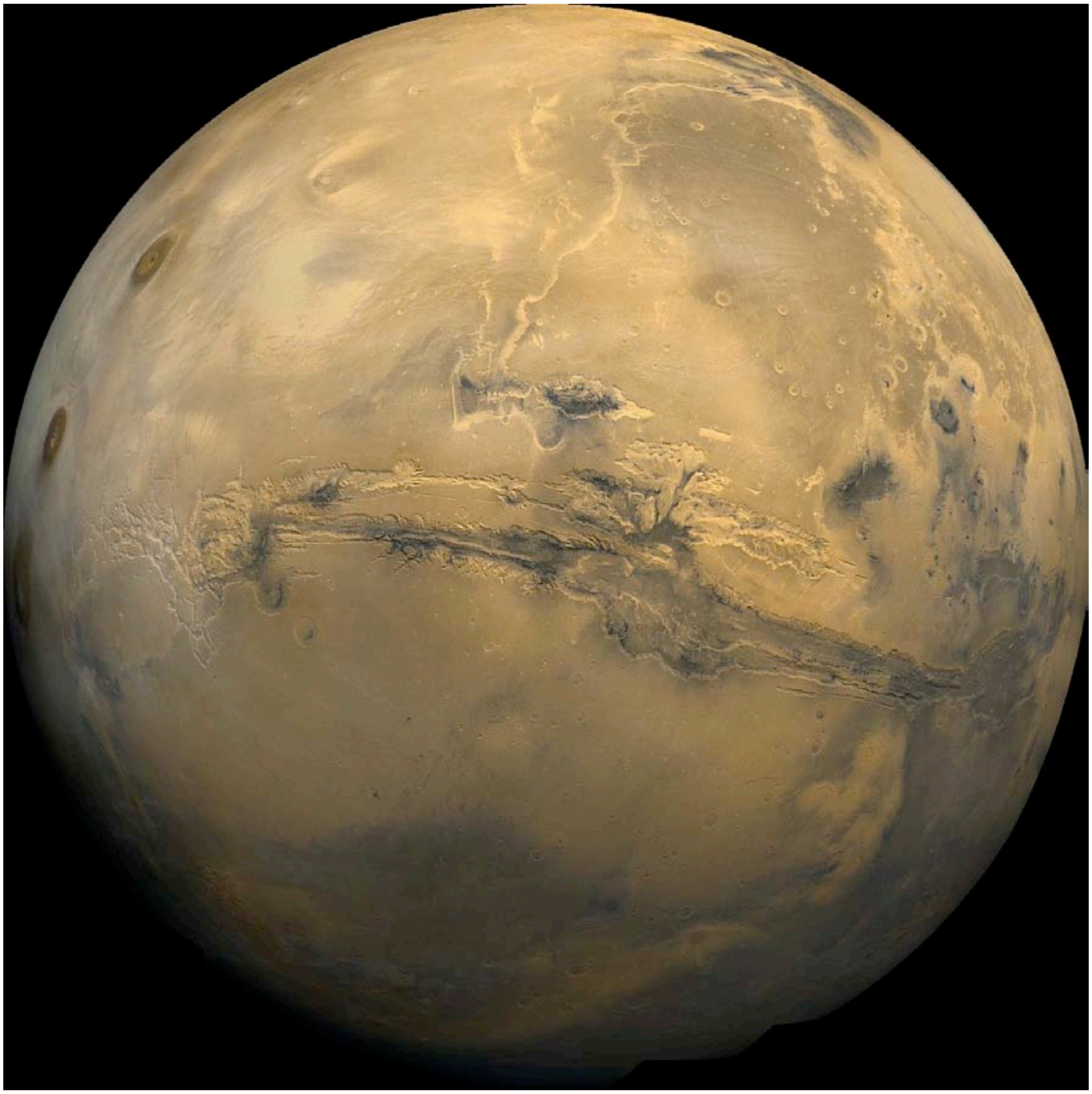
Mars Wi-Fi

ECE 6390 – Satellite Communications
Fall 2005



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I) Introduction

Problem Statement

Over the next 20 years, NASA expects to have a host of landers, rovers, aerobots (self-controlled airplanes), and even astronauts on the surface, or in the tenuous atmosphere, of the planet Mars. A system allowing uninterrupted inter-communications between all of the Mars-based assets, as well as communication between Mars-based assets and NASA facilities on earth will be needed. Since the Martian day is about 24.5 hours long (similar to Earth), ground-based landers and astronauts will not be in a direct line-of-sight with the earth so relay satellites will be required to provide 100% surface coverage.

Mars Planetary Overview

As mentioned above, the Martian day is about 24.5 hours and the Martian year is about twice that on Earth at 687 days for one revolution around the sun. Mars is, however, about one tenth the size of earth, and has two natural satellites, where the Earth only has one, the moon. Other facts about Mars and Earth are shown in Table 1 [1].

Parameter	Mars	Earth
Day (hrs)	24.6597	24.0000
Sidereal Day (hrs)	24.6229	23.9345
Sidereal Year (days)	686.980	365.256
Mass (10^{24} kg)	0.64185	5.9736
Volume (10^{10} km^3)	16.318	108.321
Topographical Range (km)	30	20
Equatorial radius (km)	3397	6378.1
Surface gravity (m/s^2)	3.71	9.80
Number of natural satellites	2	1
Distance from Earth		
Minimum (10^6 km)	55.7	--
Maximum (10^6 km)	401.3	--

Table 1 – Mars Facts

II) System Overview

The goal of this design is to provide a robust communication link but minimize required power transmitted by the Mars rovers while allowing omni-directional communications so the rovers do not depend on pointing an antenna at a specific point or being able to track a satellite as it moves across the sky. This concept led to placing the satellites as close to the surface of Mars as possible while balancing the number of satellites required and avoiding the orbits of Mars' two natural satellites. With these objectives in mind, the lowest cost solution is provided so as to not compromise a reliable communication link.

Satellites and Rovers

To assure 100% surface coverage on Mars, two Mars stationary (*MAS*) satellites and 4 medium Mars orbit (*MMO*) satellites will be used. The MAS satellites have a rotational period equal to the Martian sidereal day which gives an orbital radius of 20427.9 km. This orbit places the MAS satellites above the same point on Mars all the time. Said another way, the MAS satellites have a satellite sub point that doesn't vary with time. Analogous with geostationary satellites around earth, the MAS satellites will be along the Martian equator.

