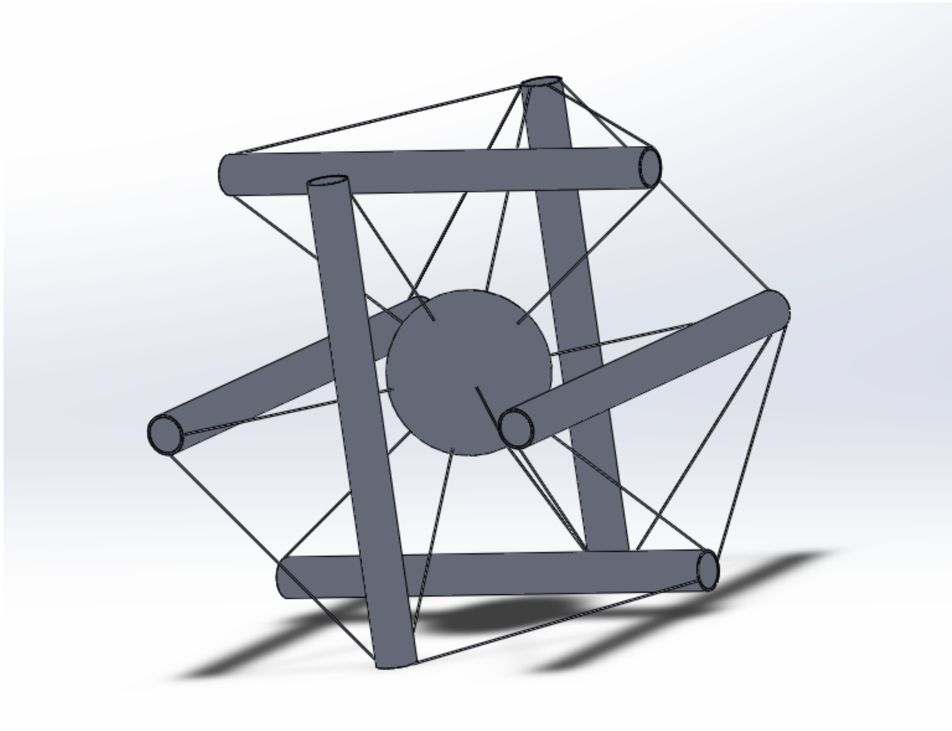

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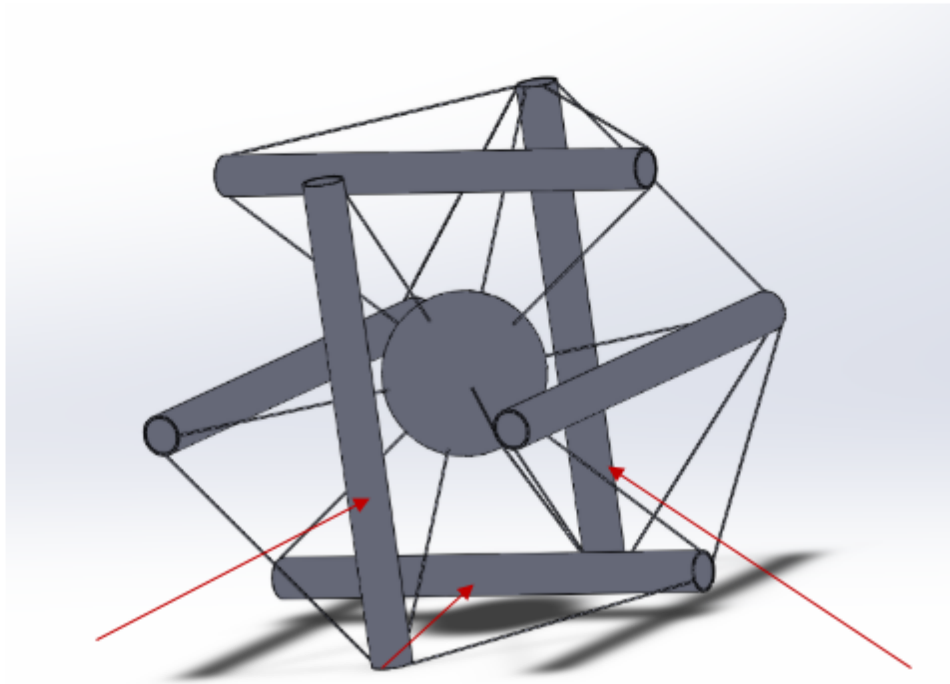

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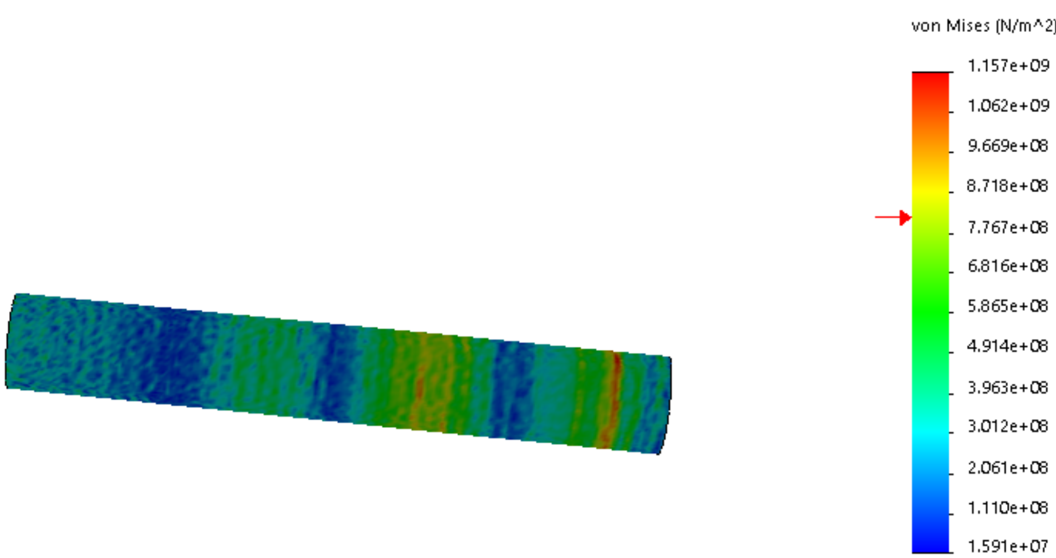

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[redacted] (Eq. 2)

[redacted] (Eq. 3)

Where the mass of TANDEM [redacted], using the equations above can calculate a more optimal drop height lower than 500m. Based on Fig. 13 and 14, a more optimal height drop is approximately 10 0m. At this height, the impact velocity is approximately 42.11 m/s and the impact energy is approximately 1.45 MJ.

