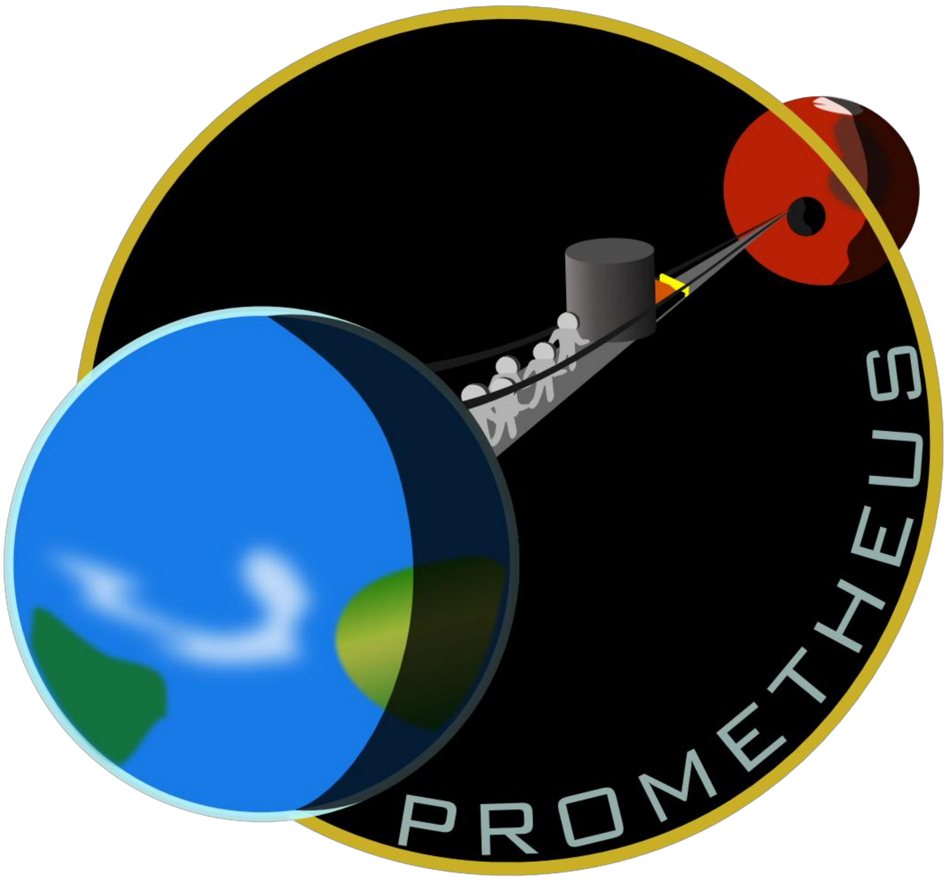
Project Prometheus

Purdue University
AAE 450 Spacecraft Senior Design
Spring 2013



Project Manager
Rachel Bodien

Assistant Project Manager
Bruno Prentice

Attitude Control
Team Leader: Brian Foss
Jim Behmer*
Ching Hao Chua*
Anurag Nandi
Kenneth Roush
Collin York*

Power and Thermal Control
Team Leader: Jeff Xie
Yu Huang
Hannah Kraus*
Eric Meier
Trym Erik Nielsen

Communications
Team Leader: Kaitie Schoenfeldt
Victor Gandarillas
Allison Shultz

Human Factors
Team Leader: Aaron Driver
Elizabeth Marandola
Pritesh Patel
Matthew Schenk
Sarah St. Clair*
Seth Trey

* Indicates Vehicle Team Leader

Mission Design
Team Leader: Cassandra Strode
Nick Kowalczyk
Randy Eckman
Thomas Just
Curtis Langlois
Mitch Sangalis
Joshua Wolf

Aerodynamics
Team Leader: Kilian Cooley
Joe Graham
Aniket Patel
Austen Wildberger

Structures
Team Leader: Jeremy Lakoskey
Christopher Riemer
Darren Shandler
Ryan Tedjasukmana
Yuming Zou

Propulsion
Team Leader: Bhuvi Nirudhoddi
Nick Edwards
Braxton Felts
Simon Hufnagel*
Junsik Kang
Christian Lysholm
Wayne Masteller
Eric Nelson*
Taddese Tessem

Special Thanks

Instructor: Dr. James Longuski
Teaching Assistant: Mr. Peter Edelman

Acknowledgements

Dr. Chan Choi
Dr. Steven Collicott
Dr. David Filmer
Dr. Michael Grant
Dr. Stephen Heister
Dr. Kathleen Howell
Dr. Inseok Hwang
Dr. David Minton
Dr. Cary A. Mitchell
Dr. Timothee Pourpoint
Mr. Blake Rogers
Mr. Sarag Saikia
Dr. Boris Yendler

1 Foreword

This report represents the culmination of an intensive spacecraft design course, AAE 450, undertaken by seniors during a single semester. The students perform a feasibility study for a specified mission goal, subject to certain constraints.

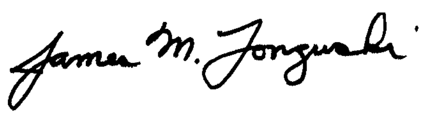
The entire class works as a single team to achieve this goal. They elect a Project Manager and an Assistant Project Manager and organize into specialized groups to study (in this case) aerodynamics, attitude control, communications, human factors, mission design, power and thermal control, propulsion, and structures.

At the end of the semester the students deliver a formal presentation of their results. Besides this report, the class provides an appendix, which contains detailed analyses of their methods and trades studies.

The quality of the work in this report is consistent with the high standards of the aerospace industry. The students who participated in this study have demonstrated that they have mastered the fundamentals of astronautics, have learned to work efficiently as a team, and have discovered innovative ways to achieve the goals of this project.

In this particular project, the students were challenged to minimize the cost of a human mission to Phobos that prepares a Martian cave for a permanent colony on Mars, subject to a number of requirements. The most important requirement is to protect the crew from space radiation. NASA has known for some time that shielding with an areal density of 100 to 200 g/cm^2 is necessary to reduce space radiation to the level of Earth background levels. Some scientists believe that even greater protection is needed ranging from 300 to 500 g/cm^2 . In this report, the requirement is set to 200 g/cm^2 which amounts to a shield wall 2 meters thick (if water is used for the shield). The resulting impact on the mass of the spacecraft strongly indicates that the concept of a Cycler vehicle which, once placed in orbit around the Sun, provides a safe haven that Mars-bound astronauts can use over and over again for succeeding crews. Thus, the use of a Cycler vehicle is one of the requirements in this design. The Phobos crew is returned to Earth after preparing the Martian cave. Succeeding crews are then enabled to use the Cycler vehicle multiple times to establish a human colony on Mars. The details of the "One-Way Mission to Mars," in which astronauts live out their lives on Mars, are provided in last year's AAE 450 report, Project Olympus (2012). The current design provides a "prequel" to the prior design and is intended to resolve the problem of how to prepare Martian caves for the human colony – a daunting task that the present design team undertook.

I believe this design team rose to the occasion to produce an important feasibility study. The leadership of the Project Manager and Assistant Project Manager as well as the outstanding cooperation of the team members were key elements in the success of their project. They have every right to feel proud of their accomplishment and I am proud of them.



Professor of Aeronautics and Astronautics
Purdue University
April 4, 2013

2 Mission Summary

2.1 Mission Requirements

In order to make the most use of every opportunity to travel to Mars, two Cycler Vehicles shall be used. Our two Cycler Vehicles shall provide an artificial gravity field of 0.38 Earth g's, equivalent to the gravity on Mars. The Cycler Vehicles shall also provide shielding against space radiation. This shielding protecting the crew Habitation Module shall have an areal density of 200 g/cm^2 and must be water. A trajectory correction maneuver of 100 m/s should be budgeted for every synodic period of the Cycler Vehicles.

Crew A shall land on Phobos to prepare the landing site for Crew 1 remotely. Crew A shall consist of eight middle aged people, four men and four women. The construction equipment shall be tele-operated by all members of Crew A. The preparation of the cave entrance ramp shall be completed within a year. Telecommunications with the Mars Builders shall be continuous during the entire time Crew A is on Phobos.

Continuous, uninterrupted, High Definition two way video communications shall be maintained between each of the astronauts and Earth.

During the landing of the Mars Builders and Maintenance Station on Mars, the landing vehicle shall hover for at least 30 seconds. The error for landing is to be less than six km with a probability of 99%.

The Phobos Hab shall provide each crew member with private quarters, each having a volume of 15 m^3. The crew common area for the Phobos Hab shall also have a volume of 15 m^3. There shall be a centrifuge in the Phobos Hab that provides 0.38 g's of artificial gravity to allow for using a toilet and shower as well as exercise. All crew members of Crew A shall be able to use these services for one hour per day. On each Cycler Vehicle, the crew private quarters shall have a volume of 30 m^3. The crew common area for the Habitation Module shall also have a volume of 30 m^3.

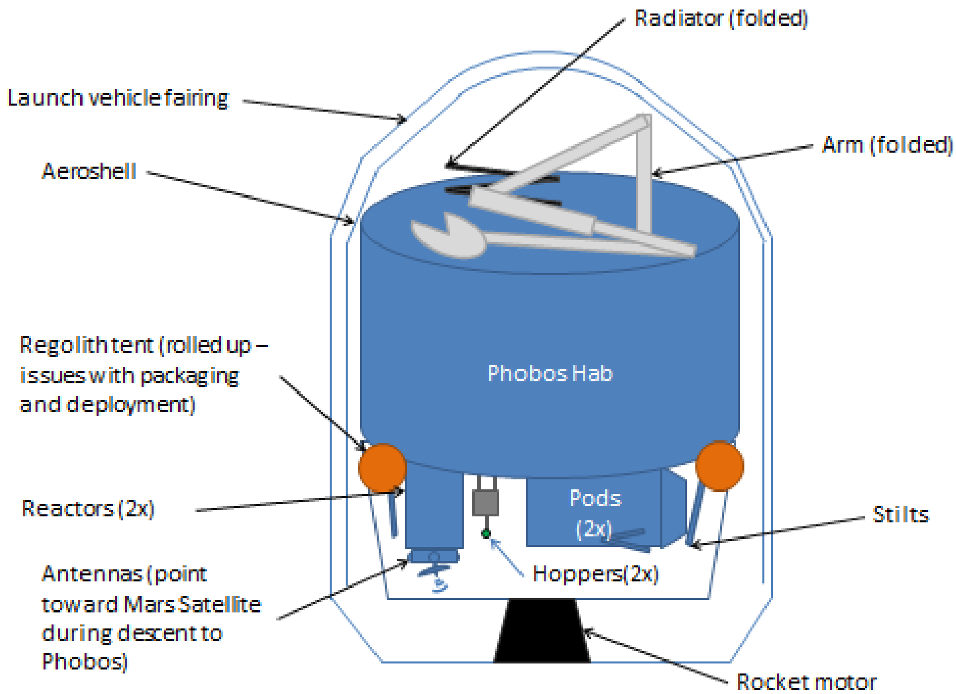
The Phobos Hab shall have a radiation shielding with an areal density of 200 g/cm^2. Crew A shall not employ in situ propellant production to return to Earth. During Crew A's stay on Phobos, they shall explore the moon with two tele-operated, robotic vehicles and two pressurized crewed vehicles. Each crewed vehicle shall be able to carry four crew members and fly a three hour mission on Phobos every day. Spacesuits for Crew A shall only be used as a safety precaution whilst in these crewed vehicles. The crewed vehicles shall be designed to allow the crew to control them inside in a "shirt-sleeve" environment. The crewed vehicles shall also have similar science instruments to the Mars rovers: lights, stereoscopic cameras, microscopes, telescopes and geologist' tools. The crewed vehicles shall also have robotic fingers, hands and arms to pick up a small boulder or a dime. They shall be faster, safer, stronger and more dexterous than crew members in space suits. The robotic vehicles shall be able to explore Phobos for 12 hours each day. The crew members shall not be subjected to direct exposure to space radiation for an accumulated period exceeding two months.

