Introduction

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. Your engineering firm is to design a system allowing uninterrupted inter-communications between all of the Mars-based assets (landers, astronauts, aerobots, etc.), as well as communication between all Mars-based assets with NASA facilities on earth. Since the Martian day is about 24.5 hours long (similar to Earth), ground-based landers and astronauts will not be in the line-of-sight to earth for periods of over 12 hours, so relay satellites will be required. Since the ground-based terminals will be at all locations on the Martian surface, 100% surface coverage must be provided.

Design Specifications

1. There may be up to fifty compact Martian ground terminals, with no aperture sizes larger than 1 m diameter.
2. Ground terminals must uplink data at up to 1.5Mbps, to be received both at Earth or by other terminals.
3. Each ground terminal must receive its own targeted data stream from the Earth at 1.5 Mbps and one additional 1.5 Mbps from one of the other Martian surface assets, which should be fully selectable
4. No terminal to satellite communication may be in the frequency ranges of 1.40-1.43 GHz, 4.9-5.0 GHz, 10.6-10.7 GHz, or 15.3-15.4 GHz
5. Communication from a Martian satellite to one of the NASA Deep Space Network (DSN) terminals bust be in one of the following frequency bands: 8.4-8.6 GHz or 31.8-32.3 GHz
6. Communication from a DSN terminal to a Martian satellite must be in one of the following frequency bands: 7.19-7.25 GHz or 34.2-34.7 GHz
7. The DSN terminal is already built, with T_{sys} = 20 K, aperture efficiency = 0.94, P_T = 500 kW.
8. The bit error rates on the overall links from the Mars stations back to earth and earth to Mars must not exceed 10^{-6}.
9. Cost per satellite: $200M
10. Cost per transmitted watt of power: $1M

Orbit Determination:

The first step in this system design was selecting the number of satellites to be used and their orbits. There is a tradeoff: closer orbits require less transmitting power, but may require more satellites. Satellites that are farther away require more transmitting power, but require fewer satellites. Since the cost of launching a satellite is much more than the cost of transmitted power, and since options like Code Division Multiple Access (CDMA) may be used (which provide a useful coding gain), satellites in "mars-stationary" orbits were used. A Mars-stationary orbit is like geostationary orbit, except with Mars as the central body.

Satellite Tool Kit (STK), with the evaluation copy of the 3D-graphics tool, was used to help determine orbit geometries. Using three equally spaced mars-stationary orbits provided almost full coverage, but did not provide coverage at the poles. Adding two Molnyia orbits (inclined, highly elliptical orbits meant to maximize coverage time at the poles), provided almost-continuous coverage, but there were still small gaps. Adding three more satellites in a mars-synchronous orbit with an inclination of 90º provided full coverage at all times.

All orbits are circular, with an eccentricity of 0 and all orbits have an orbital period of 88,642.6 seconds. This period specifies that the orbits are Mars-synchronous, since the rotational period of Mars is 24.62 hours, or 88,642.6 seconds. Other orbital elements were edited using STK. Changing the satellite's true anomaly (an orbital element) places the satellite three-dimensionally in its orbit. Thus, the space the satellites evenly, it is necessary to separate them by 120º. Initially, the satellites in the 90 –inclination orbit were also placed at 0ºº, 120º and 240º degrees respectively, but running the 3D animation in time showed that this would cause satellites to crash into each other, so the satellites were equally spaced with an offset of 60º. A summary of the orbit elements for each satellite is given in Table 1. Figure 1 is a 3D snapshot from STK of

	Period (sec)	**Eccentricity**	**Inclination (deg)**	**RAAN (deg)**	**True Anomaly (deg)**	**Semi-mjaor Axis (km)**
MarsSat1	88642.6632	0.0	0.0	0.0	0.0	20427.6844
MarsSat2	88642.6632	0.0	0.0	0.0	120.0	20427.6844
MarsSat3	88642.6632	0.0	0.0	0.0	240.0	20427.6844
MarsSat4	88642.6632	0.0	90.0	0.0	60.0	20427.6844
MarsSat5	88642.6632	0.0	90.0	0.0	180.0	20427.6844
MarsSat6	88642.6632	0.0	90.0	0.0	300.0	20427.6844

Table 1: Orbital Elements for the six MarsSat satellites

the six satellites and the planetary coverage. Figure 2 shows the initial footprints of the satellites. Figures 3&4 show close-up views of Mars with one of the satellites passing in front. The satellite in the pictures is a generic satellite from STK libraries, but MarsSat satellites will have will have two solar panel arrays that will be folded during transport via the space shuttle payload bay.