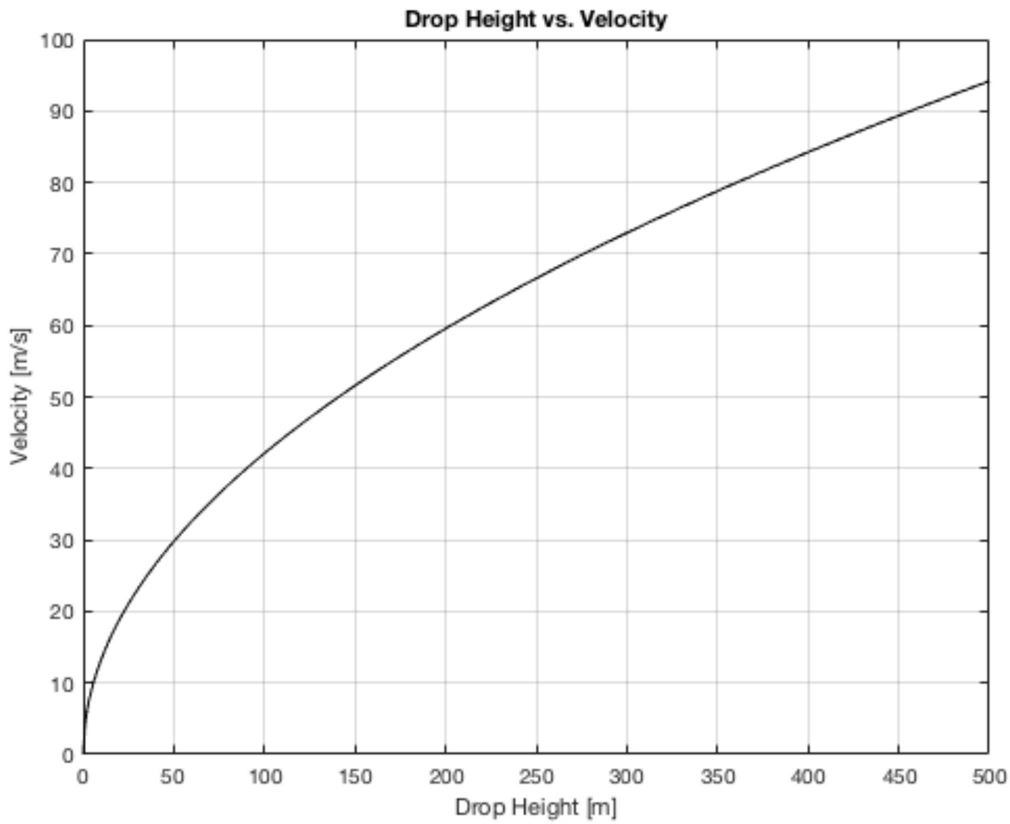

Fig. 13: Drop Height Versus Impact Velocity

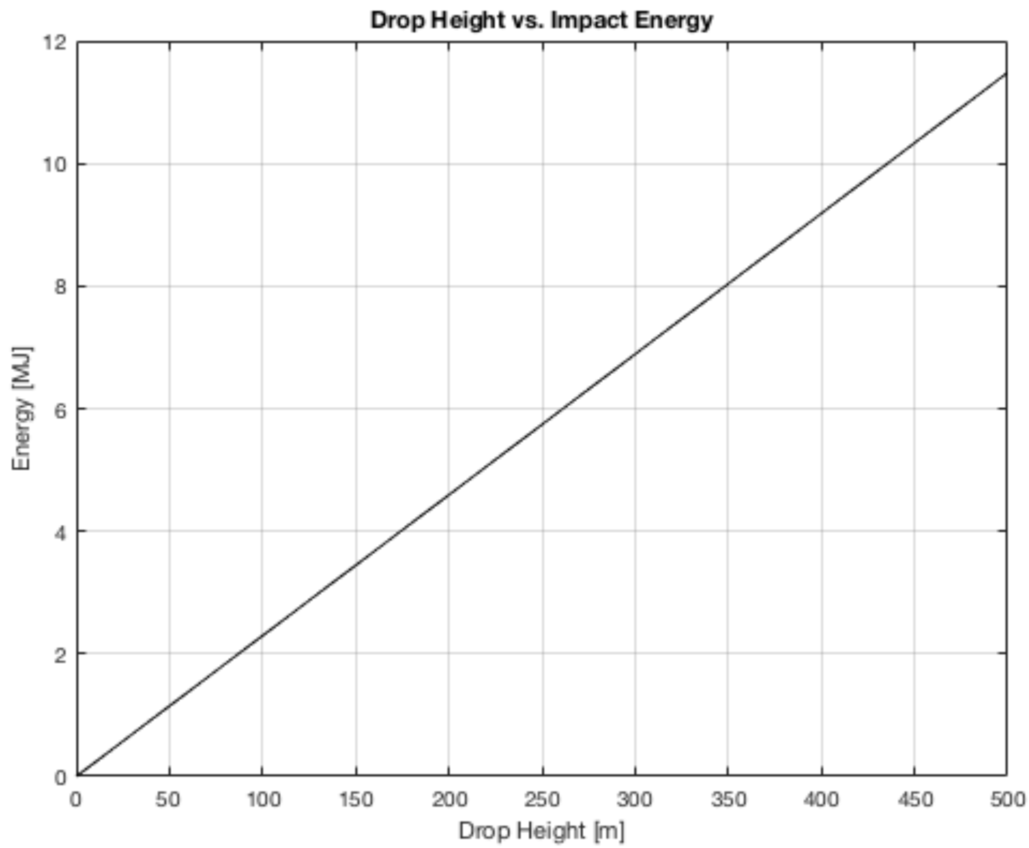

Fig. 14: Drop Height Versus Impact Energy

[redacted]

5. Locomotion and Exploration Phase

Since TANDEM is assumed to be fully functional, the tensegrity robot will be able to move around in rough terrain to find optimal areas to measure soil samples and magnetic field strengths. [redacted]

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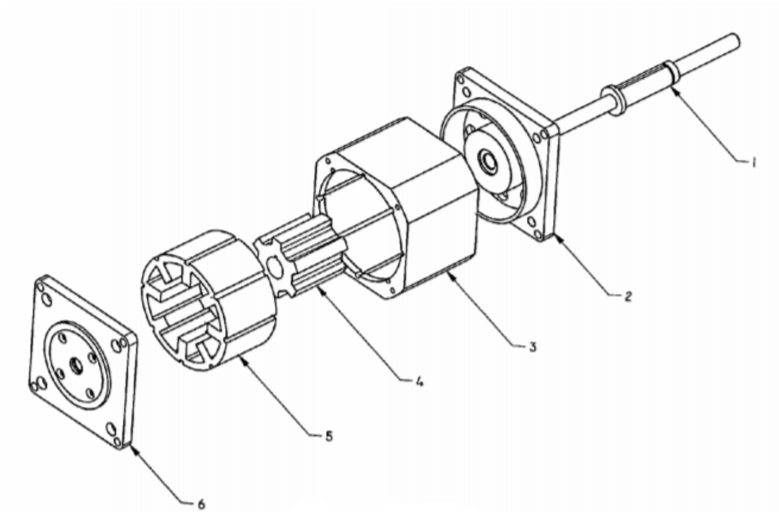

Fig. 15: Honeybee Robotics SRM motor prototype [55]

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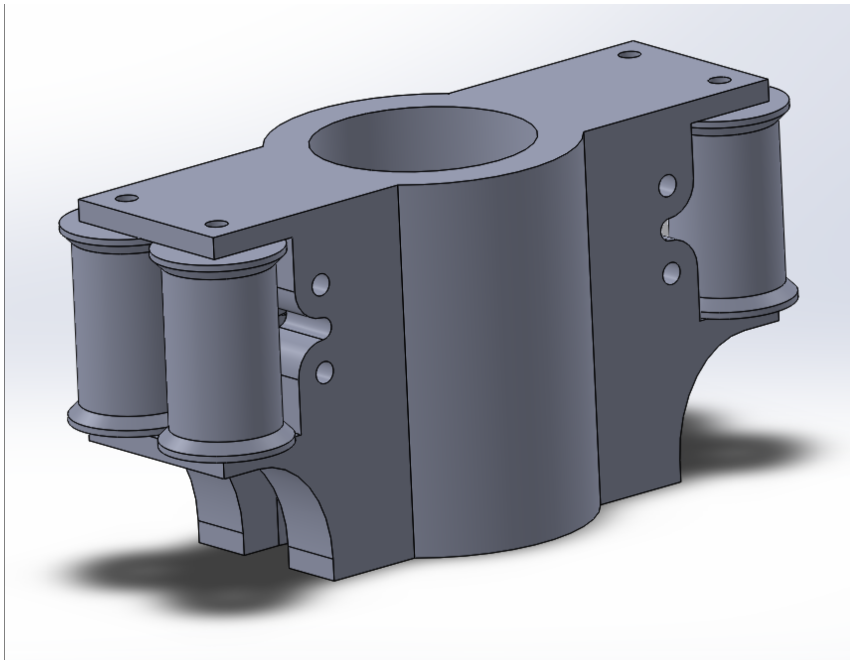