The interference by Mars' natural satellite Deimos should be minimal due to the small size of Deimos and its orbital inclination. Deimos orbits at 23459 km but is only 6.1 km in median radius with an orbital inclination of almost 2 degrees [1]. The orbital locations of the MAS satellites can be chosen to minimize proximity with Deimos but more detailed analysis and modeling will need required to assure no major problems arise. More details on the MAS orbital parameters can be found in Appendix B.1.

The medium Mars orbit (MMO) satellites will be about half as far away from Mars as the MAS satellites. With the smaller orbital radius comes a shorter orbital period according the Keppler's Laws [2]. These satellites will spin around Mars to cover the areas that a Mars stationary satellite can't see, such as the north and south poles. Actually, the MMO satellites will be responsible for covering the majority of the surface. The MMO satellites will all rotate around Mars up and down, from the south pole to the north pole and back to the south pole. This gives the orbital inclination of the MMO satellites to be almost 90^o.

The orbital radius chosen for the MMO satellites is 14000 km. This will be necessary to keep the satellites a sufficient distance from Phobos, the larger of Mars' natural satellites, orbiting at 9378 km. This is still not a very large distance from Phobos, but given that Phobos orbits around the equator and the satellites will orbit along longitude lines, the proximity will be for only very brief durations. Again, more detailed analysis and modeling will be needed to assure Phobos will not be a major problem with the MMO satellites. More details on the MMO orbital parameters can be found in Appendix B.2.

The Mars rovers can be anywhere on the surface of mars, or flying around in the atmosphere. All terminals on the surface or in the atmosphere of Mars will be referred to as rovers. Anything flying in the atmosphere will be the same as something on the surface when viewed from a satellite several thousand kilometers above the surface. This proposed design allows communication regardless of the orientation of the rover. The rover will never have to stop to align an antenna in either pointing direction or for polarization match. This is a key feature of the proposed design; to keep the rovers as simple as possible and require minimum transmitted power.

Due to fact that the rovers can be anywhere on Mars, each satellite system will assume that it has to communicate with all 50 rovers and that the rovers are at the fringes of its antenna pattern. If a more uniform distribution of rovers is assumed, system simplifications (namely required bandwidth) can be made. Doing this, however, limits capability if all rovers were to end in a single area.

Data Flow

There are two basic data paths that must be considered. The first is communication with Earth. Data must be able to be sent from a rover to Earth and from Earth to a rover at 1.5 Mbps (mega bits per second). The second communication channel is from one rover to another. This data rate must also be maintained at 1.5 Mbps.

It will be assumed that both Earth and another rover will not be communicating with a given rover at the same time. Or, if simultaneous communications are needed, interleaving will be used resulting in half the data rate. This was done to help minimize power output requirements of the rovers. A more detailed concept of operations (ConOps) will be needed to determine if simultaneous communications will be required. In that case, this system design will still be valid but will require other assumptions to be made which will be discussed later in the Communication Links section.

The basic data path is shown in Figure 1. From earth, the data is sent to one of the MAS satellites which transmits the signal to the MMO satellites and to its coverage spot on Mars. The MMO satellites then transmit the signal down to Mars. One of the MMO satellites will also send the signal to the other MAS satellite on the ‘dark side’ of Mars. That MAS satellite will then transmit the data to its coverage area completing the full surface coverage. In this way, every rover on Mars will have coverage at all times, even when it has no line-of-sight to Earth. The link is simply reversed to send data from a rover to Earth.

For one rover to send data to another rover, the data will first go to either a MMO or MAS depending on where on the surface the rover is. The MMO will send the data to a MAS. Now that the MAS has the data, it is sent back to Mars in the same way that a signal is sent from Earth. The MAS transmits to the MMOs and one MMO will pass the data along to the other MAS and all satellites will transmit the data to the surface of Mars.

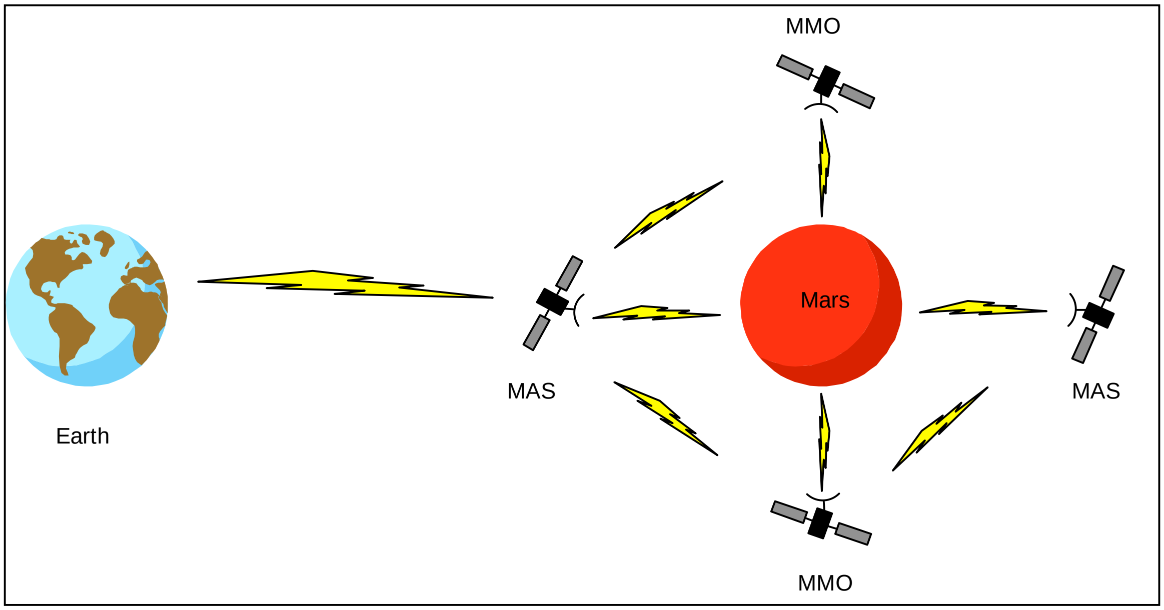


Figure 1 – Data Flow

III) System Summary

The sections that follow describe how the different parts of the communication link work together to meet the design objectives. Everything is in balance and tuned to provide reliable communications at a low system cost, low rover power requirement, and high system simplicity.

Orbits

100% surface coverage can be assured if Mars was a sphere. If a rover finds a deep canyon or steep mountain side communications may be blocked. Even though Mars is a much smaller planet that Earth, it has a much greater topographic range of 30 km [1]. With no oceans to hide a large portion of this topographic range as on Earth, the Martian mountains could block satellite coverage. Assuming there will be only the satellite communication system proposed here and no rover to rover communication or other Mars ground repeater stations, which is beyond the scope of this design, continuous communications could be disrupted. Either the paths of the rovers will have to be limited to avoid these isolated areas, or more likely, the rovers will be required to operate for a period of time without communications to explore these areas before returning to an area where satellite communications can be resumed.