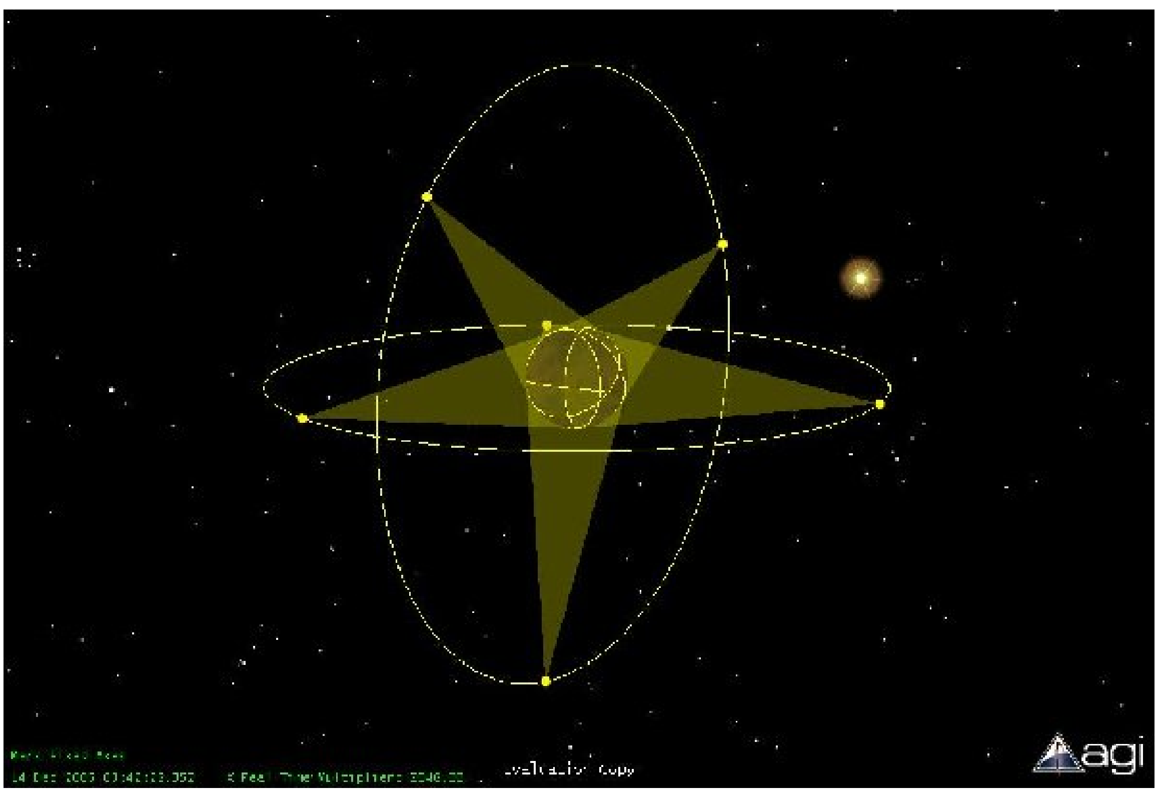

Figure 1: Three-dimensional view of MarsSat satellites and Martian coverage

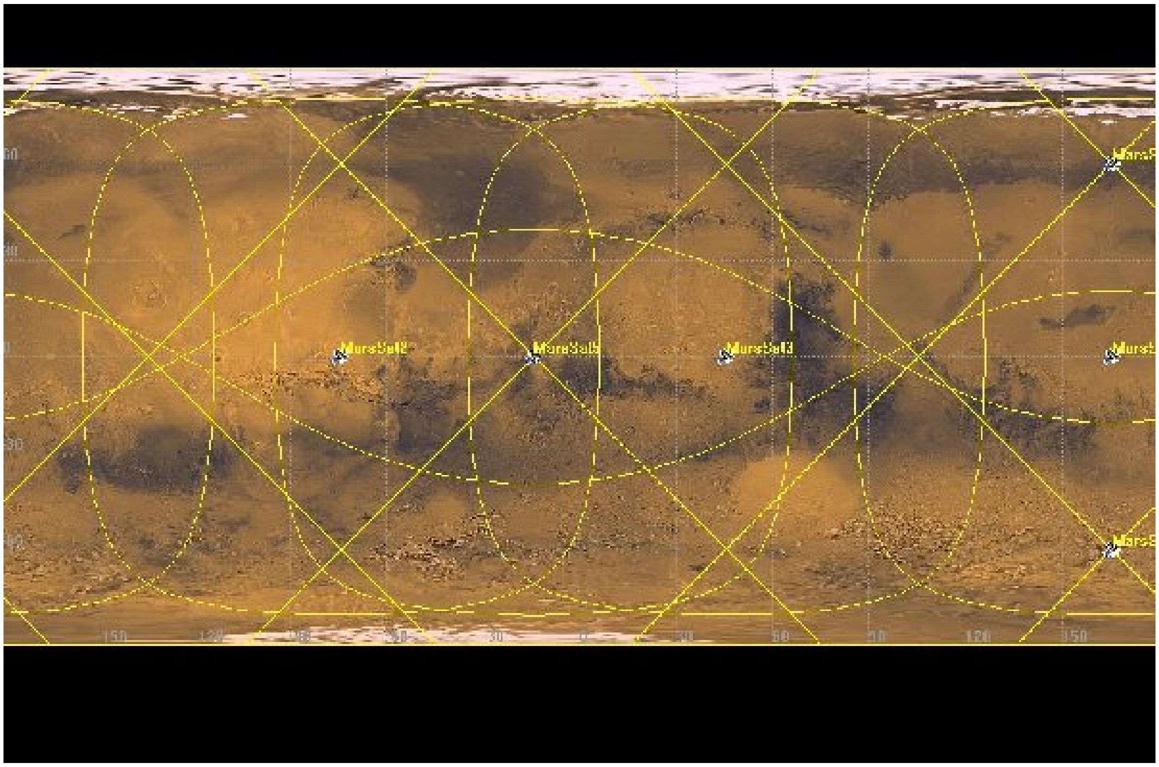

Figure 2: Two-dimensional Martian map and MarsSat coverage footprints

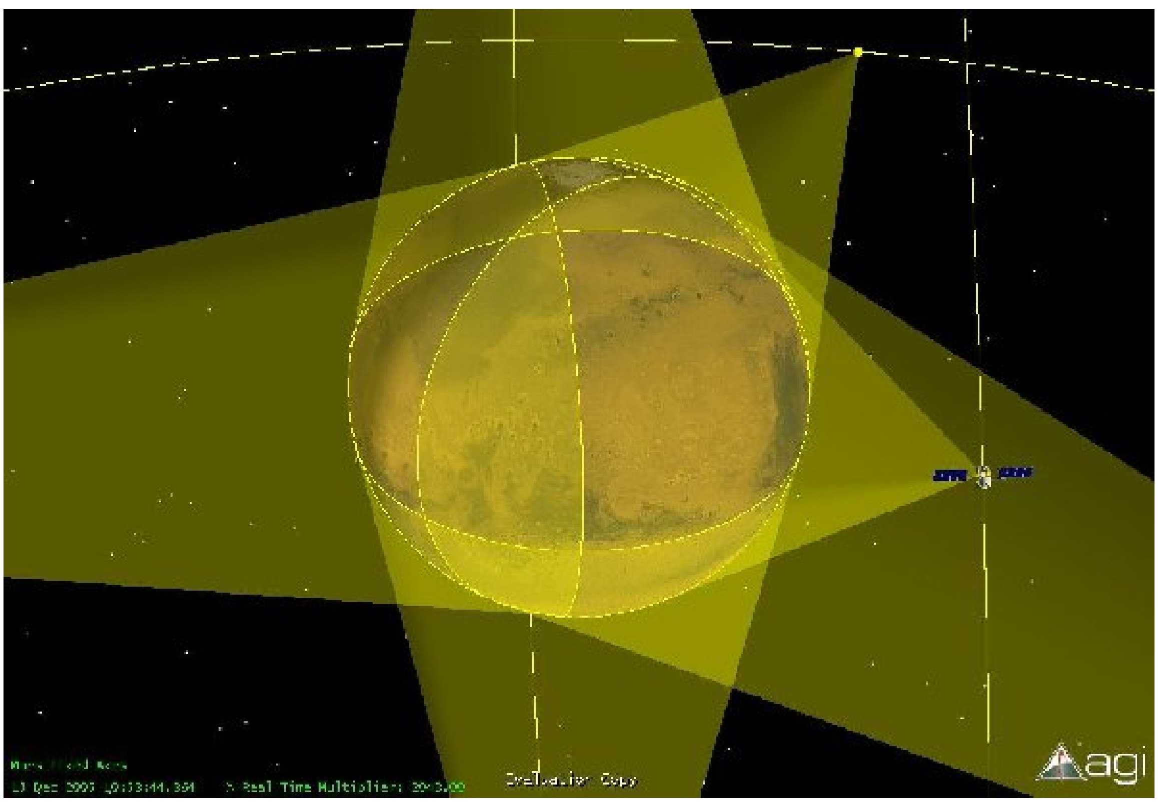

Figure 3: Three-dimensional close-up view of MarsSat Martian coverage

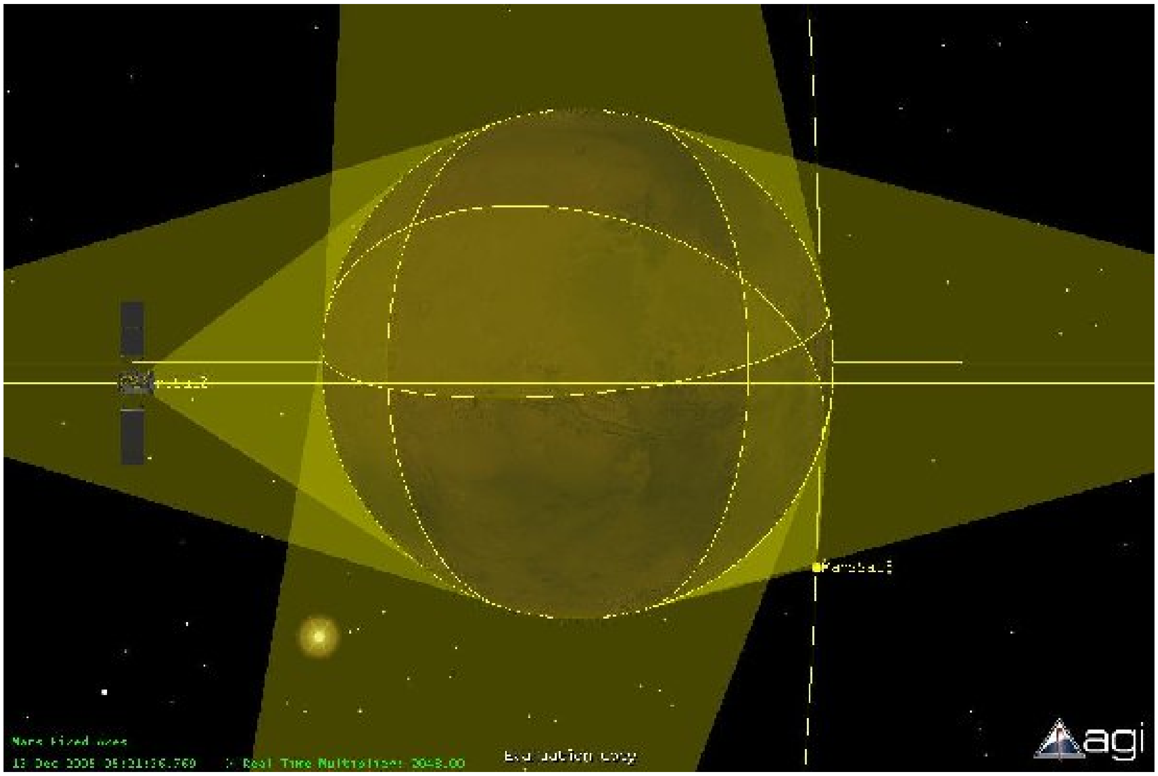

Figure 4: Three-dimensional close-up view of MarsSat2

Digital Communication Scheme:

A digital communication scheme was chosen once the orbits were determined. Requirement #8 states that the BER must not exceed 10^{-6}. Based on the BER vs. E_b/N_o chart on p. 282 of the course textbook[1], turbo coding was chosen to decrease the signal-to-noise (SNR) ratio needed to achieve the specified bit rate. This chart is valid for binary phase shift keying (BPSK), a simple modulation scheme, and is used in