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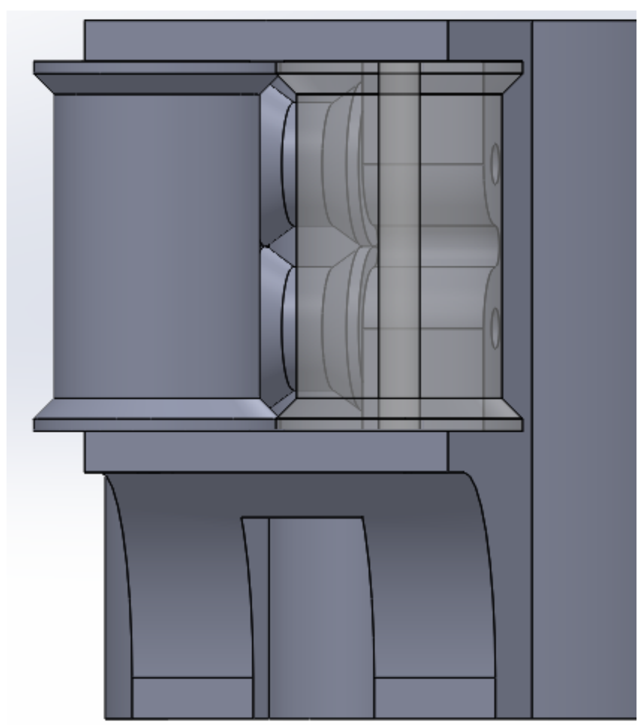

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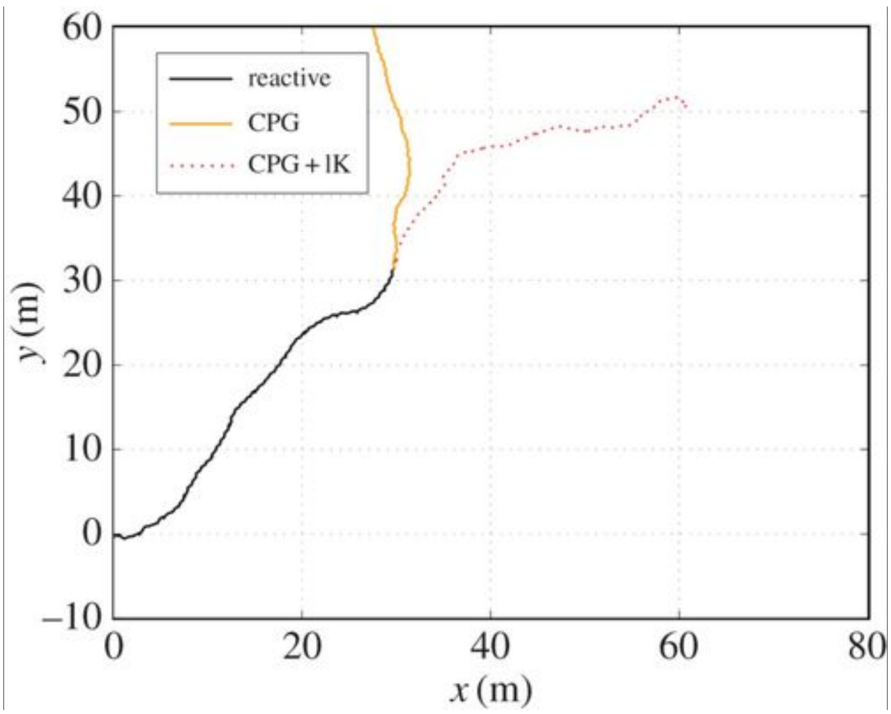

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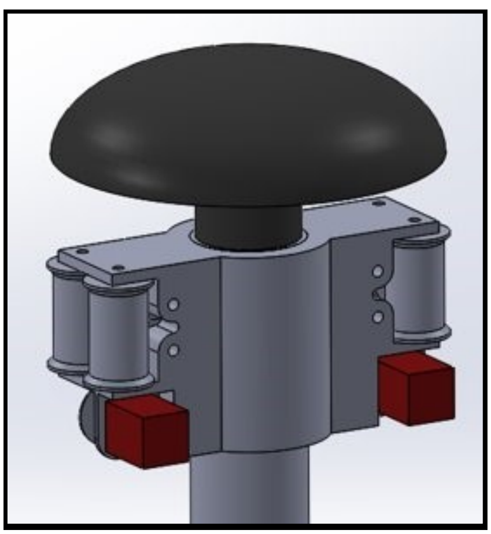

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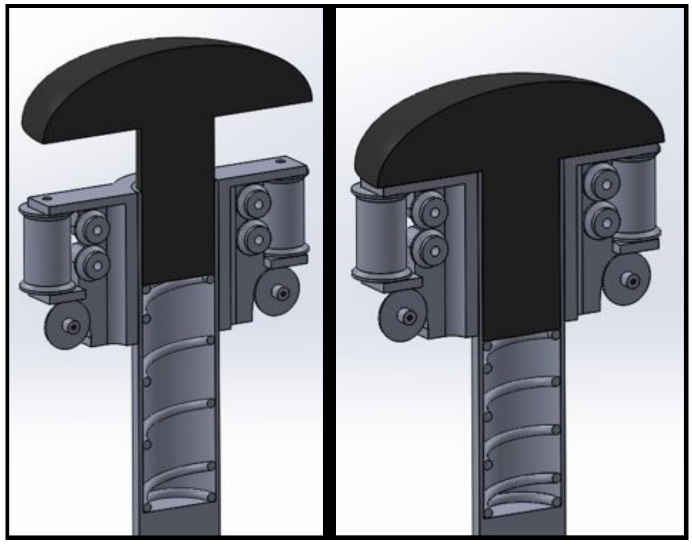

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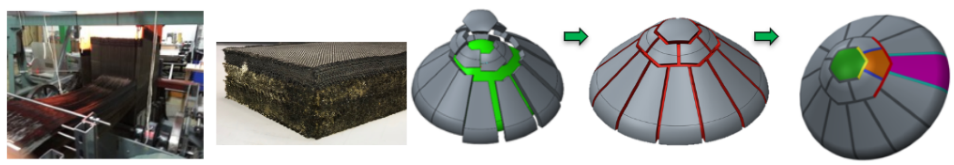

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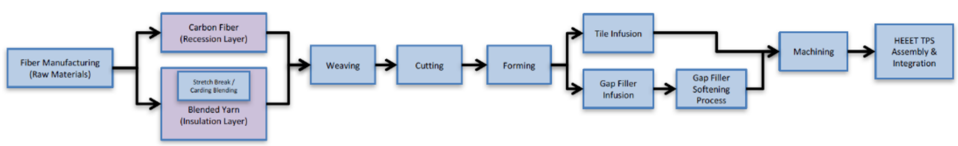

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Table 6: Scoring Matrix for Power Options

Criteria	Solar Panel	RTGs	Electrochemical Batteries	Thermal Batteries
Power Sufficiency	2	3	4	1
Size	N/A	1	5	5
Thermally Resistant	N/A	1	1	5
Operational Lifetime	5	2	5	1
Total Score	7	7	15	12

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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

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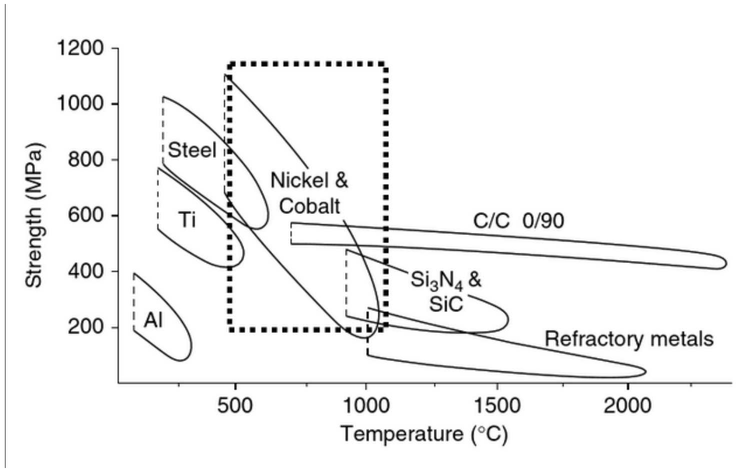

[redacted]

○ [redacted]

[redacted]. This material has a thermal conductivity of 1.35 W/m*K which is essential in reducing the heat from being transferred.