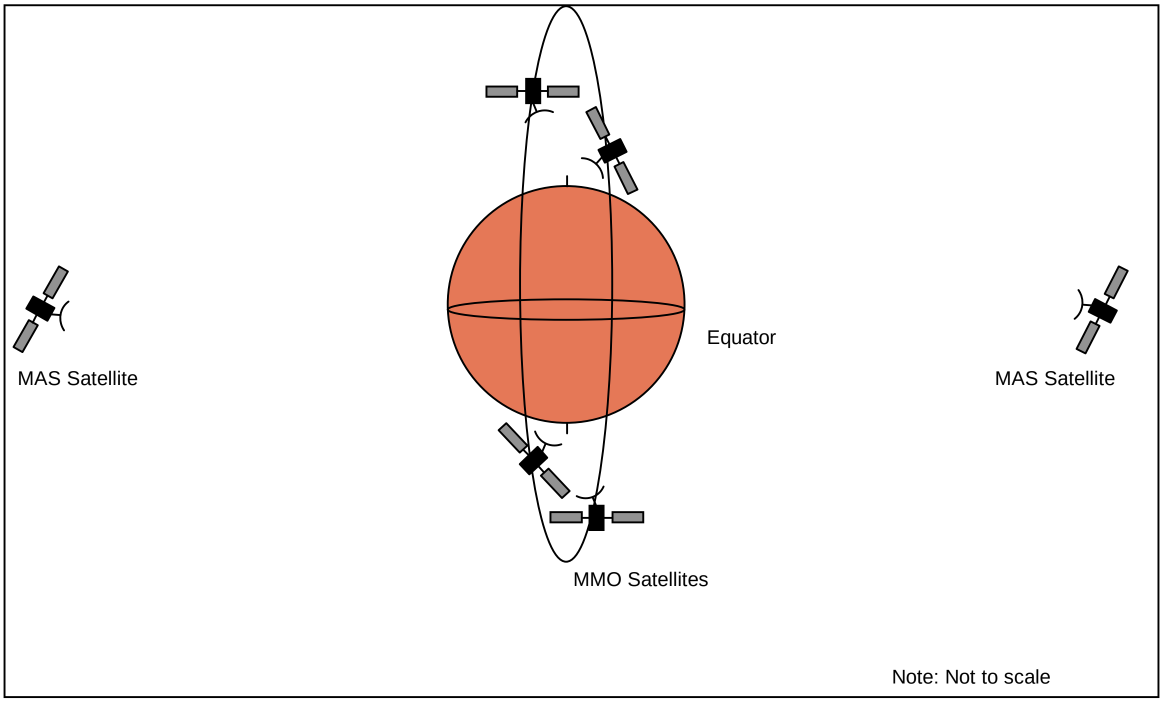


Figure 2 – Satellite Orbits

To see how these satellites will achieve 100% surface coverage, imagine a ball with 4 satellites rotating around it in the same plane, one following the other. These satellites can see most of the surface except for two spots on the sides. The center of these spots is where the MAS satellites will hover above, one on either side of Mars. See Figure 2 for a sketch of the orbits and Figure 3 for a sketch of the coverage zones for the MAS and MMO satellites.

As shown in Figure 3, the coverage area for the MAS satellites is smaller than that of the MMO satellites. This will be necessary because of the increased distance the signal will have to travel for the MAS satellites. With a smaller required coverage spot and a larger orbit radius, a narrower beam width and higher gain antenna can be used. The MMO satellites are a lot closer to Mars and hence do not need as much antenna gain to receive a given transmitted power from a Mars rover. The antenna patterns are conical, so to assure coverage at all points on the surface of Mars all the time, there will be significant overlap. The only points that will actually see the -3 dB point of satellite coverage are the 8 intersections of the MAS and MMO coverage cones and that is a moving point due to the orbit of the MMO satellites. So for most points on the surface of mars, there will be double coverage which allows a rover to chose from which satellite it receives the strongest signal.

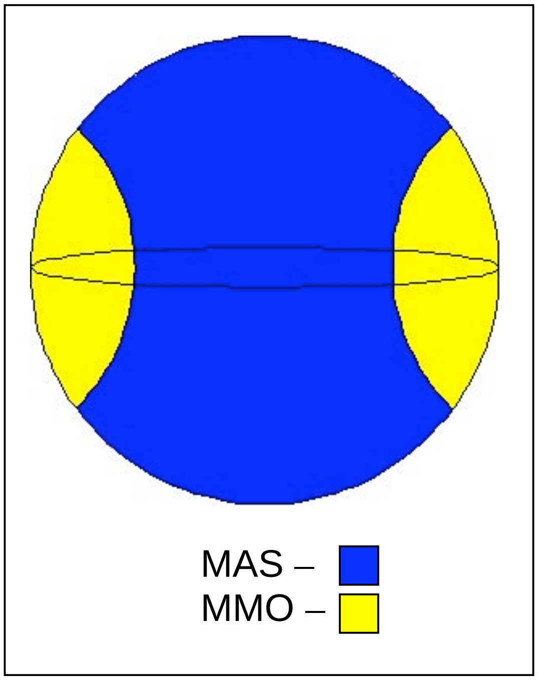


Figure 3 – MAS and MMO Coverage

Mars Stationary (MAS)

The orbital elements of the MAS satellites are summarized in Table 2. More details can be found in appendix B.1.

Orbit Radius (km)	20427.9
Altitude (km)	17030.9
Inclination	0.0
Orbit Period (hrs)	24.6229
Orbit eccentricity	0.0
Velocity (km/s)	1.448
Visibility (deg on Mars)	80.4

Table 2 – MAS Orbital Elements

Medium Mars Orbit (MMO)

The orbital elements of the MMO satellites are summarized in Table 3. More details can be found in appendix B.2.

Orbit Radius (km)	14000
Altitude (km)	10603
Inclination	90.0
Orbit Period (hrs)	13.97

Orbit eccentricity	0.0
Velocity (km/s)	1.75
Visibility (deg on Mars)	75.96

Table 3 – MMO Orbital Elements

Power Generation

An array needs to be 2.3 times larger in Mars orbit, and it must be 4.5 times larger on the surface [6] to maintain the same power output as a solar panel on Earth. Or, said another way, if an Earth satellite can generate 2100 W such as the INTELSAT VI [2], around Mars that same satellite would only generate 913 W. This will be an underestimate as the 2.3 factor was derived for a solar array in Earth's atmosphere where the INTELSAT VI is orbiting outside the atmosphere. This indicates that a power budget of about 900 W is reasonable.