the MarsSat system. Since turbo coding double the bit rate and since BPSK uses one symbol per bit, the symbol period $R_s = 3.0 * 10^6$. This is equivalent to the noise bandwidth (see p.194 of text), which therefore equals 3 MHz. From the chart, E_b/N_o = 0.7 dB for the desired bit rate. However in practice an implementation margin, I_m, must be added to obtain SNR values. Research showed that 0.5 dB is a good estimate for I_m using BPSK at bit rates on the order of 1.5 Mbps.[2] Thus, the minimum SNR needed on each communication link is 1.2 dB. This will determine many other factors in the system design.

Requirement #3 states that signals should be fully selectable, so a multiple access scheme is needed. CDMA was chosen since it provides a high coding gain, which will help minimize the necessary transmitted power needed to achieve the minimum SNR. (This is important since the cost per transmitted watt of power is $1M). The coding gain is the dB version of the linear M, the number of chips per bit. M is given by the equation: $M = Q\left(10^{\left(\frac{SNR\_min}{10}\right)}\right)$.Since this was not an integer number, the floor command in MATLAB was used to obtain M = 67. The spread noise bandwidth is equal to M times the noise bandwidth, which equals 201 MHz.

Next, a raised cosine was used for pulse shaping. A for loop was used to determine k, the maximum rolloff-factor that is needed to ensure a bandwidth of no more than 500 MHz. This is the bandwidth of the chosen frequency bands that were given in requirements #5 & #6. In other words, communication between Mars and Earth will be between 31.8 and 32.3 GHz, and communication between Earth and Mars will be between 34.2 and 34.7 GHz. Figure 5 shows a plot of the raised cosine pulse, with k = 0.2430.