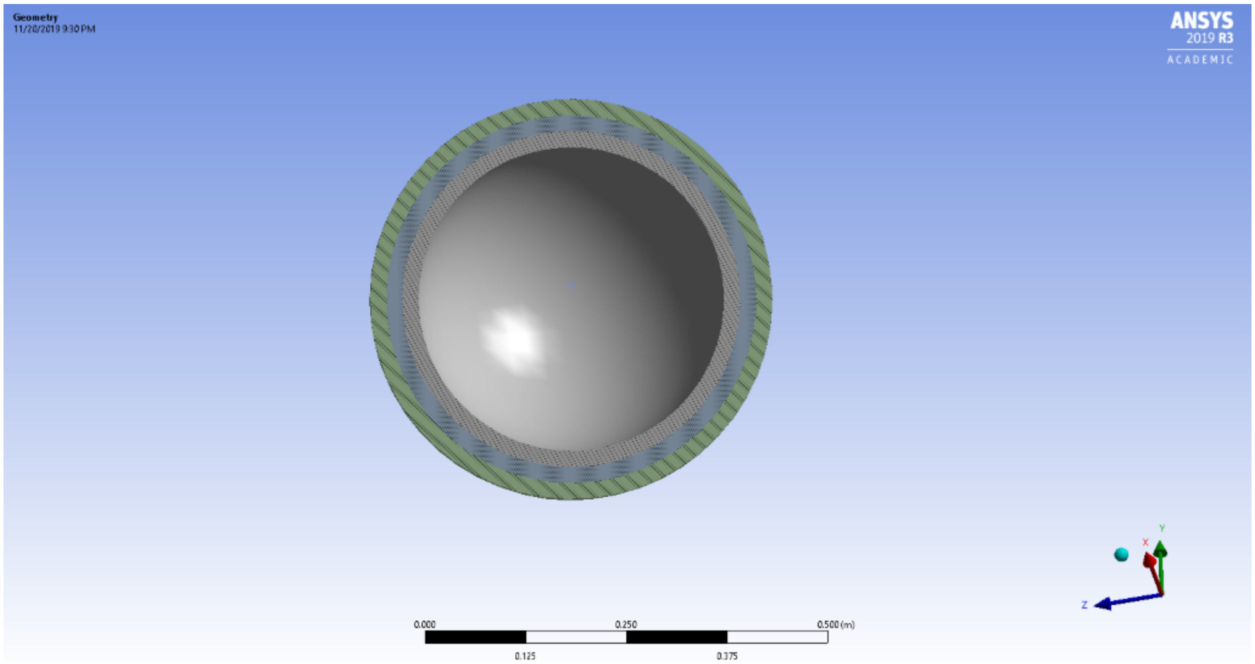

Fig. 26: Cross Section of Three Layers of the Payload Protection

[redacted] were selected based on the low thermal conductivity for reducing the heat from being transferred. Titanium provided the best strength and low thermal conductivity for a metal to hold the payload structure together.

Goal: Create a payload shell that can withstand 450°C on the outside while keeping the inside of the payload at 50 °C with the selected materials.

<u>Initial test</u>

A thermal analysis shown on Fig. 27 and 28**,** of the payload shows the expected temperatures from on the payload in the Venus environment. The sizing of the payload for Fig. 27 was selected for .5 meters for the diameter which provided. Thickness of each layer would be .02 m, which provides .44 m diameter to store the cooling and payload. The max temperature for the payload was only withstand up to [redacted]

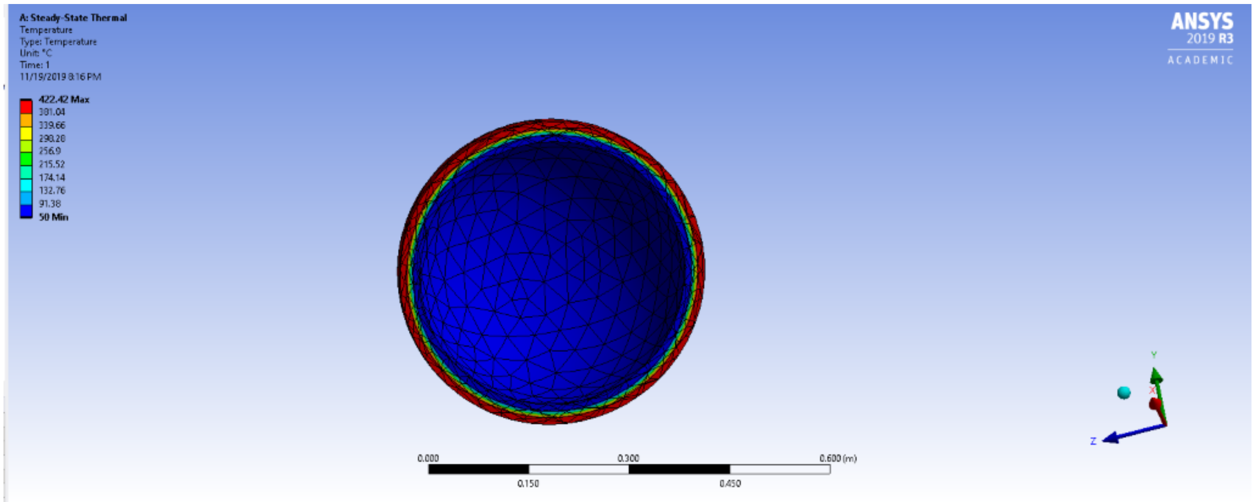

Fig. 27: Thermal Analysis of the Payload Walls for 1st Analysis

Improvements on the Test

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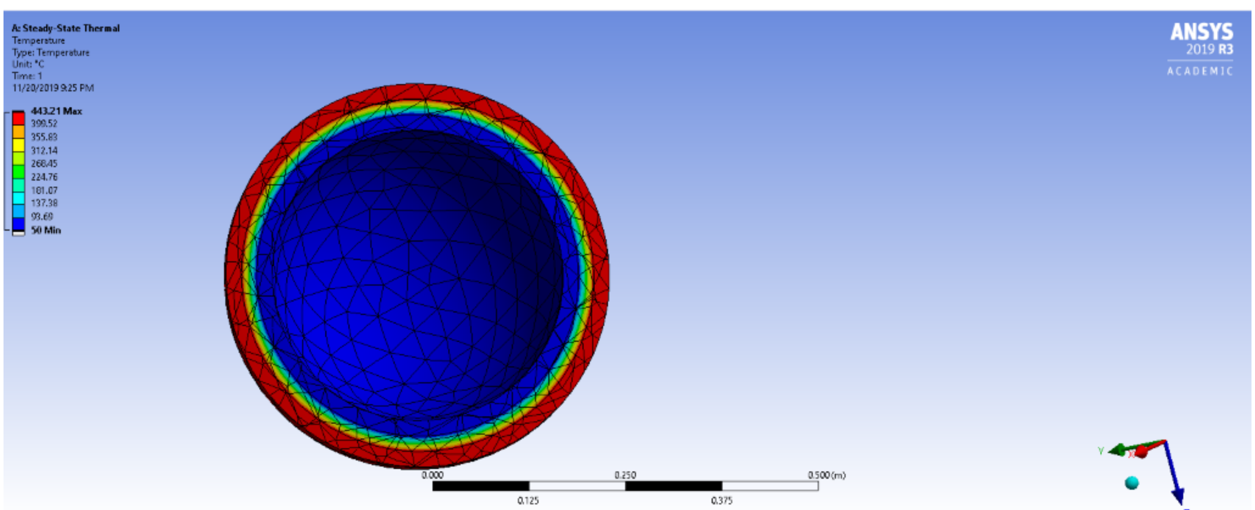

Fig. 28: Thermal Analysis of the Payload Walls for 2nd Analysis

Calculation of the Heat Penetrating Through the Sphere Layers: Finding the heat transferred through the layers [77] [redacted] [redacted]

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Based on the calculation, the amount of heat that needs to be rejected from the payload would be [redacted].