The Mars Global Surveyor uses four solar array panels (2 GaAs, 2 SI) to provide 980 W of power to the spacecraft [7]. This is a higher figure than calculated above, but again, a power budget of 900 W is reasonable. Assuming that 80% of the generated power is available for transmission and the remaining 20% is used by the electronics, temperature control, etcetera. This leaves the power budget for transmission to be around 720 W.

The Sojourner and Mars Exploration Rovers currently on Mars give a good feel for how much power can be generated using solar cells on the surface of Mars [4]. During the primary portion of their mission, 900 watt-hours were able to be produced per Martian day. Well after their primary missions the rovers were still able to produce 410 watt-hours per Martian day.

Given the 410 watt-hours of power available later in the life of a rover, if communications were maintained for the entire 24.6597 hours of the Martian day [1] transmission would only account for half of that time due to the TMD being used. If all of the power were available for communications, 33.25 watts would be available. A more detailed ConOps will tell how much time during a day a given rover would actually be transmitting. This power availability will provide a good basis for estimating that the power output of the rovers should be less than 33.25 watts to allocate some power for other things the rovers need to do such as drive around, maintain temperature control, etcetera.

Antennas and Electronics

The antennas chosen for communication to and from the rovers are all helical antennas. Helical antennas radiate circularly polarized waves so orientation of the receiving antenna does not matter. This will prove to be an advantage as the rovers will not have to worry about which way their antennas are orientated. With a linearly polarized antenna, the orientation can play a huge role in the power received. For example, if a satellite radiates vertical pol, and the rover is such that its antenna is perpendicular to that orientation, no power would be received. With circular pol, this is not a problem. So as the rovers move about, and the satellites move across the sky, perfect polarization match can be assumed.

For the same reason, communication between the MMO and MAS satellites will be accomplished with helical antennas. These communication channels will be discussed further in the next section.

The electronics used by the rovers and satellites are chosen to minimize the power the rovers are required to transmit. Binary Phase Shift Keying (BPSK) is chosen because it provides the lowest required signal to noise ratio (SNR) and Turbo Coders are used to further achieve a narrower margin in the required SNR. These two methods add up to a high required bit rate which equates to a wide bandwidth [2]. Communications to and from Mars are currently unregulated so use of a wide bandwidth will not be a problem.

To allow both the satellites and rovers to have only one antenna system, a time division multiplexing (TDM) scheme will be employed. The rovers and satellites will transmit for a period of time, and then receive for a period of time. This further increases the required bit rate and bandwidth but allows the rovers to carry a minimum payload. The transmit and receive times will be chosen long enough such that guard times and path difference timing will be negligible.

DSN

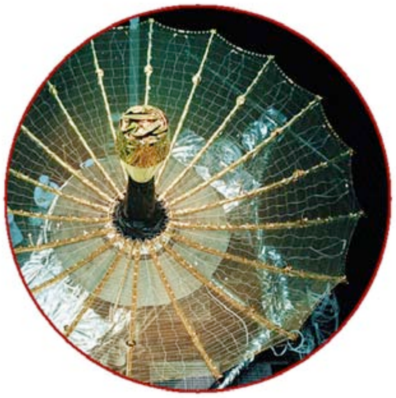
The Deep Space Network (DSN) operated by NASA consists of 3 Earth stations. One is in the Mojave Desert in California, one is outside of Madrid, Spain, and the third is at Canberra, Australia. The Earth stations are located such that at any given time, the DSN can see Mars.

Each location has a 34 meter parabolic dish antenna (shown to the right) with a system temperature of 20 K and aperture efficiency of 94%. With the capability of transmitting up to 500,000 watts, these antennas are impressive to say the least. For more information on the DSN, see reference [3].

DSN Dish	
Size (diameter, m)	34.0
Frequency (GHz)	31.8 to 34.7
Aperture Efficiency	94%
Gain at 34.45 GHz (dB)	81.51
Gain at 32.05 GHz (dB)	80.88
-3dB Beamwidth (deg)	~ 0.0158

MAS Satellite

Each of the MAS satellites will have 4 separate antenna systems. A large, 3 meter dish will be used for communicating to Earth and a horn antenna will receive from Earth. One helical antenna will be used to communicate with the MMO satellites. Finally, an array of 2,025 helical antennas will send and receive data to and from the Mars rovers. These antennas are summarized in the following tables.



Dish to Earth	
Diameter (m)	3.0
Frequency (GHz)	32.05
Aperture Efficiency	80%
Gain (dB)	59.09
-3dB Beamwidth (deg)	~ 0.195

Horn to Earth	
Aperture Area (m^2)	0.04
Length (m)	0.4
Frequency (GHz)	34.45
Gain (dB)	37.31
-3dB Beamwidth (deg)	2.20

Helix to MMO	
Number of Turns	40
Length of Helix (m)	0.2808
Frequency (GHz)	10.0
Gain (dB)	20.24
-3dB Beamwidth (deg)	18.08

Helix Array to Mars (45x45)	
Number of Turns	40
Length of Helix (m)	0.281
Width * Height (m^2)	1.025
Frequency (GHz)	10.0
Single Element Gain (dB)	20.24
Array Gain (dB)	53.30
-3dB Beamwidth (deg)	18.08

MMO Satellite

Each MMO Satellite will have 3 separate antenna systems. Two dishes will be used for communication with the MAS satellites. One dish will be on either side of the MMO satellite, one pointing at each of the MAS satellites. These antennas will have a narrow beamwidth, but the MAS satellites will stay at the same look angle from the MMO satellite as it rotates around Mars. This is due to the fact that the orbital plane is orthogonal to a line from one MAS satellite to the other.

An array of 2025 helical antennas arranged in a 45 by 45 grid will be used to receive data from Mars. Only one of the antennas in the array will be used for transmission to maintain a broad beamwidth. Because of the very high array factor, the receiving signals will require some phase correction circuitry to maintain the high gain over the required beamwidth.

Dish to MAS	
Size (diameter, m)	1.0
Frequency (GHz)	10.0
Aperture Efficiency	80%
Gain	39.43
-3dB Beamwidth (deg)	~ 1.94

Array to Mars (45x45)	
Number of Turns	18
Length of Helix (m)	0.126
Width * Height (m^2)	1.025
Frequency (GHz)	10.0
Single Element Gain (dB)	16.77
Array Gain (dB)	49.83
-3dB Beamwidth (deg)	26.95

Mars Rovers

The Mars rovers will have one antenna system for both sending data to the satellites and receiving data from the satellites. The TDM architecture allows one antenna instead of separate antennas for sending and receiving. The rover arrays will consist of several helical antennas orientated such that all of the sky is in view of an antenna. Each individual helix will be pointed in a different direction so the array will end up looking like a spiny half sphere.