Cargo flights may be launched as early as 2020, and they can use electrical propulsion but must take less than one synodic period, 2 1/7 years, to reach Mars. Crew A shall be launched by 2030, but no later than 2040. Crew A shall employ a ballute aerocapture at Mars to reach Phobos. All technologies shall be space rated before the first human flight.

Project Prometheus's main mission goal of preparing the Martian lava tubes shall have a 90% probability of success. Crew A's safe return to Earth in good health shall have a probability greater than 95%.

4.2 Phobos Landing Sequence

The Phobos Hab, Pods, Hoppers, and reactors are packaged as shown in Fig. 4.2.1. There are two Pods, two Hoppers, and two reactors. The second reactor is there as a backup.



4.2.1: Phobos Hab, Pods, Hoppers, and reactors packaged for transit

The landing sequence is as follows:

1) The cargo vehicle enters orbit around Mars and approaches Phobos by using an aerocapture maneuver. The aeroshell is shown in the launch vehicle fairing (Fig. 4.2.1).
2) The aeroshell is jettisoned.
3) The Phobos Hab lands in Stickney Crater with the Pods, Hoppers, and reactors attached.
4) The reactors start up.
5) The Phobos Hab arm removes the reactors and places them nearby.

The power and communications systems are housed in the reactors. The reactors are connected to the Phobos Hab by a cable. The final separation on Phobos between the reactors and the Phobos Hab will be approximately 50 m.

The reactors do not operate during descent or landing. This is to prevent damage from shock and vibrations. The reactors cannot be turned on for descent, turned off for landing, and then turned on again after landing. The reactors generate minimal power after landing until the crew arrives, and then run near capacity for the crew. There is an arm for regolith collection and a radiator on top of the hab. They are shown folded near the top of the fairing in Fig. 4.2.1.

Originally, the tent that holds the regolith was to lay flat on the side of the Phobos Hab in transit. This poses a problem for the propulsion team because the thrusters must be open to space and they cannot be mounted to the tent material. To solve this problem, the tent is rolled up underneath the Phobos Hab over the stilts in transit.

4.5 Phobos Landing Site Schematics

Figure 4.2.1 in the previous section shows the Phobos Hab with the tent deployed and the Crew Transfer Vehicle berthed alongside the Pods. Although this is a rudimentary schematic, it should serve as a good reference to visualize the overall configuration of the Phobos portion of the mission.

The Crew Return Vehicle berths underneath the Phobos Hab. The advantages of this are the following:

1) There is no radiation protection on the Crew Return Vehicle. If the Crew Return Vehicle docks on the top, it exposes the crew in the Phobos Hab to radiation.
2) There is also risk of damaging the heat shield when piling regolith on top of the hab.

The disadvantages to berthing underneath the Phobos Hab are the following:

1) The Crew Vehicle is 2.7 m in length and there is only a 5 m clearance beneath the hab.
2) Another problem posed by docking beneath the Phobos Hab is the pods acting as obstacles.

We mitigate the disadvantages by using the arm at the top of the Phobos Hab to berth the spacecraft to the Phobos Hab on the underside instead of risking impact by docking.

In addition to berthing the Crew Return Vehicle, the arm also collects regolith. One of the primary mission objectives that the Pods accomplish is the collection of regolith. The following factors influenced the design:

1) Pods use much less propellant if they do not need to reach the height of the roof of Phobos Hab on every pass. Despite the low gravity on Phobos, this yields major savings on propellant mass.
2) A conveyor belt (one of the designs considered) is not necessary because the arm can dump the regolith into the tent.
3) It is possible for the arm to have dual functionality: to berth the Crew Return Vehicle, and to place the regolith in the tent around the Phobos Hab to protect the crew against radiation.

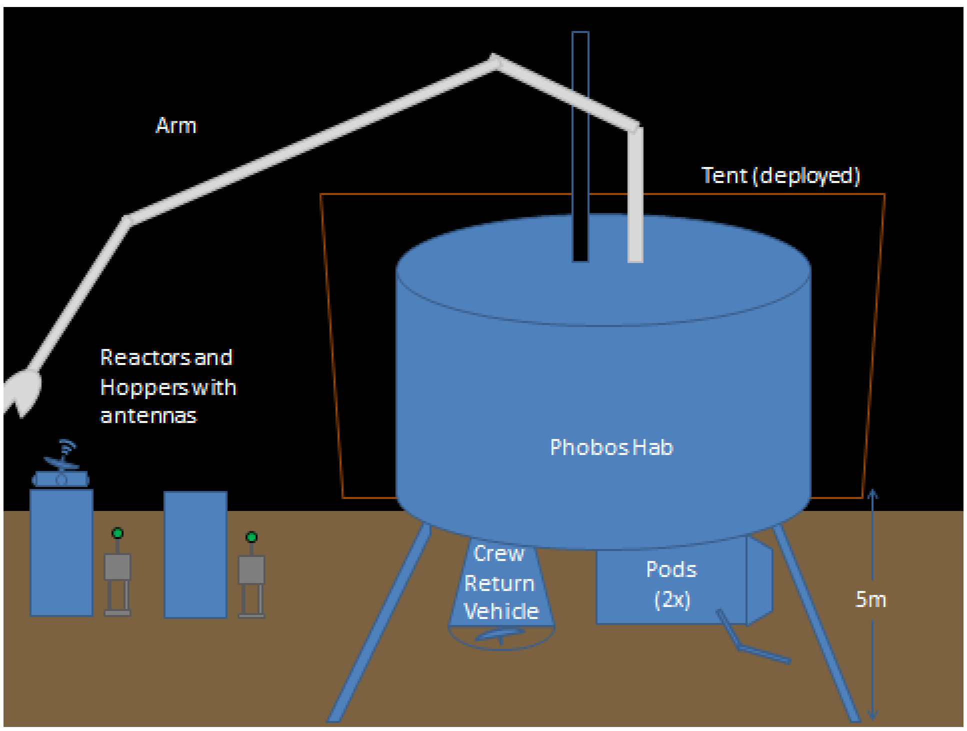
The pods collect regolith and leave it near the arm manipulator, which then places the regolith in the tent. The radiator on top of the Phobos Hab will be tall enough to avoid most of the regolith. One option was to dock the Crew Return Vehicle on top of the Phobos Hab. This would expose the crew to radiation since the Crew Transfer Vehicle would not have any shielding. In addition, the regolith would damage the exterior of the Crew Vehicle. We placed the radiator on top of the Phobos Hab with the Crew Return Vehicle docking port underneath. The radiator does not risk the lives of the crew if scratched by the regolith. The radiator is also designed to mount higher than the Crew Return.

Victor Gandarillas

4.10 Phobos Hab Communication with Mars Satellites

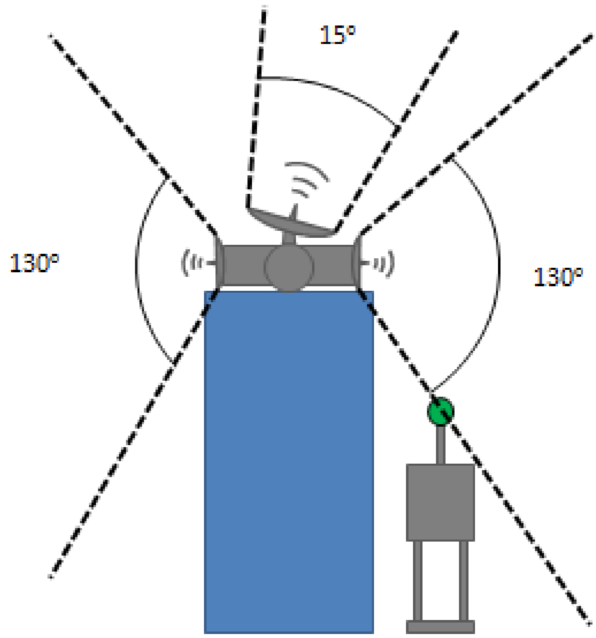
In order to communicate with the Mars Satellites on its way to Phobos, the Phobos Hab is equipped with an omnidirectional antenna. We chose an omnidirectional antenna because the power requirements for an uncrewed vehicle with no HDTV feeds is much lower than the power required for higher data rates. An omnidirectional antenna is also much lighter than a dish antenna. We also chose to use the same frequency so that we wouldn't have to add another antenna to the satellite.

After the landing phase is complete, the Phobos Hab has full HD capability with the Mars Satellites by way of the dish antenna located on the reactors (Fig. 4.10.1). When the crew arrives from the Cycler Vehicle, the Crew Transfer Vehicle approaches the Phobos Hab. The arm will capture the Crew Transfer Vehicle and berth it to the underside near the Pods. The Hoppers sit in their charging stations until the crew arrives and begins to operate them.



4.10.1: Phobos landing site schematic

The Phobos Hab communications architecture is similar to the Mars Builders communications architecture (Fig. 4.10.2). The reactors have a dish to communicate with the Mars Satellites as well as three 130 deg beamwidth dish antennas for communicating with the Pods and Hoppers.



4.10.2: Phobos communcations systems on top of reactor

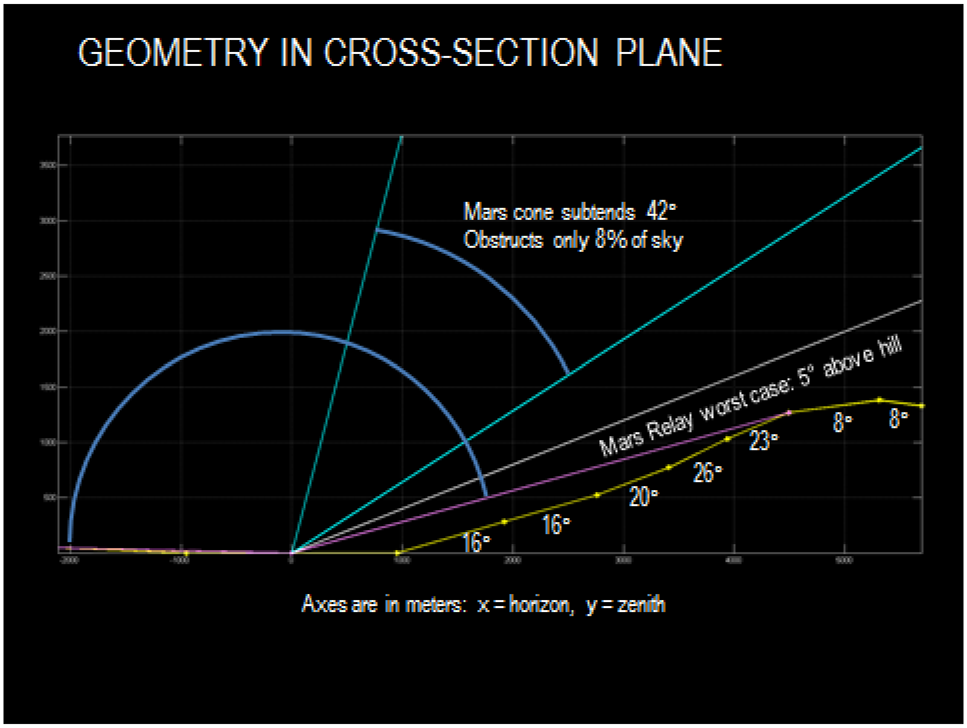
The antenna specifications for the Mars Satellite uplink and local communications dishes on Phobos are listed in Table 4.10.1.