Payload Cooling System

[redacted]

[redacted]

[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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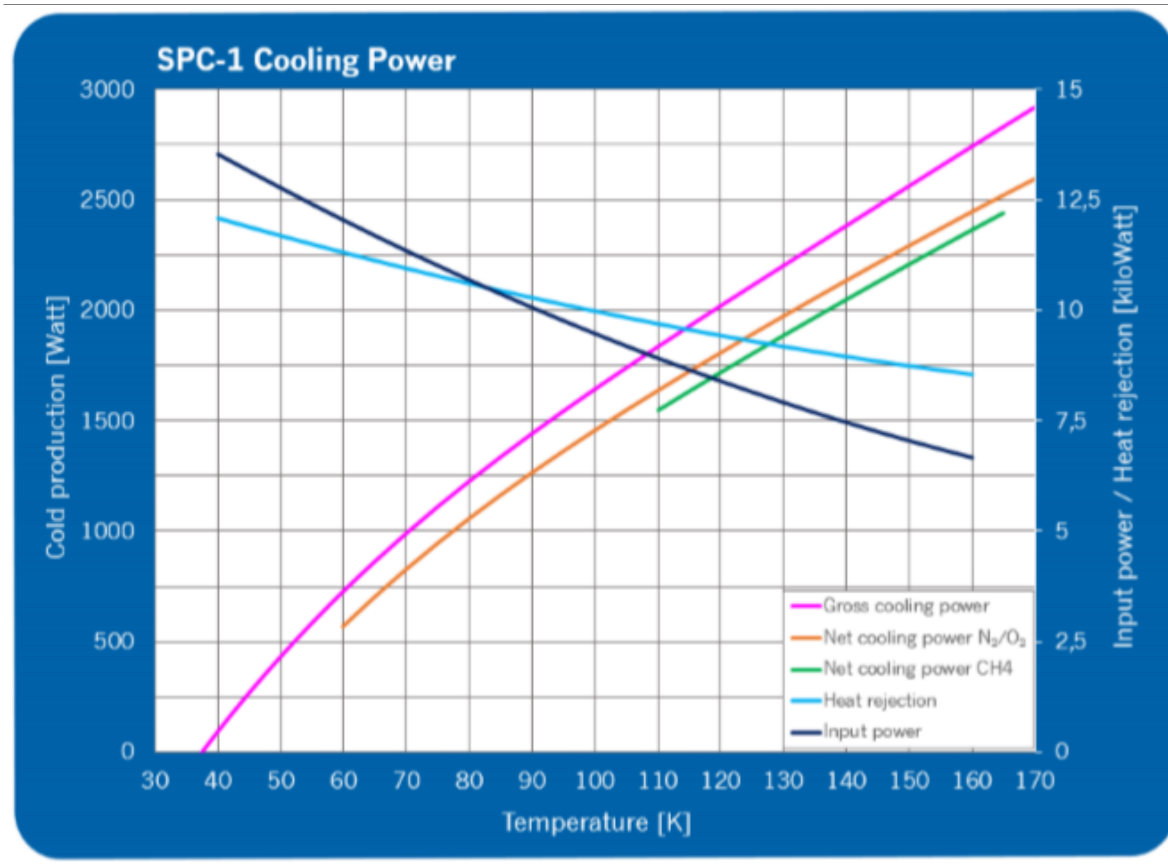

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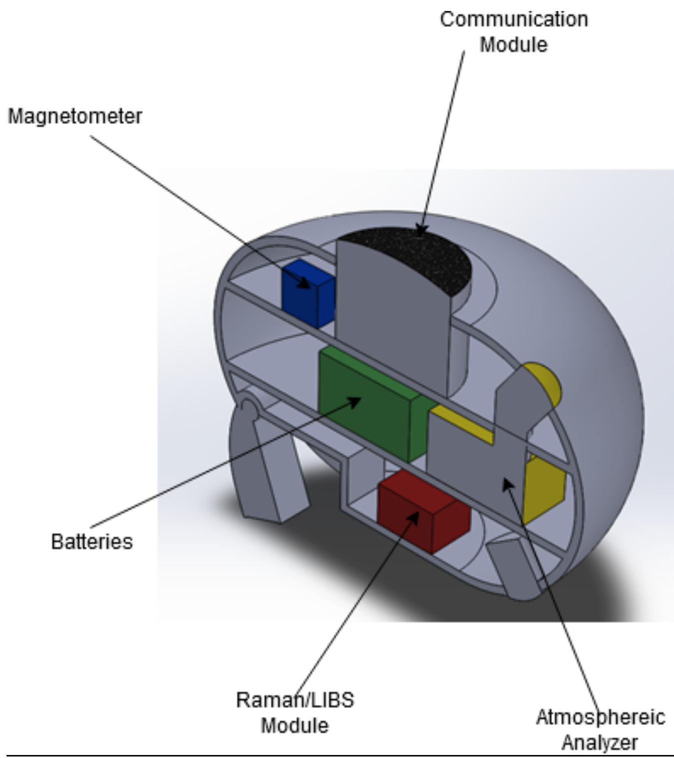

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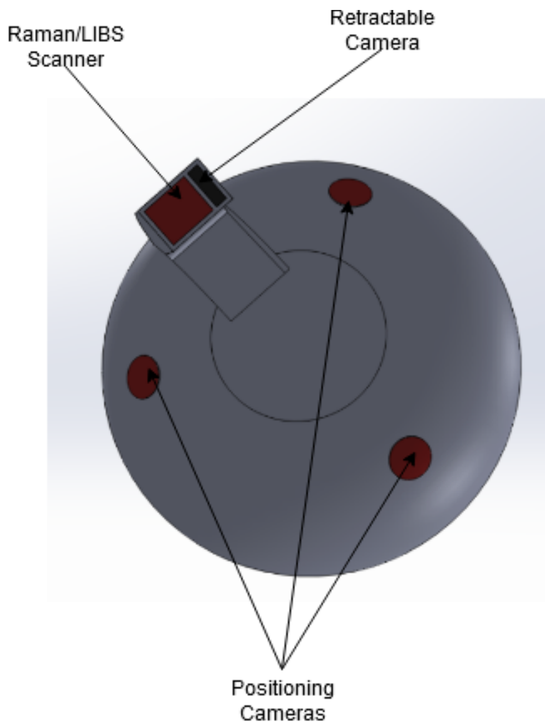

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i. Navigation Cameras (NAVs)

[redacted]

ii. Hazard Avoidance Cameras (HAZs)

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iii. Chemistry and Camera (ChemCam)

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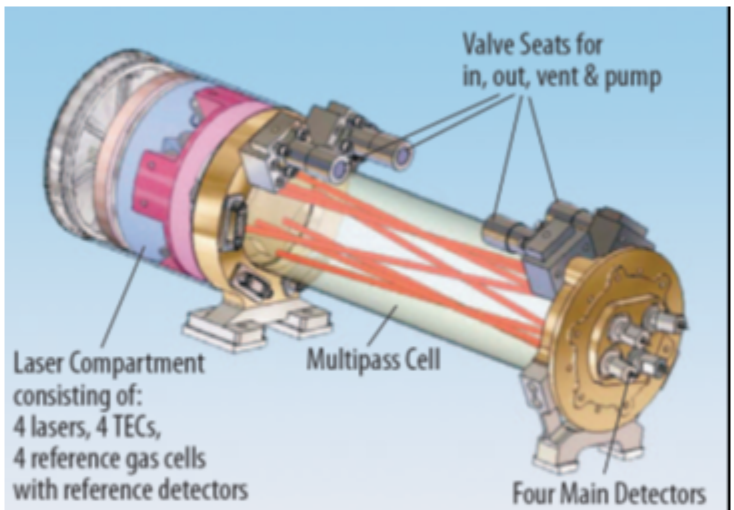