The term array is used loosely here as the antennas do not work together like a typical array. The multiple antennas are simply used to assure all of the sky is covered. A rover will only use one of the antennas at a time. Whichever antenna receives the best signal from a satellite will be the same antenna used for transmission. Because the helical antennas are small and lightweight, many antennas can be used and still give a weight savings over a dish which would have to have direction finding hardware. An array of helical antennas also has a large gain advantage over a dipole antenna. Two dipole antennas would be needed to assure polarization match, and would only have a gain of about 1.76 dB where the helical antennas have a gain of 18.99 dB as shown below.

Array to MMO	
Number of Turns	30
Length of Helix (m)	0.2106
Diameter (m)	~ 0.5
Frequency (GHz)	10.0
Gain (dB)	18.99
-3dB Beamwidth (deg)	20.88

Communication Links

Earth to MAS

The communication channel from Earth to the MAS satellites can make use of the high power available to the DSN antennas. The frequency bands available for communicating from Earth to Mars are 7.19-7.25 GHz and 34.2-34.7 GHz. The higher frequency was chosen because of the increased gain seen by the dish and horn antennas for a given aperture size. The higher frequency band also has a much wider bandwidth which will be necessary for the Frequency Division Multiple Access (FDMA) scheme employed. Code Division Multiple Access (CDMA) was considered, but due to the narrow bandwidth, FDMA provides a higher signal to noise ratio (SNR).

As in all of the communication channels, Turbo Coders will be used along with BPSK modulation. The Turbo Coders insure error free communications provided the SNR is greater than 0.7 dB. All communication links will also assume an implementation margin of 1.0 dB to provide some pad to assure a robust communication link. The link from Earth to the MAS satellites is summarized in the following table.

For the link between Earth and the MAS satellite and the reverse link, the rain intensity zone will be assumed to be zone E. This is due to looking at the rainfall at all three DSN sites (Canberra Australia, Madrid Spain, and Mojave California) [8], [9], [10] and estimating the worst case to be zone E.

Wavelength at 34.45 GHz (m)	λ	0.0087
Bit Rate (Mbps)	R_b	3.0
Transponder Bandwidth (MHz)	B	210
Noise Bandwidth (MHz)	B_N	150
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	50.0
Noise Power (W)	N	1.035e-13
Transmitted Power (W)	P_t	500,000
Transmit Antenna Gain (dB)	G_T	81.51
Receive Antenna Gain (dB)	G_R	37.30
Max Path Length (m)	r	401.3e9

Carrier Power (W)	C	1.13e-12
Clear Sky SNR (dB)		10.387
Rain Outages (% of time)		0.1

MAS to MMO

Once the data gets from Earth to the MAS satellites, the remaining links will employ a Time Division Multiplexing (TDM) scheme so separate antennas are not needed for transmission and receiving. As mentioned above, this link will use FDMA coupled with Turbo Coders and BPSK modulation. The link is summarized in the following table.

Wavelength at 10 GHz (m)	λ	0.03
Bit Rate (Mbps)	R_b	6.0
Transponder Bandwidth (MHz)	B_{50}	420
Noise Bandwidth (MHz)	B_N	300
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	50.0
Noise Power (W)	N	1.07e-13
Transmitted Power (W)	P_t	18.38
Transmit Antenna Gain (dB)	G_T	20.24
Receive Antenna Gain (dB)	G_R	39.43
Max Path Length (km)	r	24764.9
Carrier Power (W)	C	1.582e-13
SNR (dB)		1.70

MAS to Rovers

As mentioned above, this link will use TDM and FDMA coupled with Turbo Coders and BPSK modulation. Because the rovers can be anywhere in the main beam of the antenna, the -3dB gain will be used as a worst case for all calculations. The link is summarized in the following table.

Wavelength at 10 GHz (m)	λ	0.03
Bit Rate (Mbps)	R_b	6.0
Transponder Bandwidth (MHz)	B_{50}	8.4
Noise Bandwidth (MHz)	B_N	6.0
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	50.0
Noise Power (W)	N	4.14e-15
Transmitted Power (W)	P_t	180.97
Transmit Antenna Gain (dB) -3dB	G_T	17.24
Receive Antenna Gain (dB) -3dB	G_R	15.99
Max Path Length (km)	r	18825.02
Carrier Power (W)	C	6.123e-15
SNR (dB)		1.70

MMO to Rovers

As mentioned above, this link will use TDM and FDMA coupled with Turbo Coders and BPSK modulation. Because the rovers can be anywhere in the main beam of the antenna, the -3dB gain will be used as a worst case for all calculations. The link is summarized in the following table.

Wavelength at 10 GHz (m)	λ	0.03
Bit Rate (Mbps)	R_b	6.0
Transponder Bandwidth (MHz)	B_{50}	8.4
Noise Bandwidth (MHz)	B_N	6.0
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	50.0
Noise Power (W)	N	4.14e-15
Transmitted Power (W)	P_t	206.2
Transmit Antenna Gain (dB) -3dB	G_T	13.77
Receive Antenna Gain (dB) -3dB	G_R	15.99
Max Path Length (km)	r	13476.3
Carrier Power (W)	C	6.123e-15
SNR (dB)		1.70

Rovers to MMO

As mentioned above, this link will use TDM and FDMA coupled with Turbo Coders and BPSK modulation. Because the rovers can be anywhere in the main beam of the antenna, the -3dB gain will be used as a worst case for all calculations. The link is summarized in the following table.

Wavelength at 10 GHz (m)	λ	0.03
Bit Rate (Mbps)	R_b	6.0
Transponder Bandwidth (MHz)	B_{50}	420
Noise Bandwidth (MHz)	B_N	300
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	260.1
Noise Power (W)	N	1.077e-12
Transmitted Power (W)	P_t	26.5
Transmit Antenna Gain (dB) -3dB	G_T	15.99
Receive Antenna Gain (dB) -3dB	G_R	46.83
Max Path Length (km)	r	13476.3
Carrier Power (W)	C	1.59e-12
SNR (dB)		1.70

Rovers to MAS

As mentioned above, this link will use TDM and FDMA coupled with Turbo Coders and BPSK modulation. Because the rovers can be anywhere in the main beam of the antenna, the -3dB gain will be used as a worst case for all calculations. The link is summarized in the following table.