4.10.1: Phobos Hab/reactors communications antennas

Link	Frequency, GHz	Power, W	Transmit Beamwidth, deg	Transmit Antenna Diameter, m	Data Rate, Mbps	Margin, dB
Phobos Cargo [Autonomous TM] Uplink (to Mars Satellites)	1.4	0.602	360	0.0417	0.0002	3.0114
Phobos Tower [Crewed] Uplink (to Mars Satellites)	1.4	584	15	15	110.1125	3.0053
Phobos Tower Downlink (to Pods, Hoppers)	0.7	30.4	130	0.2308	88.135	3.006

We chose a 130 deg beamwidth antenna for three reasons, the first two being common to the Mars Builders tower:

- Overlapping transmission areas guarantee consistent signal strength in all directions
- The antennas are not all transmitting from the same point – there is some space between them where they mount at the top of the tower.
- The large beamwidth ensures that the signal will reach relays outside the crater (Fig. 4.10.3).



4.10.3: Chart showing visibility of sky from Phobos landing site with obstuctions; by Randy Eckman

The Phobos tower is not as tall as the Mars tower because the feasible communications range is much smaller, due to the size of Stickney Crater and the height of the edges of the crater. The height of the Phobos tower is low enough that the Pods and Hoppers are able to communicate before they first deploy.

4.12 Phobos Hab Stilts

Nomenclature

h = Vertical distance from ground to Phobos Hab, m
l = Length of each stilt, m
ρ = Density of material, kg/m^3
m = Total mass of stilts, kg
θ = Stilt angle, deg
n = Number of stilts
F_s = Side force, N
L = Smallest distance supporting point and force acting point, m
M = Moment produced by side force, Nm

Based on the mission, we want Phobos Hab to stand on Phobos, and leave enough space to allow Pods and Crew Return Vehicle to exit. Therefore we need to design a stilts system for Phobos Hab. According to the dimensions of Pods and Crew Return Vehicle, we decide to use five stilts to support Phobos Hab. There are several reasons. First of all, five stilts can make five 72 deg angles exist between every two stilts as shown in Fig 4.12.1, which means that the distance between every two stilts is about 3.5 m. It is wide enough for Pods and Crew Return Vehicle's exiting. Secondly, five stilts have more stable effect to Phobos Hab than four stilts.

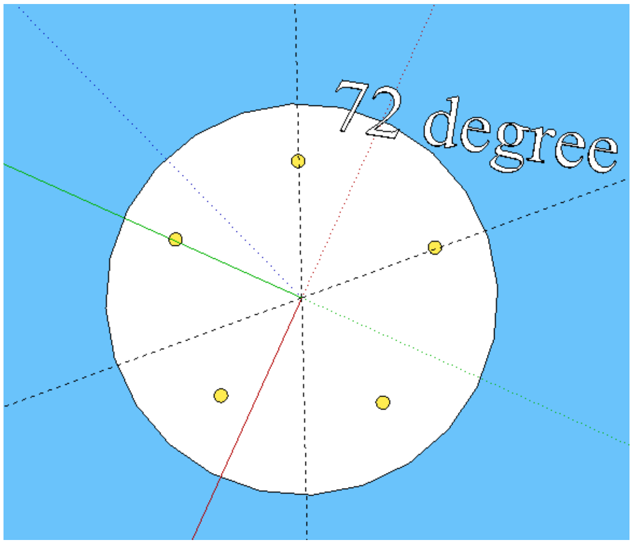


Figure 4.12.1: Five stilts design gives 72 deg angles between every two stilts to leave enough space for vehicles (by Yuming Zou).

The required distance between ground and Phobos Hab is set as 5 m. At the beginning of our design, we assume that all stilts have 0 deg stilt angle with vertical direction. Then, by using Equation 1, we find the minimum total area for five stilts with a safety factor 3.

$$\sigma = F/A \qquad \textbf{Equation 1}$$

In order to avoid bucking, we choose hollow cylinder as the basic shape of stilts, then use Equations 2 and 3 to find out the specific values for radius and thickness required.

$$F = \pi^2 EI/(KL)^2 \qquad \textbf{Equation 2}$$

$$I = 2\pi r^3 t \qquad \textbf{Equation 3}$$

The stilts system is attached on bottom of Phobos Hab, so we want to minimize its total mass. One way to achieve this purpose is to choose suitable material. We repeat the same calculation under required constrains for four different materials (steel, aluminum, bronze, and magnesium alloy). We find that Aluminum has lowest mass, see Table 4.12.1. So, we use Al 7075-T6 as material of stilts.

Table 4.12.1: Mass and properties comparisons

	Yield Stress, MPa [1]	Density, kg/m^3 [1]	Total Mass, kg
Steel	700	7850	29.2
Aluminum	480	2800	15.5
Bronze	690	8800	33.2
Magnesium Alloy	280	1830	17.0

The Fig 4.12.2 shows a 10 deg stilt angle for each stilt. The using of stilt angle is to keep Phobos Hab more stable under some uncertain reason, like self vibration, and unsteady landing level.

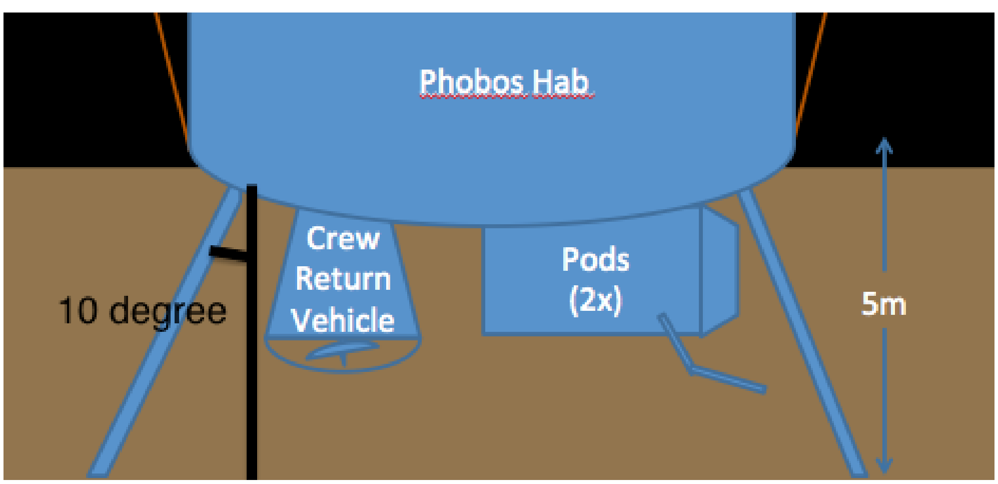


Figure 4.12.2: There is a 10 deg stilt angle for each stilt (by Victor Gandarillas).

Based on our calculations from Equation 4, 10 deg stilt angles make the stilts about 2 percent longer and heavier than stilts without angles. On the other hand, angles help Phobos Hab to stay stable under maximum 200 N side force.

$$M = F_s \times L \qquad \textbf{Equation 4}$$

Furthermore, at the bottom of each stilt, there is a U-shape plane to avoid vibrations and make the system stable.

During transporting process, in order to save more volume, we design the stilts to keep folding up and closely attached on Phobos Hab base. Once we hover the Phobos Hab to desired location and prepare for landing, we adjust the orientation of the stilts so that each stilt is 10 deg away from the vertical axis.

Table 4.12.2: Dimensions of stilts

Dimensions	Values
Height, m	2
Number of Stilts	5
Safety Factor	3
Radius of Each Stilt, m	0.073
Thickness, m	0.01
Angle, deg	10
Material	Al 7075-T6
Total Mass of Stilts, kg	15.5

Reference

[1] Barry J. Goodno, James A. Gere; Mechanics of Materials 7th Edition. Quebecor World. Toronto, Canada. 2009.

Yuming Zou

5.15 Pods and Hoppers Communications

The Pods and Hoppers will have full HD capability with the Phobos Hab. Phobos measures 26.8 × 22.4 × 18.4 km [1], so the range set for the Pods and Hoppers is 44 km; longer than the Phobos Hab dishes in order to reach communication relays scattered around the surface.

The Pods and Hoppers all have navigation and communications systems. There are ten relays, each with a range of 14 km all around Phobos. After being delivered by the Pods and Hoppers, they provide even coverage over the surface of Phobos for communication and navigation. The relays can determine their relative positions to establish a network of surface reference locations and enable the Pods and Hoppers to determine their own positions from those relative positions. The relays transmit in the GPS standard L2 frequency at 4800 bps. The Pods and Hoppers do not transmit in L2 since they only act as receivers.

Antenna specifications for the Pods, Hoppers, and relays are listed in Table 5.15.1.

5.15.1: Antenna specifications for Pods, Hoppers and Phobos relays

Link	Frequency, GHz	Power, W	Transmit Beamwidth, deg	Transmit Antenna Diameter, m	Data Rate, Mbps	Margin, dB
Phobos Pods, Hoppers Uplink (to Tower)	0.7	34.7	360	0.0833	22.135	3.0029
Phobos Relay Uplink (to Tower)	0.7	3.4	180	0.1667	44.135	3.0579
Phobos Relays Downlink (to Pods, Hoppers)	0.7	1.5	180	0.1667	88.135	30.0787
Relays (Nav)	1.5754	0.00041	180	0.0741	0.0048	3.0387

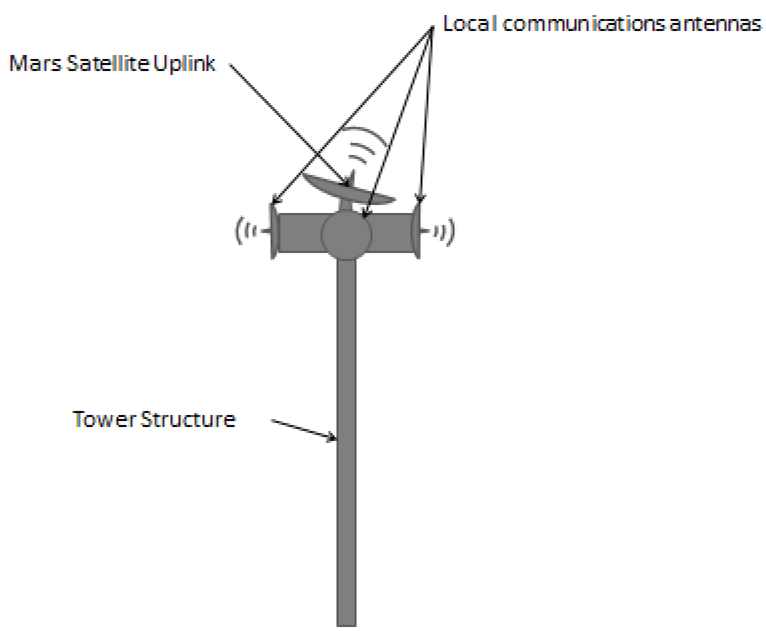
References

[1] *Phobos: Overview*. (2012, April 24). Retrieved February 28, 2013, from Solar System Exploration: http://solarsystem.nasa.gov/planets/profile.cfm?Object=Mar_Phobos