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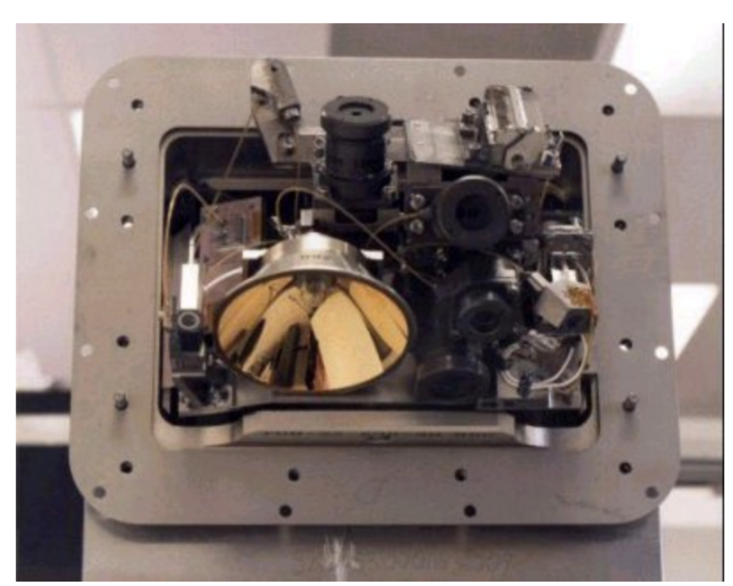

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C. Final System Model

After determining each component required for the mission in detail, an improved CAD model was created combining the new compression member and endcap design, as well as configuring the central payload with new models for the equipment that are closer to the expected actual sizes of each component. Through the research involving the sizing of the equipment, it was determined that the scientific payload would not be able to hold the entire equipment selection of the system with its current size. Due to this constraint, the size of the central payload was increased to a final diameter of .75 meters, which increased the leg length to a final length of 1.5 meters. With these adjustments, the final model was able to accurately house all of the required equipment, including an onboard controller and some additional space for extra batteries should the mission duration be modified to be longer than its initial proposal of three days. Below is the final model of the system.

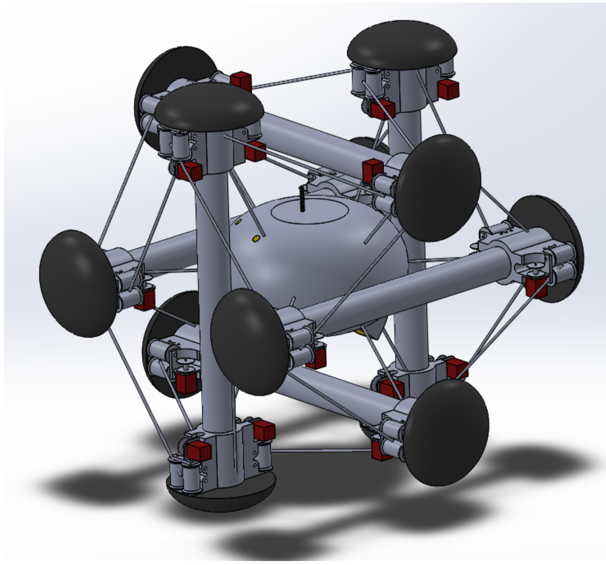

Fig. 36: Final design of TANDEM Rover

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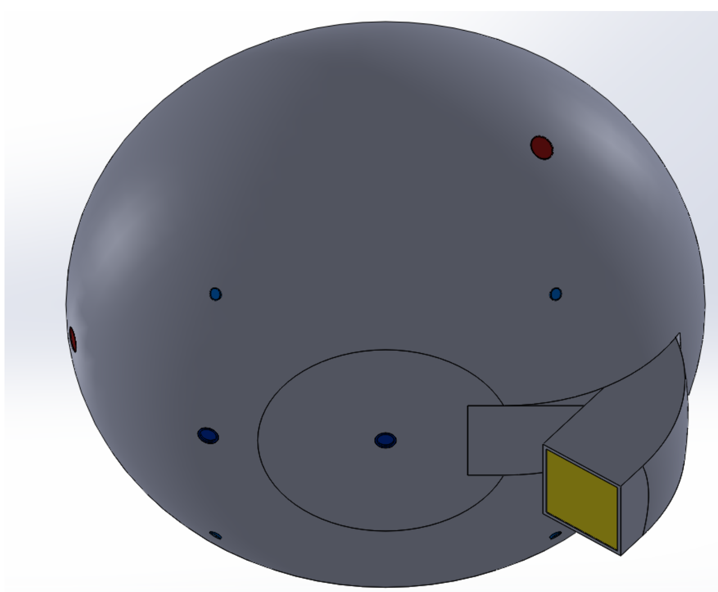

Fig. 37: underside of payload displaying camera instrumentation

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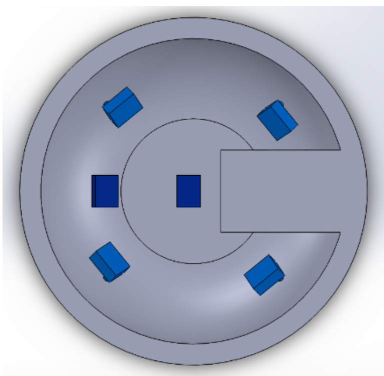

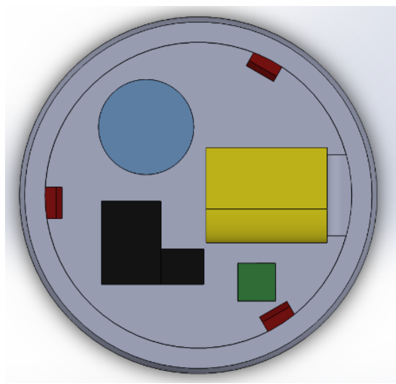

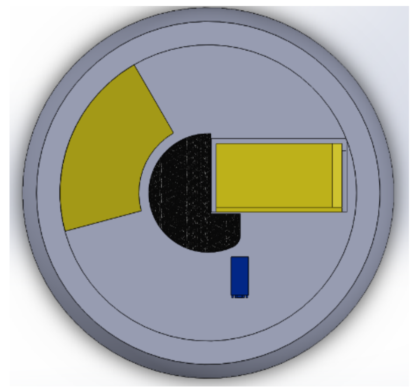

Fig. 38: bottom level of payload **Fig. 39: middle level of payload** **Fig. 40: top level of payload**

Finally, a complete view of the payload was taken without the outer shell for a better reference of the component sizing and placement throughout the system.