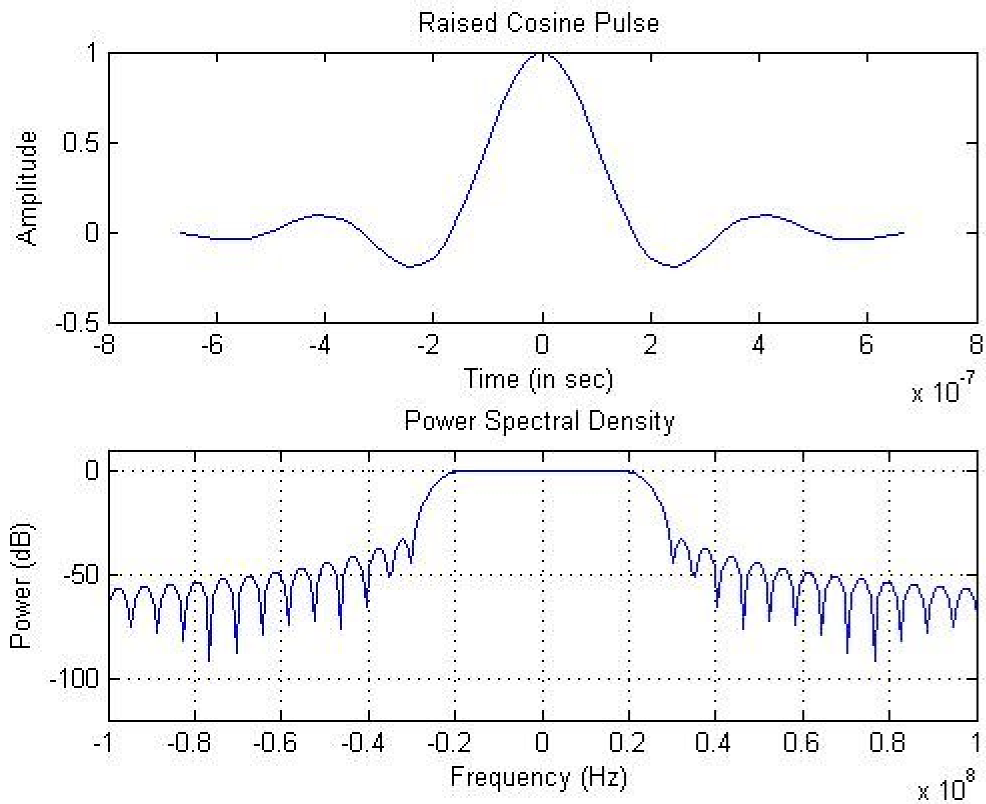

Figure 5: Raised Cosine pulse with κ = 0.2430

Before link budgets can be calculated for each communication link and before antenna determinations can be made, it is useful to calculate the noise power on each link. There are five links in this system: 1) DSN terminal to MarsSat satellite at 34.45 GHz, 2) MarsSat satellite to DSN terminal at 32.05 GHz, 3) MarsSat satellite to MarsSat terminal at 500 MHz, 4) MarsSat terminal to MarsSat satellite at 1.5 GHz, and 5) MarsSat satellite to MarsSat satellite at 1.0GHz. The frequencies for the uplink and downlink from the MarsSat satellite to the ground terminal were chosen for a few reasons. One, low frequencies means a higher wavelength, which decreases losses in the received signal power. Two, these frequencies are ultra-high frequencies (UHF), which were proposed by JPL to create a Martian communications network similar to the one designed here.[3] Three, these frequencies do not interfere with the frequencies in requirement #4. The following noise powers P_N were calculated: 1) The P_N received by a MarsSat satellite from Mars, 2) The P_N received by a MarsSat satellite from the Earth, 3) the P_N received at the DSN station from a MarsSat satellite, 4) the P_N received at the Martian terminal by a MarsSat satellite, and 5) the P_N received by a MarsSat satellite from another MarsSat satellite.

Noise power is equal to $k \cdot T_{sys} \cdot B$, where $T_{sys} = T_{physical} + T_{LNA}$. $T_{physical}$ for Earth is 290K.[4] A reliable value of $T_{physical}$ for Mars could not be found, so it was assumed as equal to the Earth. This is probably at least on the correct order of magnitude, since $T_{physical}$ for the moon is 200K.[5] The $T_{physical}$ for the MarsSat satellite is approximately equal to the cosmic background radiation at frequencies of about 1.0 GHz.[6] Thus, a $T_{physical}$ of 4K was used. T_{sys} for the DSN terminal is given to be 20K. The other T_{sys} need to be calculated using $T_{physical}$ and TLNA. TLNA can be calculated from the noise figure for an LNA. Reliable noise figures for: an LNA on a MarsSat satellite transmitting to Earth = 3.0,[7] for an LNA on a MarsSat satellite transmitting to Mars = 1.0,[8] for an LNA on a MarsSat terminal transmitting to a MarsSat satellite = 1.0,[9] and for a MarsSat satellite transmitting to a MarsSat satellite = 1.0.[8] Using these values, the following noise powers were calculated:

Received at MarsSat by Earth/DSN	-120.1520 dBW
Received at MarsSat by Mars	-120.4272 dBW
Received at MarsSat by MarsSat	-129.4906 dBW
Received at Earth/DSN from MarsSat	-132.5558 dBW
Received at Mars terminal from MarsSat	-149.5455 dBW

Table 2: Received power (dBW) for each link

Link Budget Analysis:

At this point, it is time to set up the link budget equations and make decisions about what kind of antennas to use. On the ground terminal station, a dish antenna of radius 0.5 m was used with an efficiency of 0.7, to minimize costs but also provide better SNR. A dish antenna of radius = 2 m and efficiency = 0.6 is on each satellite, for communication to DSN. There is a second dish antenna on each satellite for communication between satellites. This dish has a radius of 0.25 m and an efficiency of 0.6. There are also two horn antennas on each satellite, one for transmitting at 500 MHz and the other for receiving at 1.5 GHz. Horn antennas were chosen because the 3dB beamwidth can be calculated so that there is coverage for the entire planet, as shown in Figure 1. This 3dB beamwidth is 18.88°. Each horn antenna has an efficiency of 0.7, which is reasonable for a horn antenna. All dish antennas have a diameter no longer than 4.5m, which will fit inside the space shuttle payload bay.

Next, the worst and best-case link budget equations were written for each link. Best case occurs when a Mars-stationary satellite is transmitting to Mars' equator, so the path distance equals the satellite's altitude (17030.68 km). The "worst case" path is when a Mars-stationary satellite is transmitting to the pole, and the path distance equals 17366.00 km. The "best case" for the link between the satellite and DSN is when the Earth and Mars are at their closest point (aligned with the sun), and the "worst case" occurs when Mars and the Earth are on opposite sides of the sun. Only one case was calculated for satellite to satellite transmission, using a satellite-to-satellite distance of 35381.78 km (calculated by using the Law of Cosines).