6.14 Mars Builders Communications

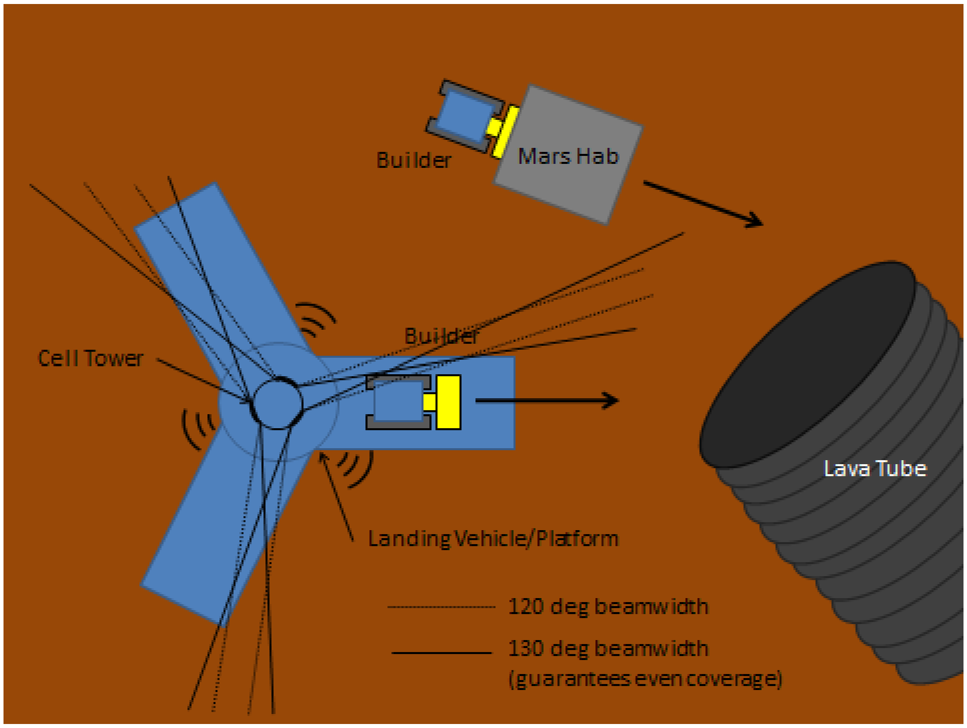
In order to place the Mars Hab in the lava tube safely for future crews, we designed teleoperated builders to land on Mars. The astronauts on Phobos operate the Mars Builders remotely to set up the Mars landing site for future crews, fulfilling their main mission objective.

Since the Mars Builders require continuous two-way communication with Phobos, we designed a dish antenna to communicate with the Mars Satellites mounted on top of a cell phone tower, which relays data to and from the Mars Builders (Fig. 6.14.1). The Mars builders will also have continuous HDTV capability for the crew to have a detailed view during normal operations and in case of repair.



6.14.1: Schematic of Mars tower with Mars Satellite uplink dish antenna and local communications dish antennas

The Mars Entry Vehicle delivers the Mars Builders and communications tower to the surface. After the Mars Builders are deployed, the tower will extend to a height of 24 m and the astronauts will be able to control and guide the Mars Builders to the lava tube (Fig. 6.14.2). The signal will be transmitted from dish antennas on the tower with 130 deg beamwidth.

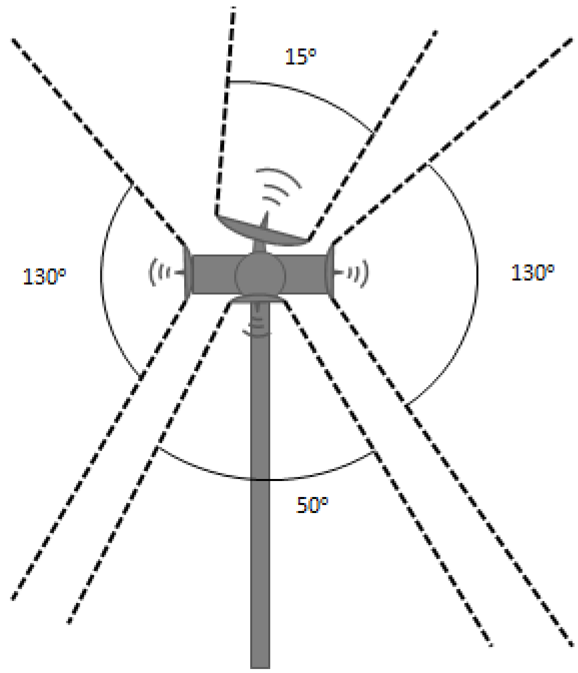


6.14.2: Top-down view schematic of Mars communications tower and Mars Builders; note difference in coverage of 120 deg vs 130 deg beamwidth

The beamwidth of the cell phone tower antennas was chosen based on power requirements. An omnidirectional antenna requires more power than a 120 deg beamwidth antenna, and the relationship is not linear. That is, three 120 deg beamwidth antennas will consume less power than one 360 deg beamwidth antenna. We chose a 130 deg beamwidth antenna for three reasons:

- Overlapping transmission areas guarantee consistent signal strength in all directions
- The antennas are not all transmitting from the same point – there is some space between them where they mount at the top of the tower.

In addition to communicating horizontally with the Mars Builders, the tower must communicate with the Mars Builders before they roll off the pad. To accomplish this, a 50 deg beamwidth antenna points down from the top of the tower at the platform where the Mars Builders sit until they roll out (Fig. 6.14.3).



6.14.3: Diagram showing area swept out by antenna beamwidths for communications tower at Mars landing site ensuring successful signal transmission to and from Mars Builders during initial roll out

The height of the Mars tower is based on [1]. The complete range should be accessible in case the entry vehicle lands up to 20 km from its intended target.

In case signals cannot reach the Mars Builders inside the lava tube, there is a relay that can establish a connection between the Builders inside the lava tube and the communications tower. The Mars builders deliver the relay to the point where the signal becomes weak near the entry point of the lava tube and continue to communicate with the tower through the relay after going down the ramp to deliver the Mars Hab.

Since the Mars Science Laboratory landed within 20 km of its target [2-3], and precision pinpoint landing is expected to be developed in some the near future, we assumed that the entry vehicle delivering the Mars Builders to the surface, landing within 20 km of the lava tube and Mars Hab. Communications hardware specifications for all vehicles landing on Mars are listed in Table 6.14.1.

6.14.1: Mars communications tower, Mars Entry Vehicle, Mars Builders, and relay communications specifications

Link	Frequency, GHz	Power, W	Transmit Beamwidth, deg	Transmit Antenna Diameter, m	Data Rate, Mbps	Margin, dB
Mars Tower Uplink (to Mars)	20.9	12.6	15	1	22.135	3.001
Mars Entry Vehicle Uplink [TM] (to Mars Satellites)	20.9	0.066	360	0.0028	0.0002	3.0995
Mars Tower Downlink (to Builders)	0.7	7	130	0.2308	44.135	3.4671
Mars Tower Downlink (to Builders - short range)	0.7	1.34E-06	50	0.6	44.135	3.003
Mars Builders Uplink (to Tower)	0.7	14	360	0.0833	22.135	3.1093
Mars Relay Uplink (to Tower)	0.7	66.1	180	0.0833	44.135	3.1986
Mars Relay Downlink (to Builders)	0.7	0.00064	180	0.1667	44.135	3.0578

The crew lives in the Phobos Hab, and traverses Phobos in the Pods. The crew also remotely pilots the Hoppers. The purpose of the Pods and Hoppers is for the crew to collect regolith for radiation shielding and to perform any science missions added during development.

References

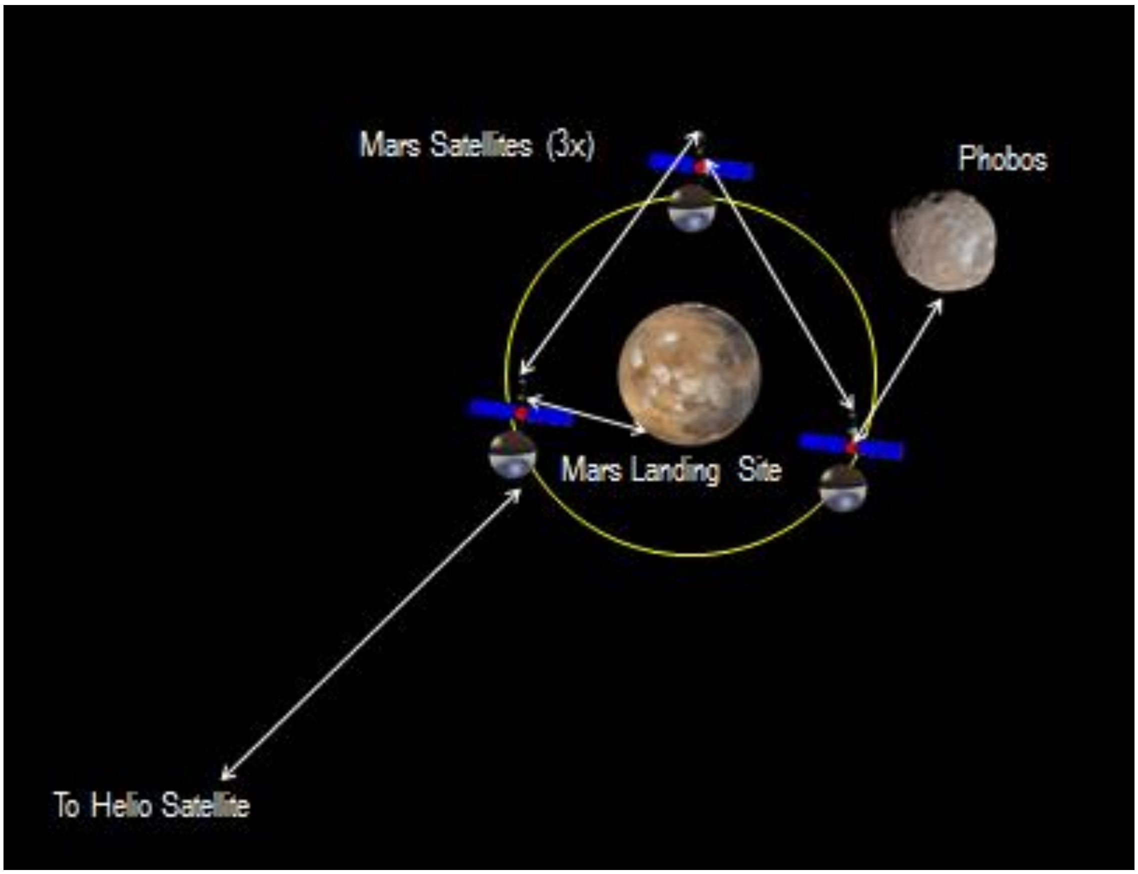
[1] Rajaraman, R. (2010). *CS 6710: Wireless Networks*. Retrieved February 28, 2013, from Northwestern University College of Computer Science: https://docs.google.com/viewer?a=v&q=cache:_UVIsqO6tuUJ:www.ccs.neu.edu/home/rraj/Courses/6710/S10/Lectures/AntennasPropagation.pdf+&hl=en&gl=us&pid=bl&srcid=ADGEESjl1MljUD0vPNj_ZXtPIySP8dX2GTczYKV2_RwPRw7rSQtezi7tqKEcAy2XrhXztIlIHN9XniAG7AkQ_BpZF-RP_NSl8

[2] *Entry, Descent, and Landing*. (n.d.). Retrieved February 28, 2013, from Jet Propulsion Laboratory, California Institute of Technology: http://mars.jpl.nasa.gov/msl/mission/timeline/edl/

[3] Webster, G. (2012, June 11). *NASA Mars Rover Team Aims for Landing Closer to Prime Science Site*. Retrieved February 28, 2013, from NASA/JPL: http://www.nasa.gov/mission_pages/msl/news/msl20120611.html

8.12 Mars Satellites Communications

There are three communications satellites in orbit around Mars, which serve as relays between Mars, Phobos, and the Helio satellite. The Mars Satellites are necessary to maintain communication between all three points in space when direct line of site is unavailable (e.g. when Phobos is on the other side of Mars from Mars Builders/Hab). Figure 8.12.1 shows the link schematic for Helio, Mars, and Phobos.