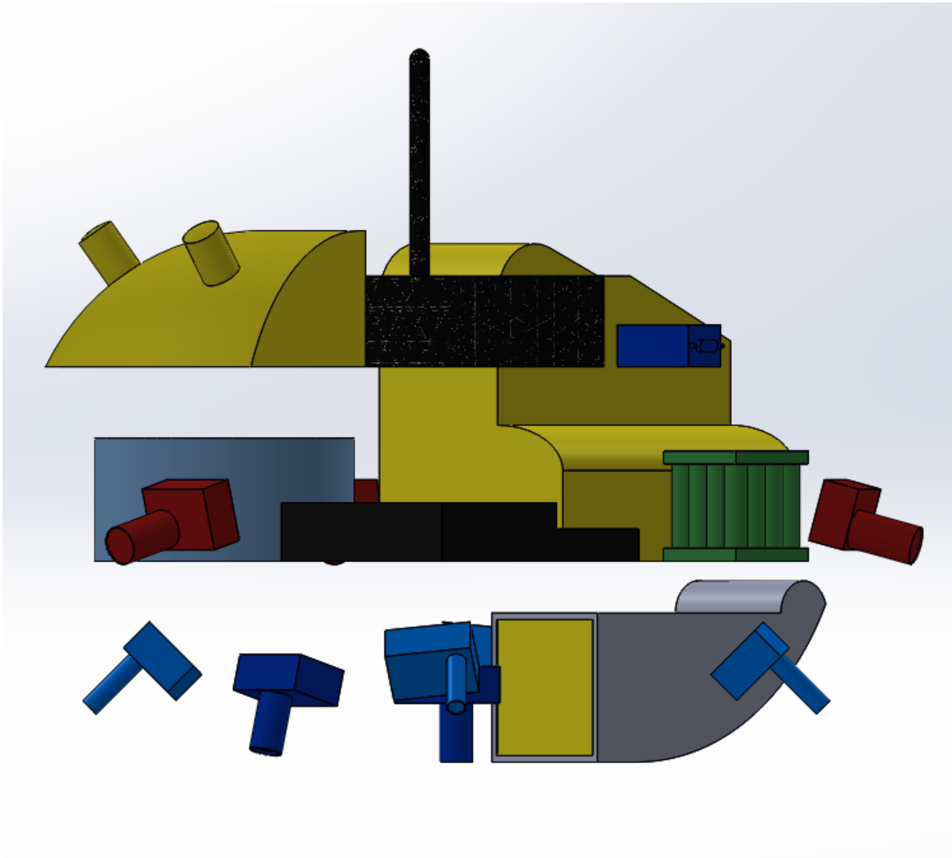

Fig. 41: Internal View of TANDEM's Central Payload

VI. Critical Design Review (CDR)

Based on the information and calculations presented in the PDR, certain tasks and decisions must be improved upon or reconsidered to further test the viability of the proposed mission outline. This means that more detailed calculations and research will be required to ensure mission success. These range from better FEA testing or power method selection.

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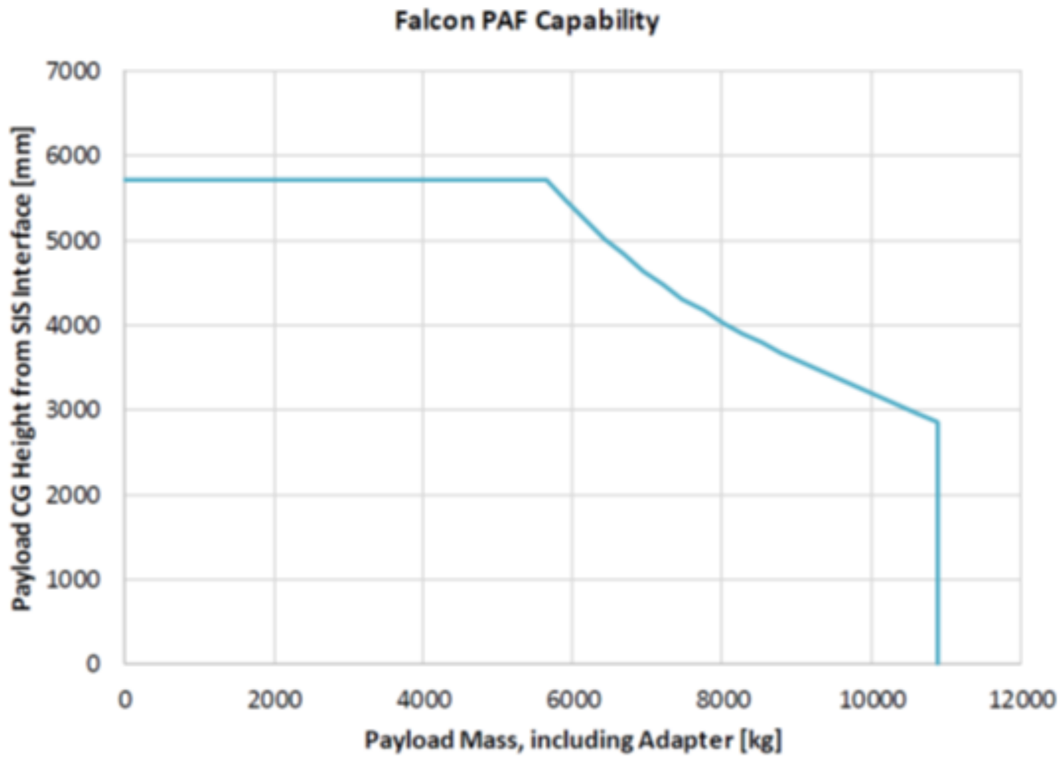
VII. Conclusion

In conclusion, the purpose of the EVOLVE mission is to fulfil the science objectives proposed by the NRC's Planetary Decadal Survey. By observing the gradual evolution of an Earth-like planet such as Venus, a variety of answers can be found from things like how life on Earth came to be, how atmospheric composition and geomorphological transformation could play potential roles in climate change, and so on. Due to the versatility of EVOLVE's tensegrity frame, including the ability to take readings and traverse terrain that were previously impossible to navigate will help to open up humanity to answers the many mysteries of the planet and also revolutionize the way future planetary explorations will be carried out in one complete system instead of many separate ones.

Appendix

Appendix A: Falcon 9 Payload Attach Fitting Capability **[19]**



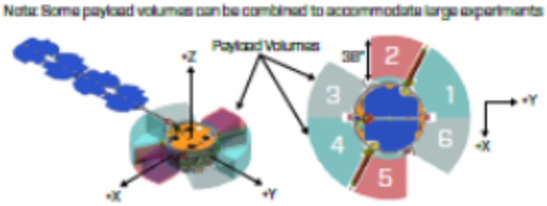
Appendix B: Current Best Estimated and Predicted Mass of EVOLVE with TANDEM

	EVOLVE with TANDEM		
	CBE	Growth	Predicted Mass
Mass List	3004 **kg**		3849.397 **kg**
Aeroshell (as covered in TANDEM report)	415		532.4
heat shield	134		174.2
Nose cap & lock ring	61	0.3	79.3
Ribs and Bearings	23	0.3	29.9
Joint Hardware	10	0.3	13
Carbon Cloth	40	0.3	52
Rigid Nose TPS	101		124.2
Nose TPS	50	0.2	60
Ribs TPS	12	0.2	14.4
Aft Cover TPS	9	0.2	10.8
Backshell	30	0.3	39
Mechanisms & Separation	60		78
Overall Deployment	60	0.3	78
System	103		133.9
Stowed Deployment Latched	19	0.3	24.7
Deployment Ring	77	0.3	100.1
Backshell Sep	7	0.3	9.1
Avionics & Power	17		22.1
Avionic Unit	4	0.3	5.2
Harness	5	0.3	6.5
Power Unit	8	0.3	10.4
Lander	2589		3316.997
Scientific Instruments	21.9		25.933
magnetometer	0.1	0.1	0.11
ChemCam	5.62	0.1	6.182
Hazcams	0.75	0.1	0.825
Navcams	1	0.1	1.1
TLS	3	0.3	3.9
S-Band antennae	10.43	0.2	12.516
Venus Descent Imagers	1	0.3	1.3
Central Payload	1662		2170.34
Tyranno Fiber	664	0.3	863.2
Aerogel	4.8	0.3	6.24
Titanium	943	0.3	1225.9
Cooling System	50	0.5	75
Power Systems	36.44		47.372
Thermal batteries	9.94	0.3	12.922
the other batteries	26.5	0.3	34.45
Structure	868.5		1073.352
Compressive Members	273.8	0.3	355.992
Tension wires	8.52	0.5	12.78
Wire Routing Systems	574	0.2	688.824
Shock absorbing systems	12.12	0.3	15.756
Motors	0.572	0.7	0.97308

Appendix C: ESPAStar Factsheet [23]

Northrop Grumman's ESPAStar platform provides a modular, cost-effective, and highly capable infrastructure resource for hosting technology development and operational payloads. The ESPAStar platform uses a customized EELV Secondary Payload Adapter (ESPA) ring as part of its structure and is capable of being launched aboard any launch vehicle that meets the Evolved Expendable Launch Vehicle (EELV) standard interface specification, and Falcon 9. The ESPAStar platform's 6 payload ports are capable of accommodating any combination of up to 6 hosted and 12 separable (fly-away) payloads (maximum 1 hosted or 2 separables per port). The payload interface at each port has been standardized, allowing for hosted and separable payload interchangeability, late payload integration, and manifest changes. The ESPAStar platform leverages the available mass margin from any EELV launch to provide an affordable path to space for payloads. The platform is optimized for GEO missions, but is adaptable for LEO and MEO missions.