Using the link budget equation: $P_R = P_T + G_T + G_R - 20 \cdot \log\left(\frac{4 \cdot \pi}{\lambda}\right) - 20 \cdot \log(r)$, the received power was calculated for each link. The worst and best-case SNR for each link was then found by subtracting the noise power from the received power and adding the coding gain. Using this method, the following SNRs were found for each link (assuming that each transmitter transmits at 2W:

Link	SNR (dBW)
Worst-case DSN to MarsSat	43.1501
Best-case DSN to MarsSat	56.8097
Worst-case MarsSat to DSN	4.8684
Best-case MarsSat to DSN	18.5280
Worst-case MarsSat to MarsTerminal	16.0042
Best-case MarsSat to MarsTerminal	16.1737
Worst-case MarsTerminal to MarsSat	3.6891
Best-case MarsTerminal to MarsSat	3.8585
MarsSat to MarsSat	29.1850

Table 3: SNR values (dBW) for each link

This design meets the requirements, as each of these links has an SNR that meets the minimum required SNR of 1.2 dBW. The cost to deploy this system would be $1.2B for the launch of the six satellites, and $12M for the transmitting power (6 satellites, each transmitting at 2W). This is a reasonable cost, considering the scope of the task. All components will fit inside the space shuttle payload bay.

References:

1. Pratt T, Bostian C, Allnutt J. Satellite Communications, 2nd Ed. John Wiley & Sons, Inc:2003.
2. http://www.ee.vt.edu/~ee5656/faq2midt.htm
3. http://marsnet.jpl.nasa.gov/
4. http://64.233.187.104/search?q=cache:pxPLF7llaR4J:www.asri.org.au/ASRI/research/satellite/australis/11radio.doc+%22noise+temperature%22+sky+1GHz&hl=en
5. http://sina.sharif.ac.ir/~barkeshli/antennas/review/9510_033.htm
6. http://www.st-andrews.ac.uk/~www_pa/Scots_Guide/RadCom/part8/page3.html
7. http://www.spaceklabs.com/Products/MM-Wave_Amplifiers/mm-wave_amplifiers.html
8. http://www.mwrf.com/Article/ArticleID/7763/7763.html
9. http://www.d2m.com/intarsiaweb/productsApps/proApps_amplifiers.html