Wavelength at 10 GHz (m)	λ	0.03
Bit Rate (Mbps)	R_b	6.0
Transponder Bandwidth (MHz)	B_{50}	420
Noise Bandwidth (MHz)	B_N	300
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	260.1
Noise Power (W)	N	1.077e-12
Transmitted Power (W)	P_t	26.5
Transmit Antenna Gain (dB) -3dB	G_T	15.99
Receive Antenna Gain (dB) -3dB	G_R	50.30
Max Path Length (km)	r	18825.02
Carrier Power (W)	C	1.81e-12
SNR (dB)		2.25

MMO to MAS

This is exactly the reverse of the MAS to MMO link described above. The only change is the transmitting and receiving antenna are reversed which does not change the link budget. It is summarized below for completeness.

Wavelength at 10 GHz (m)	λ	0.03
Bit Rate (Mbps)	R_b	6.0
Transponder Bandwidth (MHz)	B_{50}	420
Noise Bandwidth (MHz)	B_N	300
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	50.0
Noise Power (W)	N	1.07e-13
Transmitted Power (W)	P_t	18.38
Transmit Antenna Gain (dB) -3dB	G_T	39.43
Receive Antenna Gain (dB) -3dB	G_R	20.24
Max Path Length (km)	r	24764.9
Carrier Power (W)	C	1.582e-13
SNR (dB)		1.70

MAS to Earth

Similar to the link from Earth to the MAS satellites, the return link will use FDMA with Turbo Coders and BPSK modulation. Given the links already calculated, the power budget for transmission to Earth is about 500 W. The budget is summarized in the following table. Zone E will be used here as well for calculating the rain fade.

Wavelength at 32.05 GHz (m)	λ	0.00936
Bit Rate (Mbps)	R_b	3.0
Transponder Bandwidth (MHz)	B	495.3
Noise Bandwidth (MHz)	B_N	381
Implementation Margin (dB)		1.0
System Noise Temperature (K)	T_{sys}	20.0
Noise Power (W)	N	1.05e-13
Transmitted Power (W)	P_t	500
Transmit Antenna Gain (dB)	G_T	59.09
Receive Antenna Gain (dB)	G_R	80.88
Max Path Length (m)	r	401.3e9
Carrier Power (W)	C	1.71e-13
Clear Sky SNR (dB)		2.11
Rain Outages (% of time)		> 10

Redundancy

Many of the antennas used to communicate with Mars are arrays so if one element fails, the system will only be slightly less efficient and may require a slight increase in transmit power. Or in the case of the rovers if one antenna fails, a portion of the sky will not be available to see a satellite.

Additional satellites can be launched to provide a greater level of redundancy or to decrease transmit power requirements by the satellites or earth. Simply inserting satellites into the MMO orbit provides a short turnaround time to reposition the spare satellite in the place of the failed one. Similarly, additional satellites can be put into MAS orbit very close to the initial ones. If a MAS satellite failed, only a small repositioning of the MMO satellite dish antennas would be required if the new satellite was not still at the peak of the MMO's dish antenna.

As mentioned earlier, this design does not allow for Earth and a rover to simultaneously communicate with another rover. To add this capability to the system additional assumptions could be made such as how many rovers would be seen by a given satellite, and availability to employ frequency re-use. These two things could help limit the noise bandwidth (B_N) required by the satellites leaving that portion of the link unchanged. However, if a rover wanted to receive two signals, this would double the noise bandwidth and would require twice the gain from either the transmitting or receiving antenna, or twice the power to be transmitted from the satellites.

Cost Data

Each satellite is estimated at $200 million to launch and place into Mars orbit. Costs will not be incurred for the launch and landing of the mars rovers as these come from various sources not under the control of this agency, but cost will be incurred for the power requirements of the rovers. Additionally, $1 million per transmitted watt includes the cost of the required solar panel, amplifiers, other electronics and antennas. The power requirements for each element in the communication link are included below in the following table.

Link Element	**Transmit Power per satellite or rover (W)**	**Power Cost (M$)**	**Launch Cost (M$)**
MAS * 2	699.35	1398.7	400
MMO * 4	224.58	898.32	800
Rovers * 50	26.5	1325	-0-
TOTAL		3622.02	1200

This gives a total cost of $4822.02 million dollars.

Summary

In this design, reliable communications anywhere on Mars is assured by the use of Turbo Coders at all points in the link and the emphasis on minimizing rover transmit power and antenna simplicity allows the many rovers to employ a simple, low cost system.

IV) Appendices

Physical Constants and Design Parameters

Several physical constants were used throughout the calculations many of them are summarized below

c = 3e8	Speed of Light	m/s
k = 1.38e-23	Boltzman’s Constant	W/K/Hz
$\mu = GM = 42.83e3$	Keppler’s Constant for Mars	km^3/s^2

Orbit Details

MAS

$$T^2 = \frac{4*\pi^2*a^3}{\mu} \qquad \text{Keppler's Law}$$

where T is the orbit period, a is the semi-major axis, and is Keppler’s constant. For a Mars stationary, set T = sidereal day = 24.6229 hours = 88642.44 s. The orbit will be circular so a is the radius from the center of Mars. Using these values

$$\boxed{a = 20427.9 \text{ km}}$$

Visibility requirement $\cos(\gamma) = \frac{r_m}{r_s}$

where r_m is the radius of Mars (3397 km), r_s is the satellite radius and

$\cos(\gamma)$ = cos(Le)cos(Ls)cos(ls-le) + sin(Le)sin(Ls)

where Le = Mars latitude
Ls = Satellite Sub Point (SSP) latitude
le = Mars longitude
ls = SSP longitude

To calculate visibility, put the SSP at 0 latitude, 0 longitude and put the observer along the 0 longitude line and find where along the latitude an observer looses visibility to the satellite. Doing this reduces the visibility requirement to:

$$\cos(Le) = \frac{r_m}{r_s} = \frac{3397}{20427.9}$$

$$\boxed{Le = 80.4^o}$$

MMO

For the MMO, the orbit will be circular and the radius is fixed at 14000 km to avoid proximity with the natural satellites.

$$T^2 = \frac{4*\pi^2*a^3}{\mu} \qquad \text{with } a = 14000 \text{ km}$$

$\boxed{T = 50291.88 \text{ s} = 13.97 \text{ hours.}}$

Doing the same as above for the visibility

$$\cos(Le) = \frac{r_m}{r_s} = \frac{3397}{14000}$$

$\boxed{Le = 75.96^{o}}$

Antenna and Electronics Details

DSN

The 34 meter dish antenna used by the DSN operates at 32.05 GHz and 34.45 GHz. The equations for the gain of a dish antenna is given by [5]

$$G = \frac{4\pi A_{em}}{\lambda^2}\eta$$

Where A_{em} is the are of the dish (π r^2) and is the aperture efficiency.