8.12.1: Link schematic for Helio-Mars-Phobos communications links

The Mars satellites each have three dish antennas to communicate with Mars, Phobos, and the Helio satellite. The dish specifications are shown in Table 8.12.1.

8.12.1: Mars Satellite Antenna specifications

Link	Frequency, GHz	Power, W	Transmit Beamwidth, deg	Transmit Antenna Diameter, m	Data Rate, Mbps	Margin, dB
Mars Satellite Crosslink	60	47000	15	0.35	110.135	3.6175
Mars Satellite Downlink (to Phobos Hab crewed)	1.4	129	15	1	110.1125	3.0254
Mars Satellite Downlink (to Mars)	1.4	5.6	15	1	44.135	3.0305

The reason for such a narrow beamwidth is that the power requirements for such a high data rate at such a high frequency are much greater if we want to send a signal over a wider area. We chose the pointing error for the satellites based on the Attitude Control team's ability to provide 5 arcseconds accuracy. A tighter pointing error also results in a lower power requirement, so the largest pointing error for an interplanetary mission we found was a good starting point for designing these dishes. These pointing errors also apply to vehicles operating within the vicinity of Mars and Phobos.

12.129 Communications Overview

Nomenclature

P	= power, W
G	= gain, dB
θ	= beamwidth, deg
D	= dish diameter, m
F	= frequency, GHz
L_θ	= pointing loss, dB
L_s	= propagation loss, dB
η	= efficiency
$el\theta$	= pointing error
$implem\_loss$	= implementation loss, dB
$margin$	= signal margin, dB
$\frac{E_b}{N_0}$	= energy per bit to noise power spectral density ratio, dB-Hz
$\frac{E_b}{N_{0req}}$	= required energy per bit to noise power spectral density ratio, dB-Hz

We require continuous (uninterrupted) 2-way video (HDTV) communications must be maintained between each of the astronauts and Earth. In order to ensure that uncrewed vehicles would reach their intended targets, we also used a 200 bps data rate for telemetry.

This section presents an overview of our algorithm and preliminary analysis. The sections following contain the resulting communications design for the Mars Satellites, Pods and Hoppers, and Phobos Hab.

The algorithm we used was provided by Professor Filmer. Using frequency, power, pointing errors, propagation path length, data rate, and bit error rate as inputs, the algorithm calculates the signal margin. A margin of 3 dB is required for the signal to be detected at the receiver.

The algorithm uses power in dB, and converts it by Equation 1.

$$P = 10\log_{10}(P) \qquad \textbf{Equation 1}$$

Peak transmit antenna gain is calculated as follows.

$$G = 44.3 - 20\log(\theta) \qquad \textbf{Equation 2}$$

Dish diameter is calculated in Equation 3.

$$D = 21/(f_{GHz}\theta) \qquad \textbf{Equation 3}$$

Pointing loss is calculated from pointing error:

$$L_\theta = -12(el\theta)^2$$ **Equation 4**

Frequency and propagation length are input to equation 5 to determine pace propagation loss .

$$L_s = 147.55 - 20\log S - 20 log f$$ **Equation 5**

Peak receive antenna gain is calculated from equation 6.

$$G = -159.59 + 20logD + 20logf + 10log\eta$$ **Equation 6**

Using power, line loss, transmit antenna gain, receiver pointing loss, propagation and polarization loss, receiver gain, system noise temperature, and bit rate, energy per bit to noise power spectral density ratio is calculated.

$$E_b/N_o = P + L_l + G_t + L_{pr} + L_s + L_a + G_r + 228.6 - 10logT - 10logR$$ **Equation 7**

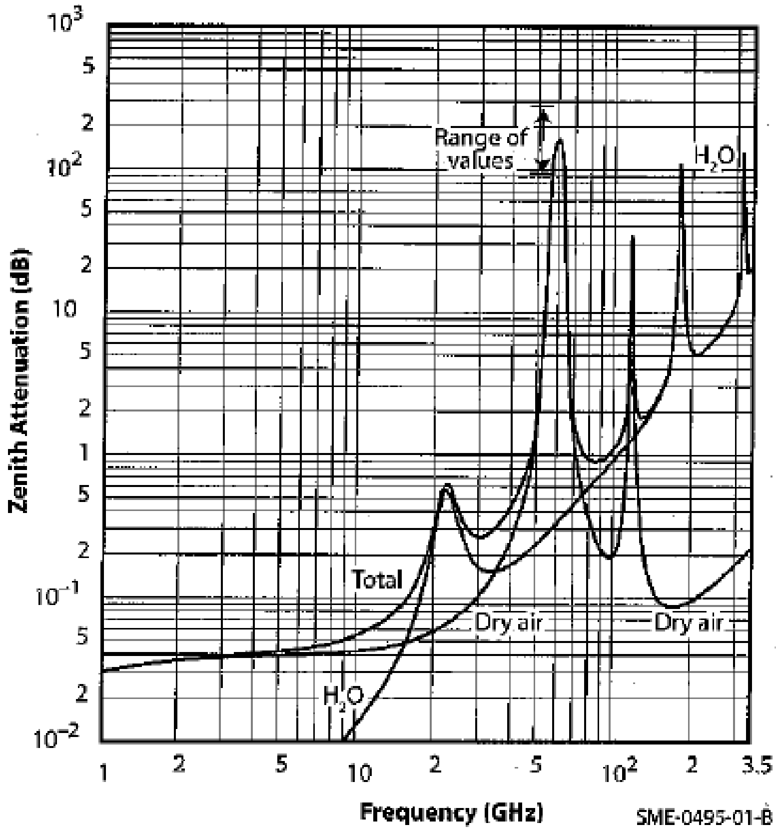
Equivalent isotropic radiated power can also be determined by equation 8.

$$EIRP = P + L_l + G_t$$ **Equation 8**

Finally, margin is calculated.

$$margin = \frac{E_b}{N_0} - \frac{E_b}{N_{0_{req}}} + implem\_loss$$ **Equation 9**

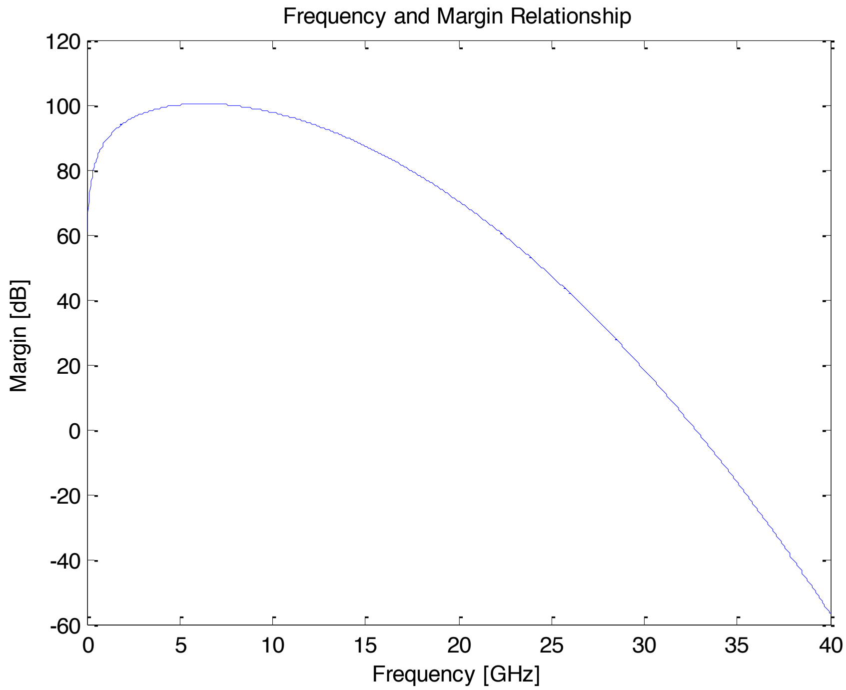
We chose polarization and propagation loss based on Fig. 12.129.1. We chose the most conservative value of -0.6 dB for transmissions that traveled through an atmosphere.



12.129.1: Polarization and propagation loss vs. frequency for various gases

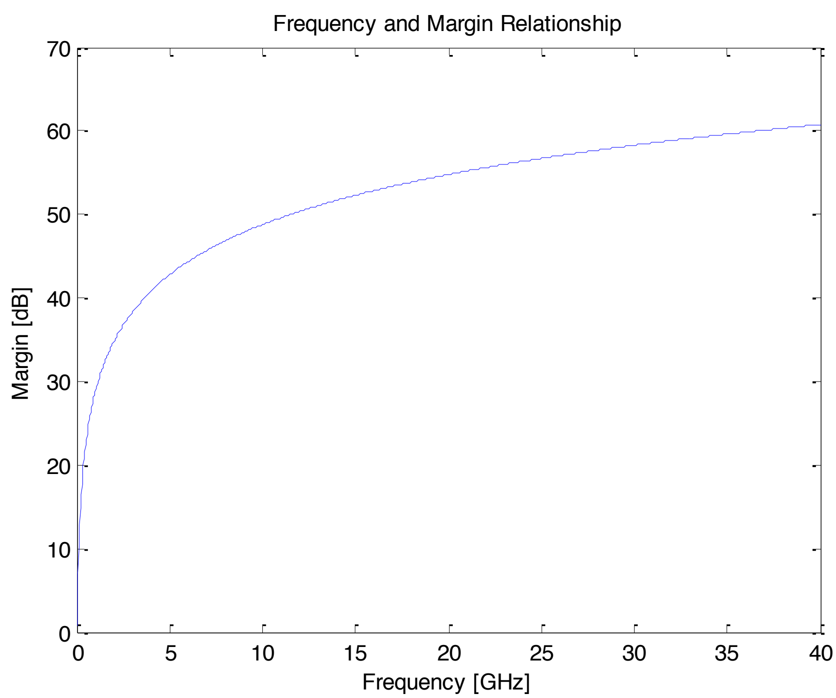
Omnidirectional antennas were given a transmitting and receiving pointing error of zero. Pointing error and beamwidth are directly proportional to power; an increase in pointing error or beamwidth will increase power. The relationship is nonlinear, so adding antennas to cover a wider area will require less power than a single antenna to cover the same area.

The margin peaks in the frequency range (Fig. 12.129.2) and drops off for higher frequencies. We considered this relationship when selecting short range frequencies, but kept with convention for satellite frequencies for longer range transmissions.