Appendix: MATLAB Code

```
% Lisa Moyer
% ECE 6390 Final Project
% Martian Network
% December 13, 2005

clear;
clc;

% ---------------------------------------------------------------------
%                   Digital Transmission
% ---------------------------------------------------------------------

% Turbo coding & BPSK
% -------------------
BER = 10^-6;                % between Mars & Earth
R_b_given = 1.5*10^6;       % bps
R_b = 2*R_b_given           % bps, because using turbo coding (p.282)
R_s = R_b                   % bps, because using BPSK
B_n = R_s                   % Hz, (p.194)
Eb_No = 0.7;                % dB (p.282)
Im = 0.5;                   % dB, Implementation margin, see:
                            %    http://www.ee.vt.edu/~ee5656/faq2midt.htm
CNR_min = Eb_No + Im;       % dB


% Multiple Access: CDMA
% ---------------------
SNR_min = CNR_min           % dB
Q = 51;                     % 50 Mars Terminals + 1 Earth Terminal
M = floor(Q*10^(SNR_min/10))% chips/bit (p.262)
coding_gain = 10*log10(M)   % dB, coding gain
B_n_spread = M*B_n          % Hz, noise bandwidth spread by M


% Pulse Shaping: Raised Cosine
% ----------------------------
B_max = 500 * 10^6;         % Hz, b/c of CDMA pick larger BW
for k = 1:-0.001:0,         % iteratively solve for k, rolloff factor
   BW = 2*(1+k)*R_s;
   if BW*M <= B_max,
      break;
   end
end
k
f0 = R_s;
t1 = -2/f0;                 % first sample
t2 = -t1;                   % second sample
N = 512;                    % number of time-domain samples
t = linspace(t1,t2,64);     % creates a time-domain axis
f = (-N/2:N/2-1)/(t2-t1);   % creates a frequency-domain axis
x = (sin(2*pi*f0*t)./(2*pi*f0*t)).*(cos(2*pi*k*t*f0)./(1-(4*k*f0*t).^2));
                            % (above: raised cosine)
```

```
% subplot(2,1,1)
% plot(t,x)
% xlabel('Time (in sec)');ylabel('Amplitude');title('Raised Cosine Pulse');
% X = fft(x,N);
% XX = abs(fftshift(X))*(t2-t1)/N;
% XX_new = 20*log10(XX/max(XX));
% subplot(2,1,2)
% plot(f,XX_new), axis([-100e6 100e6 -120 10]), grid on
% xlabel('Frequency (Hz)');ylabel('Power (dB)');
% title('Power Spectral Density');


% Noise Power on Links
% --------------------
k = 1.381*10^-23;           % Boltzman's constant

NF_LNA_MarsSat_Earth = 3.0;
  % dB, moderate bandwidth LNA from Spacek
NF_LNA_MarsSat_Mars = 1.0;
  % dB, http://www.mwrf.com/Article/ArticleID/7763/7763.html
NF_LNA_MarsTerm = 1.0;
  % dB, http://www.d2m.com/intarsiaweb/productsApps/proApps_amplifiers.html
NF_LNA_MarsSat_MarsSat = 1.0;

T_LNA_MarsSat_Earth = 290*10^((NF_LNA_MarsSat_Earth)/10 - 1);
T_LNA_MarsSat_Mars = 290*10^((NF_LNA_MarsSat_Mars)/10 - 1);
T_LNA_MarsTerm = 290*10^((NF_LNA_MarsTerm)/10 - 1);
T_LNA_MarsSat_MarsSat = 4*((NF_LNA_MarsSat_MarsSat)/10 - 1);

Tsys_DSN = 20;
        % K, given in problem
Tsys_MarsTerm = 4 + T_LNA_MarsTerm;
        % 4K - see reference chart, 4K is about sky noise temp at 1.5GHz
Tsys_MarsSat_Earth = 290 + T_LNA_MarsSat_Earth;
        % 290K - http://www.satcom.co.uk/article.asp?article=5&section=7
Tsys_MarsSat_Mars = 290 + T_LNA_MarsSat_Mars;
        % 290K - assume about the same as Earth, could not find data
Tsys_MarsSat_MarsSat = 4 + T_LNA_MarsSat_MarsSat;

Pn_atSat_fromEarth = 10*log10(k*Tsys_MarsSat_Earth*B_n_spread)
         % Rx at MarsSat from Earth
Pn_atEarth_fromSat = 10*log10(k*Tsys_DSN*B_n_spread)
         % Rx at Earth from MarsSat
Pn_atMars_fromSat = 10*log10(k*Tsys_MarsTerm*B_n_spread)
         % Rx at Mars from MarsSat
Pn_atSat_fromMars = 10*log10(k*Tsys_MarsSat_Mars*B_n_spread)
         % Rx at MarsSat from Mars
Pn_atSat_fromSat = 10*log10(k*Tsys_MarsSat_MarsSat*B_n_spread)



% ---------------------------------------------------------------------
%                     Link Budget Analysis
% ---------------------------------------------------------------------
```

```
MarsSat_altitude = 17030.684417 * 10^3;     % m
Mars_radius = 3397 * 10^3;                  % m, from STK
c = 3.0*10^8;                               % m
Mars_perihelion = 206644545000;             % m, Wikipedia
Mars_aphelion  = 249228730000;              % m, Wikipedia
Earth_perihelion = 147098074000;            % m, Wikipedia
Earth_aphelion = 152097701000;              % m, Wikipedia
Mars_distance = (Mars_perihelion + Mars_aphelion)/2;
Earth_distance = (Earth_perihelion + Earth_aphelion)/2;
f_MarsSattoTerm = 500*10^6;                 % Hz, in UHF range
f_MarsTermtoSat = 1*10^9;                   % Hz, in UHF range
f_DSNtoSat = 34.45 * 10^9;                  % Hz
f_SattoDSN = 32.05 * 10^9;                  % Hz
f_SattoSat = 1*10^9;                        % Hz
l_MarsTermtoSat = c/f_MarsTermtoSat;
l_MarsSattoTerm = c/f_MarsSattoTerm;