In this case A_{em} = π 1.5^2 = 907.92 for a 34 meter dish. An aperture efficiency of 94% will be assumed and λ = 0.00936 m.

$\boxed{G = 122414745.946 = 80.88 \text{ dB}}$ at 32.05 GHz

The half power beamwidth (HPBW) can be estimated by

$$G = \frac{33000}{\Theta_{HP}\Phi_{HP}}$$

where $\Theta_{hp} = \Phi_{hp}$ is the half power beamwidths in the theta and phi directions which are the same for a circular dish antenna.

$\boxed{HPBW = \Theta_{hp} = \Phi_{hp} = 0.0164^{o}}$ at 32.05 GHz

Now re-do the calculations for 34.45 GHz so λ = 0.0087 m

$\boxed{G = 141692477.946 = 81.51\text{dB}}$ at 34.45 GHz

$\boxed{HPBW = \Theta_{hp} = \Phi_{hp} = 0.015^{o}}$ at 34.45 GHz

MAS Satellite

The 3 meter dish antenna used to send to Earth operates at 32.05 GHz. The equations for the gain of a dish antenna is given by [5]

$$G = \frac{4\pi A_{em}}{\lambda^2}\eta$$

Where A_{em} is the are of the dish (π $*r^2$) and η is the aperture efficiency.

In this case A_{em} = π $*1.5^2$ = 7.0686 for a 1 meter dish. An aperture efficiency of 80% will be assumed and λ = 0.00936 m.

$\boxed{G = 811046.585 = 59.09 \text{ dB}}$

The half power beamwidth (HPBW) can be estimated by

$$G = \frac{33000}{\Theta_{HP}\Phi_{HP}}$$

where $\Theta_{\text{hp}} = \Phi_{\text{hp}}$ is the half power beamwidths in the theta and phi directions which are the same for a circular dish antenna.

$$\boxed{\text{HPBW} = \Theta_{\text{hp}} = \Phi_{\text{hp}} = 0.202^{\circ}}$$

The horn antenna used to receive signals from Earth operates at 34.45 GHz. The equation for the gain of a horn antenna given by [5]

$$G = 0.81\left[4\pi \frac{ab}{\lambda^2}\right]$$

where a and b are the dimensions of the aperture

In this case a = b = 0.2 m and λ = 0.0087 m

$$\boxed{\text{G} = 5379.18 = 37.31\ \text{dB}}$$

For a horn antenna where a = b, the HPBW can be estimated by

$$HPBW = \frac{50.6\lambda}{a} = \frac{50.6\lambda}{b}$$

$$\boxed{\text{HPBW} = 2.20^{\circ}}$$

The single helix used to send and receive from the MMO satellites operates at 10.0 GHz so $\lambda = 0.00936$ m. The design procedure for a helical antenna starts with choosing a couple parameters [5]. For optimum design choose

$\alpha = 14^{\circ}$ which is the spiral angle

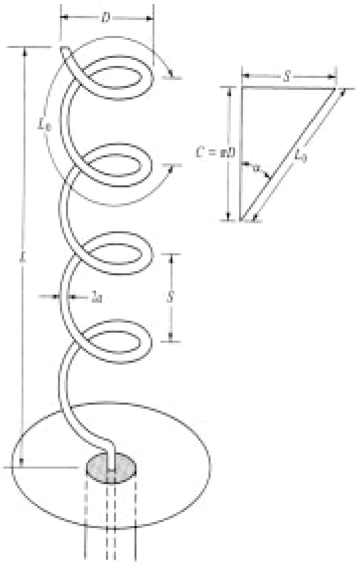
d = 0.3λ which is the diameter of the helix

From here, the circumference is calculated by π * d.

So C = 0.94λ

and the coil spacing S = C*tan(α) = 0.324λ.

The total length of the helix is just going to be n*S where n is the number of turns



$$\boxed{\text{L} = \text{S*n}}$$

With the physical geometry determined, the gain and HPBW can be calculated

$$\boxed{G = 12 * S_\lambda * C_\lambda * n}$$

where n is the number of turns in the helix and S_λ and C_λ are S / λ and C / λ respectively.

$$\boxed{HPBW = \frac{52}{C_{\lambda}\sqrt{n * S_{\lambda}}} = \frac{114.36}{\sqrt{n}}}$$

These last three equations will be used for calculating all the helical antennas
For the single helix used in communications with the MMO satellites

n = 40
L = 0.2808 m
G = 105.6 = 20.24 dB
HPBW = 18.08^o

n was chosen as 40 because a 40 turn antenna starts to get pretty long and the gain begins to fall off with increasing n if n gets to large. More detailed analysis would be needed to determine how much gain, now large n can get, and still meet structural requirements without losing too much efficiency.

The array of helical antennas used to communicate with the Mars rovers has 45 by 45 of the antennas described above with n=40.
The gain of a single element is 105.6 so the gain of 45*45=2025 antennas is 2025*105.6.

Array Gain = 213840 = 53.30 dB

The HPBW for the array will be very narrow due to the large number of elements used. When transmitting, only one element is used so the HPBW is simply 18.08^o, but when receiving, some phase correction circuitry will be needed to maintain the full gain over the entire required beam width of 18.08^o.

MMO Satellite

The array of helical antennas used to communicate with the Mars rover has 45 by 45 antennas where n = 18. The number of turns was chosen so that the HPBW corresponded to a coverage area on Mars equal to the area visible to that satellite. The equations given above are used here keeping the frequency at 10.0 GHz.

n = 18
L = 0.126 m
G = 47.52 = 16.77 dB for a single element
HPBW = 26.95^o
G = 96228 = 49.83dB for the entire array

Similar to the array used by the MAS, this array will require phase correction to maintain the gain over the HPBW of a single element.