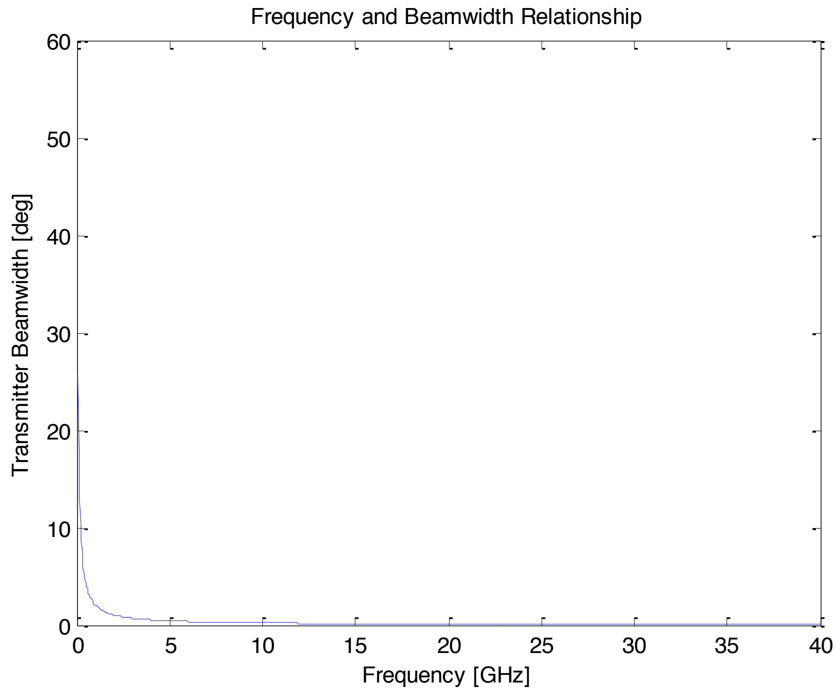
12.129.2: Frequency selection based on location of peak margin

For smaller transmitter and receiver dish sizes, higher frequencies yield higher margin (Fig. 12.129.2).



12.129.3: Frequency vs margin plot showing margin increasing with frequency for dishes of 1 m (transmitter) and 10 m (receiver)

The relationship between frequency and beamwidth is inversely proportional (Fig. 12.129.4), so for higher frequencies and longer ranges, (e.g. Mars and Helio Satellites), more precise attitude control is required.



12.129.4: Plot showing inverse relationship between frequency and transmitter beamwidth

References

[5] Filmer, D. (n.d.). Untitled. Unpublished manuscript, Purdue University, West Lafayette, IN. Link Budget Calculations

Antenna specifications

12.129.1: Antenna specifications for Mars Satellites, Mars Builders, Phobos Hab, Phobos Pods, Phobos Hoppers, and corresponding relay systems

	Frequency, GHz	Power, W	Transmitter Line Loss, dB	Transmit Beamwidth, deg	Transmit Antenna Diameter, m
Mars Satellite Crosslink	60	47000	-1	1	0.35
Mars Satellite Downlink (to Phobos Hab crewed)	1.4	129	-1	15	1
Mars Satellite Downlink (to Mars)	1.4	5.6	-1	15	1
Mars Tower Uplink (to Mars)	20.9	12.6	-1	15	1
Mars Entry Vehicle Uplink [TM] (to Mars Satellites)	20.9	0.066	-1	360	0.0028
Mars Tower Downlink (to Builders)	0.7	7	-1	130	0.2308
Mars Tower Downlink (to Builders - short range)	0.7	1.34E-06	-1	50	0.6
Mars Builders Uplink (to Tower)	0.7	14	-1	360	0.0833
Mars Relay Uplink (to Tower)	0.7	66.1	-1	180	0.0833
Mars Relay Downlink (to Builders)	0.7	0.00064	-1	180	0.1667
Phobos Cargo [Autonomous TM] Uplink (to Mars Satellites)	1.4	0.602	-1	360	0.0417
Phobos Tower [Crewed] Uplink (to Mars Satellites)	1.4	584	-1	1	15
Phobos Tower Downlink (to Pods, Hoppers)	0.7	30.4	-1	130	0.2308
Phobos Pods, Hoppers Uplink (to Tower)	0.7	34.7	-1	360	0.0833
Phobos Relay Uplink (to Tower)	0.7	3.4	-1	180	0.1667
Phobos Relays Downlink (to Pods, Hoppers)	0.7	1.5	-1	180	0.1667
Relays (Nav)	1.5754	0.00041	-1	180	0.0741

12.129.2: Antenna specifications for Mars Satellites, Mars Builders, Phobos Hab, Phobos Pods, Phobos Hoppers, and corresponding relay systems (continued)

	Peak Transmit Antenna Gain, dB	Transmit Antenna Pointing Error, deg	Receiver Beamwidth, deg	Receiver Antenna Diameter, m
Mars Satellite Crosslink	53.4186	0.02	0.35	1
Mars Satellite Downlink (to Phobos Hab crewed)	20.7782	1.15	15	1
Mars Satellite Downlink (to Mars)	20.7782	1.15	15	1
Mars Tower Uplink (to Mars)	20.7782	1.15	15	1
Mars Entry Vehicle Uplink [TM] (to Mars Satellites)	-6.8261	0	15	1
Mars Tower Downlink (to Builders)	2.0211	0	360	0.2308
Mars Tower Downlink (to Builders - short range)	10.3206	0	360	0.2308
Mars Builders Uplink (to Tower)	-6.8261	0	130	0.2308
Mars Relay Uplink (to Tower)	-0.8055	0	130	0.2308
Mars Relay Downlink (to Builders)	-0.8055	0	360	0.2308
Phobos Cargo [Autonomous TM] Uplink (to Mars Satellites)	-6.8261	1.15	15	1
Phobos Tower [Crewed] Uplink (to Mars Satellites)	20.7782	1.15	15	1
Phobos Tower Downlink (to Pods, Hoppers)	2.0211	0	360	0.0833
Phobos Pods, Hoppers Uplink (to Tower)	-6.8261	0	0.2308	0.2308
Phobos Relay Uplink (to Tower)	-0.8055	0	180	0.1667
Phobos Relays Downlink (to Pods, Hoppers)	-0.8055	0	180	0.1667
Relays (Nav)	0.0741	0	180	0.0741

12.129.3: Antenna specifications for Mars Satellites, Mars Builders, Phobos Hab, Phobos Pods, Phobos Hoppers, and corresponding relay systems (continued)

	Receiver Antenna Pointing Error, deg	Transmit Antenna Pointing Loss, dB	Transmit Antenna Gain, dB
Mars Satellite Crosslink	0.02	-0.0392	53.3795
Mars Satellite Downlink (to Phobos Hab crewed)	1.15	-0.0705	20.7076
Mars Satellite Downlink (to Mars)	1.15	-0.0705	20.7076
Mars Tower Uplink (to Mars)	1.15	-0.0705	20.7076
Mars Entry Vehicle Uplink [TM] (to Mars Satellites)	1.15	-0.00012245	-0.68262
Mars Tower Downlink (to Builders)	0	0	2.0211
Mars Tower Downlink (to Builders - short range)	0	0	10.3206
Mars Builders Uplink (to Tower)	0	0	-6.8261
Mars Relay Uplink (to Tower)	0	0	-0.8055
Mars Relay Downlink (to Builders)	0	0	-0.8055
Phobos Cargo [Autonomous TM] Uplink (to Mars Satellites)	1.15	-0.00012245	-6.8262
Phobos Tower [Crewed] Uplink (to Mars Satellites)	1.15	-0.0705	20.7076
Phobos Tower Downlink (to Pods, Hoppers)	0	0	2.0211
Phobos Pods, Hoppers Uplink (to Tower)	0	0	-6.8261
Phobos Relay Uplink (to Tower)	0	0	-0.8055
Phobos Relays Downlink (to Pods, Hoppers)	0	0	-0.8055
Relays (Nav)	0	0	-0.8055

12.129.4: Antenna specifications for Mars Satellites, Mars Builders, Phobos Hab, Phobos Pods, Phobos Hoppers, and corresponding relay systems (continued)

	Equivalent Isentropic Radiated Power, dBW	Propagation Path Length, km	Space Loss, dB	Propagation and Polarization Loss, dB
Mars Satellite Crosslink	99.1004	2822000	-257.0240	0
Mars Satellite Downlink (to Phobos Hab crewed)	40.8135	8212	-173.6620	0
Mars Satellite Downlink (to Mars)	27.1895	2512	-163.3730	-0.06
Mars Tower Uplink (to Mars)	30.7113	2512	-186.8530	-0.6
Mars Entry Vehicle Uplink [TM] (to Mars Satellites)	-19.6307	2512	-186.8530	-0.6
Mars Tower Downlink (to Builders)	9.4721	20	-115.3730	-0.6
Mars Tower Downlink (to Builders - short range)	-49.4084	0.024	-56.9562	-0.6
Mars Builders Uplink (to Tower)	3.6352	20	-115.3730	-0.6
Mars Relay Uplink (to Tower)	16.3966	44	-122.2210	-0.6
Mars Relay Downlink (to Builders)	-33.7437	0.145	-72.5793	-0.6
Phobos Cargo [Autonomous TM] Uplink (to Mars Satellites)	-10.0102	8212	-173.6620	0
Phobos Tower [Crewed] Uplink (to Mars Satellites)	47.3718	8212	-173.6620	0
Phobos Tower Downlink (to Pods, Hoppers)	15.8499	10	-122.2210	0
Phobos Pods, Hoppers Uplink (to Tower)	7.5772	10	-122.2210	0
Phobos Relay Uplink (to Tower)	3.5093	14	-112.2750	0
Phobos Relays Downlink (to Pods, Hoppers)	-0.0445	14	-112.2750	0
Relays (Nav)	-35.6776	14	-119.3210	0

12.129.5: Antenna specifications for Mars Satellites, Mars Builders, Phobos Hab, Phobos Pods, Phobos Hoppers, and corresponding relay systems (continued)

	Peak Receiver Antenna Gain, dB	Receiver Antenna Pointing Loss, dB	Receiver Antenna Gain, dBi	System Noise Temperature, K	Data Rate, Mbps
Mars Satellite Crosslink	53.3767	-0.0392	53.3375	682	110.1350
Mars Satellite Downlink (to Phobos Hab crewed)	20.7362	-0.0705	20.6657	135	110.1350
Mars Satellite Downlink (to Mars)	20.7362	-0.0705	20.6657	135	44.1350
Mars Tower Uplink (to Mars)	44.2166	-0.0705	44.146	614	22.1350
Mars Entry Vehicle Uplink [TM] (to Mars Satellites)	44.2166	-0.0705	44.1460	614	0.0002
Mars Tower Downlink (to Builders)	-6.8680	0	-6.8680	135	44.1350
Mars Tower Downlink (to Builders - short range)	-6.8680	0	-6.8680	135	44.1350
Mars Builders Uplink (to Tower)	1.9791	0	1.9791	614	22.1350
Mars Relay Uplink (to Tower)	-0.8474	0	-0.8474	614	44.1350
Mars Relay Downlink (to Builders)	-6.8680	0	-6.8680	135	44.1350
Phobos Cargo [Autonomous TM] Uplink (to Mars Satellites)	20.7362	-0.0705	20.6657	614	0.0002
Phobos Tower [Crewed] Uplink (to Mars Satellites)	20.7362	20.73	20.6657	614	110.1350
Phobos Tower Downlink (to Pods, Hoppers)	-6.8680	0	-6.8680	135	88.1350
Phobos Pods, Hoppers Uplink (to Tower)	1.9791	0	1.9791	614	22.1350
Phobos Relay Uplink (to Tower)	-0.8474	0	-0.8474	614	44.1350
Phobos Relays Downlink (to Pods, Hoppers)	-0.8474	0	-0.08474	135	88.1350
Relays (Nav)	-0.8474	0	-0.8474	135	0.0048

12.129.6: Antenna specifications for Mars Satellites, Mars Builders, Phobos Hab, Phobos Pods, Phobos Hoppers, and corresponding relay systems (continued)