l_DSNtoSat = c/f_DSNtoSat;
l_SattoDSN = c/f_SattoDSN;
l_SattoSat = c/f_SattoSat;
ThreedBbeamwidth = 18.88;                   % degrees

% Calculate worst & best case r for link between MarsSat & MarsTerm

r_sat_term_worst = sqrt(MarsSat_altitude^2 + Mars_radius^2)
r_sat_term_best = MarsSat_altitude;

% Calculate worst & best care r for link between DSN & MarsSat

r_DSN_sat_worst = Mars_distance + Earth_distance;
r_DSN_sat_best = Mars_distance - Earth_distance;

% Calculate distance between two satellites in same plane

r_sat_sat = 35381.787279*1000;              % m, from Law of Cosines


% Antenna: DSN Dish
% ------------------
DSN_radius = 17;                  % m, given
DSN_efficiency = 0.94;            % given
PT_DSN = 10*log10(500000);        % dB

% Antenna: Mars Ground Terminal Dish
% ---------------------------------
MarsTerm_radius = 0.5;            % m, given
MarsTerm_efficiency = 0.7;        % CHOOSE
PT_MarsTermtoSat = 10*log10(2);   % dB, CHOOSE VARIABLE

% Antenna: Mars Satellite Dish to DSN
% ----------------------------------
MarsSattoDSN_radius = 2;          % m, CHOOSE
MarsSattoDSN_efficiency = 0.6;    % CHOOSE
PT_MarsSattoDSN = 10*log(2);      % CHOOSE
```

```
% Antenna: Mars Horn (Tx) to Mars Terminal (0.5 GHz)
% --------------------------------------------------
MarsSattoTerm_efficiency = 0.7;     % CHOOSE
MarsSattoTerm_diameter = 75*l_MarsSattoTerm/ThreedBbeamwidth;
PT_MarsSattoTerm = 10*log(2);

% Antenna: Mars Term to Mars Horn (Rx) (1.5 GHz)
% ----------------------------------------------
MarsTermtoSat_efficiency = 0.7;     % CHOOSE
MarsTermtoSat_diameter = 75*l_MarsTermtoSat/ThreedBbeamwidth;

% Antenna: Dish for Satellite to Satellite
% ----------------------------------------
MarsSattoSat_radius = 0.25;        % m, CHOOSE
MarsSattoSat_efficiency = 0.6;      % CHOOSE
PT_MarsSattoSat = 10*log(2);        % dB, CHOOSE VARIABLE



% Link: DSN (tx) to MarsSat (rx)
% ------------------------------
Gain_DSN = 10*log10(4*pi*pi*DSN_radius^2*DSN_efficiency/(l_DSNtoSat)^2);
Gain_MarsSat =
10*log10(4*pi*pi*MarsSattoDSN_radius^2*MarsSattoDSN_efficiency/(l_DSNtoSat)^2);
PR_worst = PT_DSN + Gain_DSN + Gain_MarsSat - 20*log10(4*pi/l_DSNtoSat) -
20*log10(r_DSN_sat_worst);
PR_best = PT_DSN + Gain_DSN + Gain_MarsSat - 20*log10(4*pi/l_DSNtoSat) -
20*log10(r_DSN_sat_best);

SNR_DSNtoMarsSat_worst = PR_worst - Pn_atSat_fromEarth + coding_gain
SNR_DSNtoMarsSat_best = PR_best - Pn_atSat_fromEarth + coding_gain

% Link: MarsSat (tx) to DSN (rx)
% ------------------------------
Gain_DSN = 10*log10(4*pi*pi*DSN_radius^2*DSN_efficiency/(l_SattoDSN)^2);
Gain_MarsSat =
10*log10(4*pi*pi*MarsSattoDSN_radius^2*MarsSattoDSN_efficiency/(l_SattoDSN)^2);
PR_worst = PT_MarsSattoDSN + Gain_DSN + Gain_MarsSat - 20*log10(4*pi/l_SattoDSN) -
20*log10(r_DSN_sat_worst);
PR_best = PT_MarsSattoDSN + Gain_DSN + Gain_MarsSat - 20*log10(4*pi/l_SattoDSN) -
20*log10(r_DSN_sat_best);

SNR_MarsSattoDSN_worst = PR_worst - Pn_atEarth_fromSat + coding_gain
SNR_MarsSattoDSN_best = PR_best - Pn_atEarth_fromSat + coding_gain

% Link: MarsSat (tx) to MarsTerm (rx)
% -----------------------------------
Gain_MarsSat =
10*log10(MarsSattoTerm_efficiency*(pi*MarsSattoTerm_diameter/l_MarsSattoTerm)^2);
Gain_MarsTerm =
10*log10(4*pi*pi*MarsTerm_radius^2*MarsTerm_efficiency/(l_MarsSattoTerm)^2);
PR_worst = PT_MarsSattoTerm + Gain_MarsSat + Gain_MarsTerm -
20*log10(4*pi/l_MarsSattoTerm) - 20*log10(r_sat_term_worst);
```

```
PR_best = PT_MarsSattoTerm + Gain_MarsSat + Gain_MarsTerm -
20*log10(4*pi/l_MarsSattoTerm) - 20*log10(r_sat_term_best);

SNR_MarsSattoTerm_worst = PR_worst - Pn_atMars_fromSat + coding_gain
SNR_MarsSattoTerm_best = PR_best - Pn_atMars_fromSat + coding_gain

% Link: MarsTerm (tx) to MarsSat (rx)
% ----------------------------------
Gain_MarsSat =
10*log10(MarsTermtoSat_efficiency*(pi*MarsTermtoSat_diameter/l_MarsTermtoSat)^2);
Gain_MarsTerm =
10*log10(4*pi*pi*MarsTerm_radius^2*MarsTerm_efficiency/(l_MarsTermtoSat)^2);
PR_worst = PT_MarsTermtoSat + Gain_MarsTerm + Gain_MarsSat -
20*log10(4*pi/l_MarsTermtoSat) - 20*log10(r_sat_term_worst);
PR_best = PT_MarsTermtoSat + Gain_MarsTerm + Gain_MarsSat -
20*log10(4*pi/l_MarsTermtoSat) - 20*log10(r_sat_term_best);

SNR_MarsTermtoSat_worst = PR_worst - Pn_atSat_fromMars + coding_gain
SNR_MarsTermtoSat_best = PR_best - Pn_atSat_fromMars + coding_gain

% Link: MarsSat (tx) to MarsSat (rx)
% ---------------------------------
Gain_MarsSat =
10*log10(4*pi*pi*MarsSattoSat_radius^2*MarsSattoSat_efficiency)/(l_SattoSat^2);
PR = PT_MarsSattoSat + Gain_MarsSat + Gain_MarsSat - 20*log10(4*pi/l_SattoSat) -
20*log10(r_sat_sat);

SNR_MarsSattoSat = PR - Pn_atSat_fromSat + coding_gain
```