The dish antenna used to communicate with the MAS satellites is 1.0 m in diameter, operates at 10.0 GHz and has an aperture efficiency of 80%. The equations developed for the DSN dish apply here so

G = 8770.0 = 39.43 dB
HPBW = 1.94^o

Mars Rovers

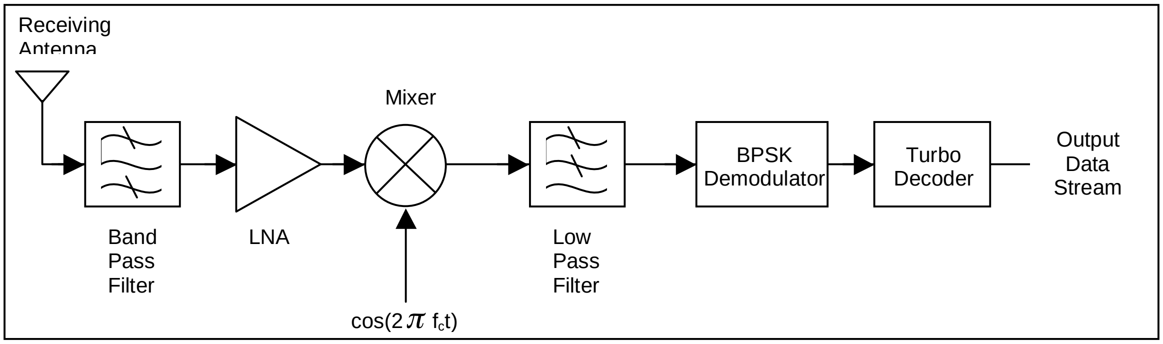
The rovers will have only one antenna system operating at 10 GHz. This will consist of many helical antennas grouped together so that each antenna points in a different direction. The number of turns is determined by gain requirements balanced with a small HPBW resulting in more antennas needed to cover the entire sky and helix length for mechanical reasons. In the end,

n = 30
L = 0.2106 m
G = 79.25 = 18.99 dB
HPBW = 20.88^o

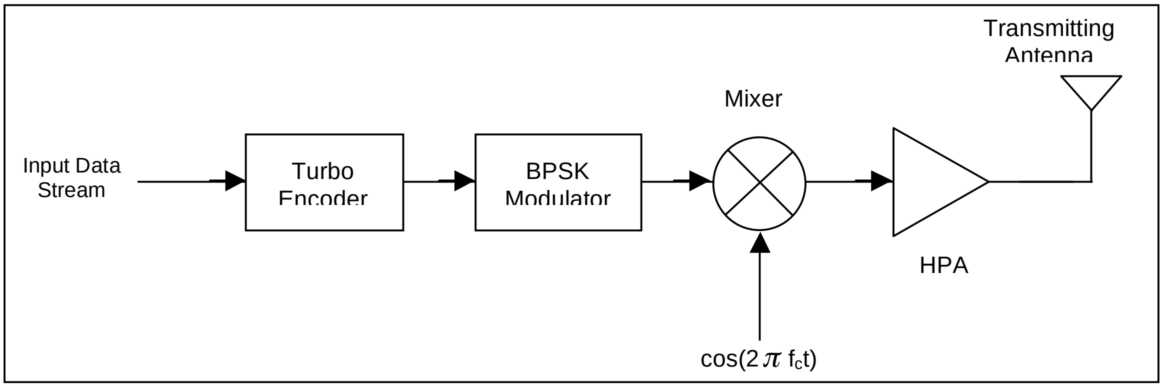
With the antennas arranged together so it will look like a spiny half sphere, the total size will end up being about 0.5 m diameter half sphere.

Electronics Details

All links in this design use FDMA coupled with Turbo Coders and BPSK modulation. Therefore all the electronics needed to send these signals are the same. Below are block diagrams of the transmitting and receiving systems. The following figures are simplified block diagrams, more detailed analysis is needed to refine the details.



Receiving Structure



Transmitting Structure

Where LNA = low noise amplifier
f_c = carrier frequency
HPA = high power amplifier

Link Details

All links in this design use FDMA coupled with Turbo Coders and BPSK modulation. Therefore the equations governing the links will all be the same. Only antenna gains, system temperatures, and output power are changed from link to link. The requirement for error free communications using a Turbo Coder is that the energy per bit if greater than 0.7 dB. BPSK was chosen because the energy per bit is equal to the carrier to noise ratio (CNR) which also equals the SNR.

All parameters are summarized in the communication link section and the governing equations are provided below.

Transponder Bandwidth	$B = R_b * (1 + \alpha)$	(or 50 * B for the satellites)
Noise Bandwidth	$B_N = R_b$	(or 50 * B_N for the satellites)
System Temperature	$T_{sys} = T_{BB} + T_{LNA}$	
Noise Power	$N = k*B_N*T_{sys}$	
Carrier Power	$C = P_t \frac{G_t G_r \lambda^2}{(4\pi * r)^2}$	
Signal to Noise Ratio	$SNR = \frac{C}{N}$	(SNR = CNR for BPSK)

Where R_b = bit rate
α = root raised cosine filter fall off rate
T_{BB} = black body temperature
T_{LNA} = equivalent temperature of the low noise amplifier (LNA)
k = Boltzman's constant
P_t = transmitted power
G_t = gain of the transmitting antenna
G_r = gain of the receiving antenna
λ = wavelength of the carrier frequency
r = path length

Rain Fade

Rain fade will be calculated by the following method.
1) α and k will be determined for the desired frequency by linear interpolation of the tables [2].
2) The rain height will be assumed to be 4 km [2] with a look angle of 45°. L_{eff} = 5.66 km
3) The rain fade (in dB) is calculated by $RF = L_{eff} * k * R^{\alpha}$
where R is the rain rate in mm/hr.

For the link from Earth to the MAS (at 34.5 GHz), the excess clear sky SNR = 10.387 – 1.7 = 8.687. This will be allocated to rain fading giving

RF = 8.687

α_v = 0.96805 α_h = 0.9841 α = 0.96805 (average of α_v and α_h)

k_v = 0.23135 k_h = 0.26035 k = 0.23135 (average of k_v and k_h)

which corresponds to a rain rate R = 6.53 mm/hr

In zone E, this will be slightly better than 0.1% outage time.

For the link from the MAS satellite to Earth (at 32 GHz), the excess clear sky SNR = 2.11 – 1.7 = 0.41. This will be allocated to rain fading giving

RF = 0.41

α_v = 0.9858

k_v = 0.1956

which corresponds to a rain rate R = 0.365 mm/hr

The DSN will transmit linear polarized waves to the MAS so vertical pol can be assumed. In zone E, this will be slightly greater than 10% of the time. This is a high number, but in reality, with 3 dishes on Earth in the DSN, there will usually be 2 antennas visible from Mars. If it is raining at one DSN station, the other one can be used minimizing outage time.

In order for the link to maintain a rain outage of 0.3%, which corresponds to a rain rate of 2.4 mm/hr a margin of 2.62 dB is needed. This margin would require

P_t = 829.85 W

This is most of the assumed power generation of 900 W for the Mars satellites. However it is still within the realm of possibility that if there was significant rain fading at a given time, more power could be used for transmission for a short time and deplete the battery supply which could then be renewed at a later time when a clear sky link has been re-established.

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