	Eb/N0, dB	Carrier Signal-to-noise RatiodB-Hz	Bit Error Rate, --	Required Eb/N0, dB	Implementation Loss, dB	Margin, dB
Mars Satellite Crosslink	15.2175	95.6368	0.00001	9.6	-2	3.6175
Mars Satellite Downlink (to Phobos Hab crewed)	14.6254	95.0438	0.00001	9.6	-2	3.0254
Mars Satellite Downlink (to Mars)	14.6605	91.1084	0.00001	9.6	-2	3.0305
Mars Tower Uplink (to Mars)	14.6010	88.0518	0.00001	9.6	-2	3.0010
Mars Entry Vehicle Uplink [TM] (to Mars Satellites)	14.6995	37.7098	0.00001	9.6	-2	3.0995
Mars Tower Downlink (to Builders)	17.4671	93.9282	0.00001	12	-2	3.4671
Mars Tower Downlink (to Builders - short range)	17.0030	93.4641	0.00001	12	-2	3.0030
Mars Builders Uplink (to Tower)	17.1093	90.5601	0.00001	12	-2	3.1093
Mars Relay Uplink (to Tower)	17.1986	93.6464	0.00001	12	-2	3.1986
Mars Relay Downlink (to Builders)	17.0578	93.5057	0.00001	12	-2	3.0578
Phobos Cargo [Autonomous TM] Uplink (to Mars Satellites)	14.6114	95.0237	0.00001	9.6	-2	3.0114
Phobos Tower [Crewed] Uplink (to Mars Satellites)	14.6053	95.0237	0.00001	9.6	-2	3.0053
Phobos Tower Downlink (to Pods, Hoppers)	14.6060	94.0575	0.00001	9.6	-2	3.0060
Phobos Pods, Hoppers Uplink (to Tower)	14.6029	88.0537	0.00001	9.6	-2	3.0029
Phobos Relay Uplink (to Tower)	14.6579	91.1057	0.00001	9.6	-2	3.0579
Phobos Relays Downlink (to Pods, Hoppers)	14.6787	94.1302	0.00001	9.6	-2	30.0787
Relays (Nav)	14.6387	51.4511	0.00001	9.6	-2	3.0387

Antenna Dimensions

12.129.7: Antenna dimensions for Phobos tower, Phobos Pods/Hoppers, Phobos relays, Mars Satellites, Mars tower, Mars builders, and Phobos Hab TM communications

	Mass, kg	Depth, m	Volume, m^3
Phobos Tower Uplink Antenna (to Mars Satellites)	15.3171	0.6599	0.0057
Phobos Tower Downlink Antenna (to Pods, Hoppers)	10.9038	0.0207	0.004
Phobos Pods Uplink Antenna (to Phobos Tower)	0.1219	0.8034	0.00004515
Phobos Relay Downlink Antenna (to Pods [NAV])	2.1934	0.0008127	17.532
Phobos Relay Uplink Antenna (to Relay)	1.8446	0.00068346	0.0443
Phobos Relay Downlink Antenna (to Pods)	2.1503	0.00079675	5.4657
Mars Satellite Downlink Antenna (to Mars)	39.0999	2.068	0.0145
Mars Satellite Downlink Antenna (to Phobos)	39.0999	2.068	0.0145
Mars Satellite Crosslink Antenna (to Mars Satellite)	39.0999	2.068	0.0145
Mars Satellite Crosslink Antenna (to Helio satellite)	554.891	2.0898	0.2451
Mars Tower Uplink Antenna (to Mars Satellite)	1.5483	0.6637	0.00057367
Mars Builder Uplink Antenna (to Tower)	0.6886	4.8779	0.00025515
Mars Tower Downlink Antenna (to Builders)	10.9038	0.0207	0.004
Mars Tower Downlink Antenna (to Builders, initial roll-out)	0.0245	9.0929E-06	2.262
Phobos Hab TM Uplink Antenna (to Mars Satellite)	1.0871	0.0234	0.00040281

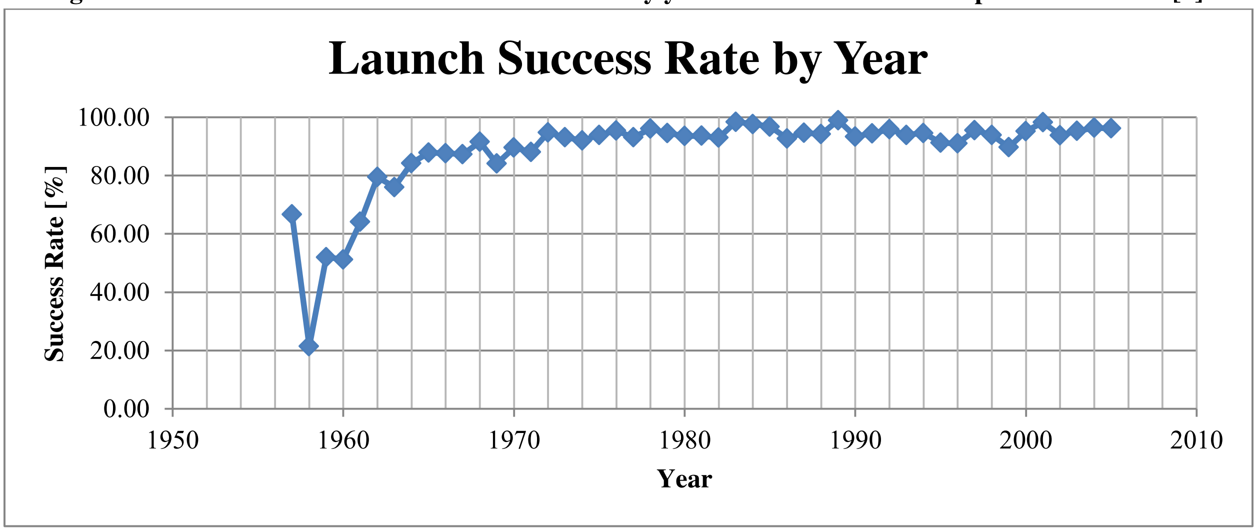
12.166 Risk Assessment

Table 12.166.1: Historical launch vehicle statistics by year since the first orbital spacecraft launch.[1}

Year	LV Failures	Total Launches	Success Rate [%]
1957	1	3	66.67
1958	22	28	21.43
1959	12	25	52
1960	20	41	51.22
1961	19	53	64.15
1962	17	83	79.52
1963	17	71	76.06
1964	16	102	84.31
1965	16	132	87.88
1966	17	138	87.68
1967	18	142	87.32
1968	11	131	91.6
1969	20	126	84.13
1970	13	125	89.6
1971	16	135	88.15
1972	6	115	94.78
1973	8	117	93.16
1974	9	113	92.04
1975	8	132	93.94
1976	6	132	95.45
1977	9	131	93.13
1978	5	128	96.09
1979	6	111	94.59
1980	7	109	93.58
1981	8	127	93.7
1982	9	129	93.02
1983	2	129	98.45
1984	3	129	97.67
1985	4	126	96.83
1986	8	110	92.73
1987	6	114	94.74
1988	7	121	94.21
1989	1	102	99.02
1990	8	121	93.39
1991	5	91	94.51
1992	4	97	95.88
1993	5	83	93.98

1994	5	93	94.62
1995	7	80	91.25
1996	7	78	91.03
1997	4	90	95.56
1998	5	83	93.98
1999	8	78	89.74
2000	4	85	95.29
2001	1	59	98.31
2002	4	65	93.85
2003	3	64	95.31
2004	2	56	96.43
2005	2	53	96.23

Figure 12.166.1: Historical launch vehicle statistics by year since the first orbital spacecraft launch.[1]



References

[1] Astronautix, (n.d.), "Launch Vehicle Launch Log". Retrieved January 23rd 2013, from http://www.astronautix.com/data/index.htm

12.167 Detailed Analysis of the Unmanned Spacecraft Subsystem Cost Model

The Unmanned Spacecraft Subsystem Cost Model requires inputs for each subsystem, or vehicle in our case, and uses constants provided through linear regression of past space missions to complete the model and provide a total mission cost. The inputs for each vehicle can be seen below in tables 12.167.1 – 12.167.7.

Table 12.167.1: Cycler Vehicle Subsystem Cost

Cycler Vehicle Subsystem Cost									
TOTAL COST:	$ 79,249 mil								
Attitude Control/COM									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	9.674
X_1	Mass	8265.4	kg	16.06	13.6	48.1	1.9	b_1	0.2428
X_2	Data Rate	22157.5	kbps	60.63	149	600	0	b_2	0.0064
X_3	Pointing	144	arcsec	327	302	900	5	b_3	-0.004
Y	$ 2,158	million							
Propulsion									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	-12.8
X_1	Mass	1432000	kg	72.9	59	220.1	7.4	b_1	0.05376
X_2	Ln Isp	9.567805	-	6.1	1	8.2	5.4	b_2	3.202
Y	$ 77,002	million							
Structures/Mechanical Build Up									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.833
X_1	Mass	464000	kg	136	71	337	14	b_1	0.01
Y	$ 4,642	million							
Thermal									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.817
X_1	Redundancy	0.8	-	0.8	0.4	1	0	b_1	1.068
X_2	Active/Passive	1	-	0.1	0.3	1	0	b_2	4.255
Y	$ 7	million							
Power									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	5.08
X_1	Rad Dosage	4000	krads	349	972	4000	5	b_1	0.002
X_2	AMTEC	200	ordinal	21.9	58.5	200	0	b_2	0.1579
X_3	Adv Si	10500	ordinal	2038	3198	10500	0	b_3	0.001
X_4	GsAs/HT	4600	ordinal	304	1110	4600	0	b_4	0.002
X_5	GaAs	7900	ordinal	553	1900	7900	0	b_5	0.0022
Y	$ 82	million							

Table 12.167.2: Phobos Hab Subsystem Cost

Phobos Hab Vehicle Subsystem Cost										
TOTAL COST:		$ 2,043	million							
Attitude Control										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	9.674	
X_1	Mass	400	kg	16.06	13.6	48.1	1.9	b_1	0.2428	
X_2	Data Rate	111000	kbps	60.63	149	600	0	b_2	0.0064	
X_3	Pointing	54000	arcsec	327	302	900	5	b_3	-0.004	
Y	$ 601	million								
Propulsion										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	-12.8	
X_1	Mass	25000	kg	72.9	59	220.1	7.4	b_1	0.05376	
X_2	Ln Isp	6.884405	-	6.1	1	8.2	5.4	b_2	3.202	
Y	$ 1,353	million								
Structures/Mechanical Build Up										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	1.833	
X_1	Mass	71.28	kg	136	71	337	14	b_1	0.01	
Y	$ 3	million								
Thermal										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	1.817	
X_1	Redundancy	0.8	-	0.8	0.4	1	0	b_1	1.068	
X_2	Active/Passive	1	-	0.1	0.3	1	0	b_2	4.255	
Y	$ 7	million								
Power										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	5.08	
X_1	Rad Dosage	4000	krads	349	972	4000	5	b_1	0.002	
X_2	AMTEC	200	ordinal	21.9	58.5	200	0	b_2	0.1579	
X_3	Adv Si	10500	ordinal	2038	3198	10500	0	b_3	0.001	
X_4	GsAs/HT	4600	ordinal	304	1110	4600	0	b_4	0.002	
X_5	GaAs	7900	ordinal	553	1900	7900	0	b_5	0.0022	
Y	$ 82	million								