Note: Some payload volumes can be combined to accommodate large experiments



Facts At A Glance

- Accommodates combinations of hosted (6 max) or separable (12 max) payloads at all mounting ports
- 1086 kg payload (181 kg per Port)
- Multi-year mission life
- 1.6 Mbps downlink, AFSCN-compatible, Type 1 encryption
- Low jitter
- Attitude knowledge <20 µrad (1σ)
- ≥400 m/s delta-V, any direction
- EELV SIS Rev B compliant
- Full complement of electrical interfaces:
- Power
- Data
- Discrete I/O

Specifications

Spacecraft

Orbit:	Optimized for GEO, adaptable for LEO and MEO missions
Design Life:	Multi-year mission life, single string
Dry Mass (no P/Ls):	430-470 kg (orbit dependent)
Dimensions (no P/Ls):	62" dia. x 24" ht.
Fuel Capacity:	310 kg
Payload Mass:	1086 kg (181 kg per port)
Total Power (BOL):	1200 W via four-panel solar array
Payload Peak Power:	Tailorable based on mission profile
Battery:	96 A-hr Li-ion
Downlink Rate:	256 kbps/1.6 Mbps via AFSCN Higher downlink rates available upon request
Uplink Rate:	2.0 kbps via AFSCN Higher uplink rates available upon request
Payload Data Storage:	36 Gbytes non-TMR, non-volatile, 500 kbytes/day/payload SOH
Pointing Control:	< 20 μrad (1σ) via 3-Axis RWA control
Attitude Knowledge:	< 20 μrad (1σ)
Jitter at Payload Interface:	< 30 μrad, (1σ), >0.1 Hz
Slew Rate:	≥ 1.2 deg/sec
Position Control:	12x 1-N and 4x 22-N REAs, 6 DoF control
Position Knowledge:	< 100 m
Avionics:	IAU, BRE440 processor, Virtex 5 FPGA, 40 GB memory

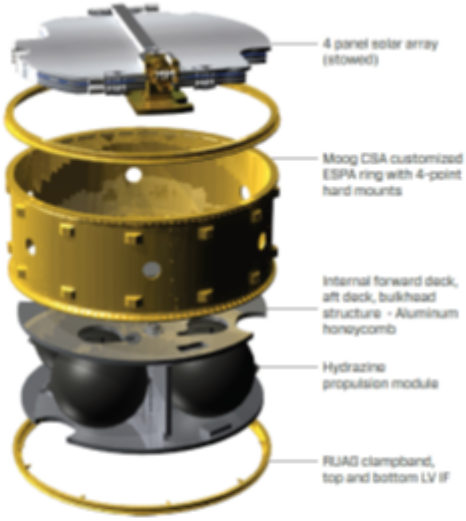
Mission Services

- Mission Analysis
- Payload Integration
- Testing and Verification
- Launch Vehicle Integration
- Launch Operations
- Mission Operation
- Safety & Mission Assurance

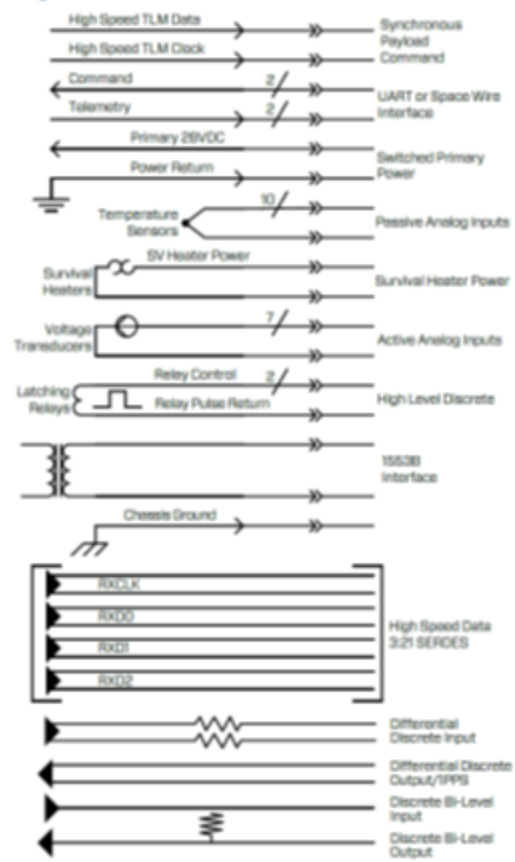
For more information:

Carol Welsch
Senior Director, Business Development
Space Systems Group
(571) 342-0100
carol.welsch@ngc.com

ESPAStar Platform



Payload Electrical Services



THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN

Appendix D: MAG-3 Magnetometer Data Sheet [41]

SpaceQuest

MAG-3 Satellite Magnetometer

The MAG-3 is a 3-axis satellite fluxgate magnetometer supporting reliable and accurate spacecraft attitude measurements. This space-qualified component and its predecessors have flown on numerous space missions and is particularly well suited to the radiation environments of high LEO orbits.

Key Features

- → 3-Axis Measurement
- → Radiation Tolerant
- → Low Mass Rugged Design
- → Space Qualified (TRL-9)

Performance Specifications

Accuracy:	± 0.75% of Full Scale (0.5% typical)
Linearity:	± 0.015% of Full Scale (15 to 34 VDC input) ± 0.15% of Full Scale (5 V option)
Sensitivity:	100 µV/nT (other sensitivities available)
Scale Factor Temperature Shift:	0.007% Full Scale/°C Typical
Analog Output Options:	±10 Volts = ±100µT or ±5 Volts = ±60µT (other options available)
Axial Alignment:	Orthogonality Better Than ± 1 degree

SpaceQuest, Ltd. 3554 Chain Bridge Road, Suite 400 Fairfax, Virginia 22030 I 703. 424. 7801 I www.spacequest.com

MAG-3

Performance Specifications *(continued)*

Noise:	12 picoTesla RMS/ √Hz @1 Hz <100 picoTesla RMS/√ Hz @1 Hz (0 to 5 Volt Model)
Analog Output @ Zero Field:	± 0.025 Volt
Zero Shift with Temperature:	± 0.6 nT/°C
Susceptibility to Perming:	± 8 nT Shift with ± 5 Gauss Applied
Output Impedance:	332 Ω ± 5%
Frequency Response:	3 dB @ > 500 Hz (to > 4 kHz Wideband)
Over Load Recovery:	± 5 Gauss Slew < 2 ms

Electrical Specifications

Input Voltage:	15 to 34 VDC or 5 Volt Regulated
Power Consumption:	Voltage Dependent (30 mA at any input voltage)
Connectors:	9 Pin Male "D" Type

Mechanical and Environmental

Mass:	100 grams
Size:	3.51 cm x 3.23 cm x 8.26 cm
Operating Temperature:	-55°C to +85°C
Radiation:	> 10 Krad TID

Heritage

- Bigelow Aerospace Genesis-1
- Bigelow Aerospace Genesis-2
- Georgia Tech PROX-1
- Naval Research Laboratory

Acknowledgments

This Space Mission Design Research would have not been possible without the support of NASA and the University at Buffalo. [redacted]

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[1] K. Schroeder, J. Samareh, and J. Bayandor, “TANDEM: Tension Adjustable Network for Deploying Entry Membrane,” Journal of Spacecraft and Rockets, vol. 55, no. 6, pp. 1379–1392, 2018.

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