Table 12.167.3: Mars Builders Subsystem Cost

Mars Builders Subsystem Cost									
TOTAL COST:		$ 1,807	million						
Attitude Control									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	9.674
X_1	Mass	15.3	kg	16.06	13.6	48.1	1.9	b_1	0.2428
X_2	Data Rate	91000	kbps	60.63	149	600	0	b_2	0.0064
X_3	Pointing	54000	arcsec	327	302	900	5	b_3	-0.004
Y	$ 380	million							
Propulsion									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	-12.8
X_1	Mass	24800	kg	72.9	59	220.1	7.4	b_1	0.05376
X_2	Ln Isp	5.71373	-	6.1	1	8.2	5.4	b_2	3.202
Y	$ 1,339	million							
Structures/Mechanical Build Up									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.833
X_1	Mass	99250	kg	136	71	337	14	b_1	0.01
Y	$ 994	million							
Thermal									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.817
X_1	Redundancy	0.8	-	0.8	0.4	1	0	b_1	1.068
X_2	Active/Passive	1	-	0.1	0.3	1	0	b_2	4.255
Y	$ 7	million							
Power									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	5.08
X_1	Rad Dosage	4000	krads	349	972	4000	5	b_1	0.002
X_2	AMTEC	200	ordinal	21.9	58.5	200	0	b_2	0.1579
X_3	Adv Si	10500	ordinal	2038	3198	10500	0	b_3	0.001
X_4	GsAs/HT	4600	ordinal	304	1110	4600	0	b_4	0.002
X_5	GaAs	7900	ordinal	553	1900	7900	0	b_5	0.0022
Y	$ 82	million							

Table 12.167.4: Pods and Hoppers Subsystem Cost

Pods and Hoppers Subsystem Cost										
TOTAL COST:		$ 6,708	million							
Attitude Control										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	9.674
X_1	Mass	15.3	kg	16.06	13.6	48.1	1.9	b_1	0.2428
X_2	Data Rate	223000	kbps	60.63	149	600	0	b_2	0.0064
X_3	Pointing	5400	arcsec	327	302	900	5	b_3	-0.004
Y	1419.0	million							
Propulsion										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	-12.8
X_1	Mass	96706.178	kg	72.9	59	220.1	7.4	b_1	0.05376
X_2	Ln Isp	5.669880923	-	6.1	1	8.2	5.4	b_2	3.202
Y	5204.3	million							
Structures/Mechanical Build Up										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	1.833
X_1	Mass	3920	kg	136	71	337	14	b_1	0.01
Y	41.033	million							
Thermal										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	1.817
X_1	Redundancy	0.8	-	0.8	0.4	1	0	b_1	1.068
X_2	Active/Passive	0	-	0.1	0.3	1	0	b_2	4.255
Y	$ 3	million							
Power										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	5.08
X_1	Rad Dosage	4000	krads	349	972	4000	5	b_1	0.002
X_2	AMTEC	200	ordinal	21.9	58.5	200	0	b_2	0.1579
X_3	Adv Si	10500	ordinal	2038	3198	10500	0	b_3	0.001
X_4	GsAs/HT	4600	ordinal	304	1110	4600	0	b_4	0.002
X_5	GaAs	7900	ordinal	553	1900	7900	0	b_5	0.0022
Y	$ 82	million							

Table 12.167.5: Crew Transfer Vehicle Subsystem Cost

Crew Transfer Vehicle Subsystem Cost									
TOTAL COST:		$ 5,131	million						
				Attitude Control					
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	9.674
X_1	Mass		kg	16.06	13.6	48.1	1.9	b_1	0.2428
X_2	Data Rate		kbps	60.63	149	600	0	b_2	0.0064
X_3	Pointing		arcsec	327	302	900	5	b_3	-0.004
Y	$	10	million						
				Propulsion					
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	-12.8
X_1	Mass	93500	kg	72.9	59	220.1	7.4	b_1	0.05376
X_2	Ln Isp	5.940171	-	6.1	1	8.2	5.4	b_2	3.202
Y	$	5,033	million						
				Structures/Mechanical Build Up					
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.833
X_1	Mass	6600	kg	136	71	337	14	b_1	0.01
Y	$	68	million						
				Thermal					
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.817
X_1	Redundancy	0.8	-	0.8	0.4	1	0	b_1	1.068
X_2	Active/Passive	1	-	0.1	0.3	1	0	b_2	4.255
Y	$	7	million						
				Power					
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	5.08
X_1	Rad Dosage	4000	krads	349	972	4000	5	b_1	0.002
X_2	AMTEC	200	ordinal	21.9	58.5	200	0	b_2	0.1579
X_3	Adv Si	10500	ordinal	2038	3198	10500	0	b_3	0.001
X_4	GsAs/HT	4600	ordinal	304	1110	4600	0	b_4	0.002
X_5	GaAs	7900	ordinal	553	1900	7900	0	b_5	0.0022
Y	$	82	million						

Table 12.167.6: Communication Satellites Subsystem Cost

Communication Satellites Subsystem Cost										
TOTAL COST:		$ 1,804	million							
Attitude Control										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	9.674	
X_1	Mass	165	kg	16.06	13.6	48.1	1.9	b_1	0.2428	
X_2	Data Rate	225000	kbps	60.63	149	600	0	b_2	0.0064	
X_3	Pointing	414	arcsec	327	302	900	5	b_3	-0.004	
Y	$	1,488	million							
Propulsion										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	-12.8	
X_1	Mass	5818	kg	72.9	59	220.1	7.4	b_1	0.05376	
X_2	Ln Isp		-	6.1	1	8.2	5.4	b_2	3.202	
Y	$	300	million							
Structures/Mechanical Build Up										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	1.833	
X_1	Mass	20000	kg	136	71	337	14	b_1	0.01	
Y	$	202	million							
Thermal										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	1.817	
X_1	Redundancy	0.8	-	0.8	0.4	1	0	b_1	1.068	
X_2	Active/Passive	0	-	0.1	0.3	1	0	b_2	4.255	
Y	$	3	million							
Power										
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**		
X_0	Constant	1	-	-	-	-	-	b_0	5.08	
X_1	Rad Dosage	349	krads	349	972	4000	5	b_1	0.002	
X_2	AMTEC	21.9	ordinal	21.9	58.5	200	0	b_2	0.1579	
X_3	Adv Si	2038	ordinal	2038	3198	10500	0	b_3	0.001	
X_4	GsAs/HT	304	ordinal	304	1110	4600	0	b_4	0.002	
X_5	GaAs	553	ordinal	553	1900	7900	0	b_5	0.0022	
Y	$	13	million							

Table 12.167.7: Entry Descent and Landing Subsystem Cost

Entry Descent and Landing Subsystem Cost									
TOTAL COST:		$ 308	million						
Attitude Control									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	9.674
X_1	Mass	72.94	kg	16.06	13.6	48.1	1.9	b_1	0.2428
X_2	Data Rate		kbps	60.63	149	600	0	b_2	0.0064
X_3	Pointing	7.2	arcsec	327	302	900	5	b_3	-0.004
Y	$ 27	million							
Propulsion									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	-12.8
X_1	Mass	4970	kg	72.9	59	220.1	7.4	b_1	0.05376
X_2	Ln Isp	5.75149	-	6.1	1	8.2	5.4	b_2	3.202
Y	$ 273	million							
Structures/Mechanical Build Up									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.833
X_1	Mass	121679	kg	136	71	337	14	b_1	0.01
Y	$ 1,219	million							
Thermal									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	1.817
X_1	Redundancy	0.8	-	0.8	0.4	1	0	b_1	1.068
X_2	Active/Passive	0	-	0.1	0.3	1	0	b_2	4.255
Y	$ 3	million							
Power									
Parameters				**Avg**	**Std**	**Max**	**Min**	**coefficients**	
X_0	Constant	1	-	-	-	-	-	b_0	5.08
X_1	Rad Dosage		krads	349	972	4000	5	b_1	0.002
X_2	AMTEC		ordinal	21.9	58.5	200	0	b_2	0.1579
X_3	Adv Si		ordinal	2038	3198	10500	0	b_3	0.001
X_4	GsAs/HT		ordinal	304	1110	4600	0	b_4	0.002
X_5	GaAs		ordinal	553	1900	7900	0	b_5	0.0022
Y	$ 5	million							

12.168 Detailed Analysis of the Federation of American Scientists Cost Tool

The Federation of American Scientists made an online tool which has different coefficients for different types of space vehicles. Table 12.168.1 contains the inputs used with their online tool and the outputs obtained for each vehicle.

Table 12.168.1: List of Inputs and Outputs for the Federation of American Scientists AMCM Cost Tool

Cycler		input	units
Quantity		2	-
Dry Weight		4248307	lbs
Mission Type		Manned Habitat	-
IOC Year		2022	-
Block Number		1	-
Difficulty		Very High	-
		Output	
Cost	$	197,185	million
Phobos Hab		input	units
Quantity		1	-
Dry Weight		180779	lbs
Mission Type		Manned Habitat	-
IOC Year		2025	-
Block Number		1	-
Difficulty		High	-
		Output	
Cost	$	10,911	million
Mars Builder		input	units
Quantity		2	-
Dry Weight		2425	lbs
Mission Type		Lunar Rover	-
IOC Year		2025	-
Block Number		1	-
Difficulty		Low	-
		Output	
Cost	$	424	million
Mars Sat		input	units
Quantity		3	-
Dry Weight		15652	lbs
Mission Type		Communication	-
IOC Year		2024	-
Block Number		1	-
Difficulty		Low	-

		Output	
Cost	$	2,567	million
Helio Sat	input		units
Quantity		2	-
Dry Weight		15873	lbs
Mission Type		Communication	-
IOC Year		2024	-
Block Number		1	-
Difficulty		Low	-
		Output	
Cost	$	2,036	million
Crew Transfer	input		units
Quantity		1	-
Dry Weight		123458	lbs
Mission Type		Manned Reentry	-
IOC Year		2030	-
Block Number		1	-
Difficulty		Average	-
		Output	
Cost	$	10,420	million
Mars Hab	input		units
Quantity		1	-
Dry Weight		187393	lbs
Mission Type		Manned Habitat	-
IOC Year		2026	-
Block Number		1	-
Difficulty		High	-
		Output	
Cost	$	11,255	million
Repair Station	input		units
Quantity		1	-
Dry Weight		11023	lbs
Mission Type		Planetary Lander	-
IOC Year		2025	-
Block Number		1	-
Difficulty		Low	-
		Output	
Cost	$	3,037	million
Pod	input		units
Quantity		2	-
Dry Weight		3527	lbs
Mission Type		Lunar Rover	-

IOC Year		2026	-
Block Number		1	-
Difficulty		Average	-
		Output	
Cost	$	849	million
Hopper		input	units
Quantity		2	-
Dry Weight		1323	lbs
Mission Type		Lunar Rover	-
IOC Year		2026	-
Block Number		1	-
Difficulty		Average	-
		Output	
Cost		447	
Total Cost:	$	239,131	million

12.169 Detailed Analysis of Advanced Mission Cost Model Scaled to the Apollo Program

As stated previously, we use the Apollo Program to scale our AMCM constants. We do this by putting in the know inputs and adjusting the cost model's constants until we get the desired output. The result of this is seen below in table 12.169.1:

Table 12.169.1: AMCM constants scaled to Apollo Program

System Cost	**\$ 20,447[a]**	**million**	Apollo Cost	\$ 20,444[a] million
Constants		Inputs		
α	2	Q	11	-
β	2	M	291,447	lbs
Ξ	1	S	1	-
δ	2	IOC	1968	-
ε	4	B	2	-
φ	2.6	D	4	-
ϒ	2.2			

[a]In 1969 US dollars

Using the constants obtained, we can apply the AMCM o our mission inputs and obtain our system cost, which we see in table 12.169.2 below:

Table 12.169.2: Apollo Scaled AMCM Applied to Project Prometheus

System Cost	**\$ 125,959[a]**	**million**		
Constants		Inputs		
α	2	Q	18	-
β	2	M	9,024,450	lbs
Ξ	1	S	1	-
δ	2	IOC	2022	-
ε	4	B	1	-
ϕ	2.6	D	3	-
ϒ	2.2			

[a]In 1969 US dollars