ECE 6390 Project : Communication system

December 9, 2008

1. Overview

The Martian GPS network consists of 18 satellites (3 constellations of 6 satellites). One master satellite of each constellation will be equipped with high gain antennas to communicate with Earth. The control data will be used both on uplink and the downlink in order to send control signals from Earth to Mars and also to receive feedback from Mars to Earth.

Three links are considered in this mission

- Earth-Mars : full duplex
- Mars orbit - Mars surface : simplex
- Inter-satellite : full duplex

2. Earth Mars Link Design

2.1 Earth Mars distance

A simple model for Earth to Mars distance computation gives the following variation

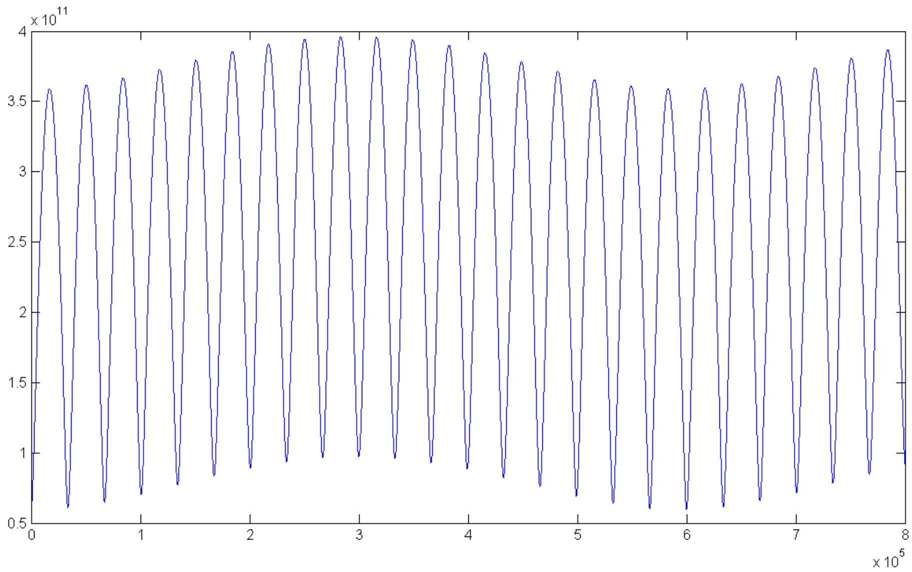

Figure 1: Simple Earth Mars distance simulation

The assumptions for this model were :

- the orbits of Earth and Mars are in the same plane.
- The two perihelions of both planets are aligned with the center of the Sun

Below is the plot given in Ref[4] which uses a more complex and realistic model :

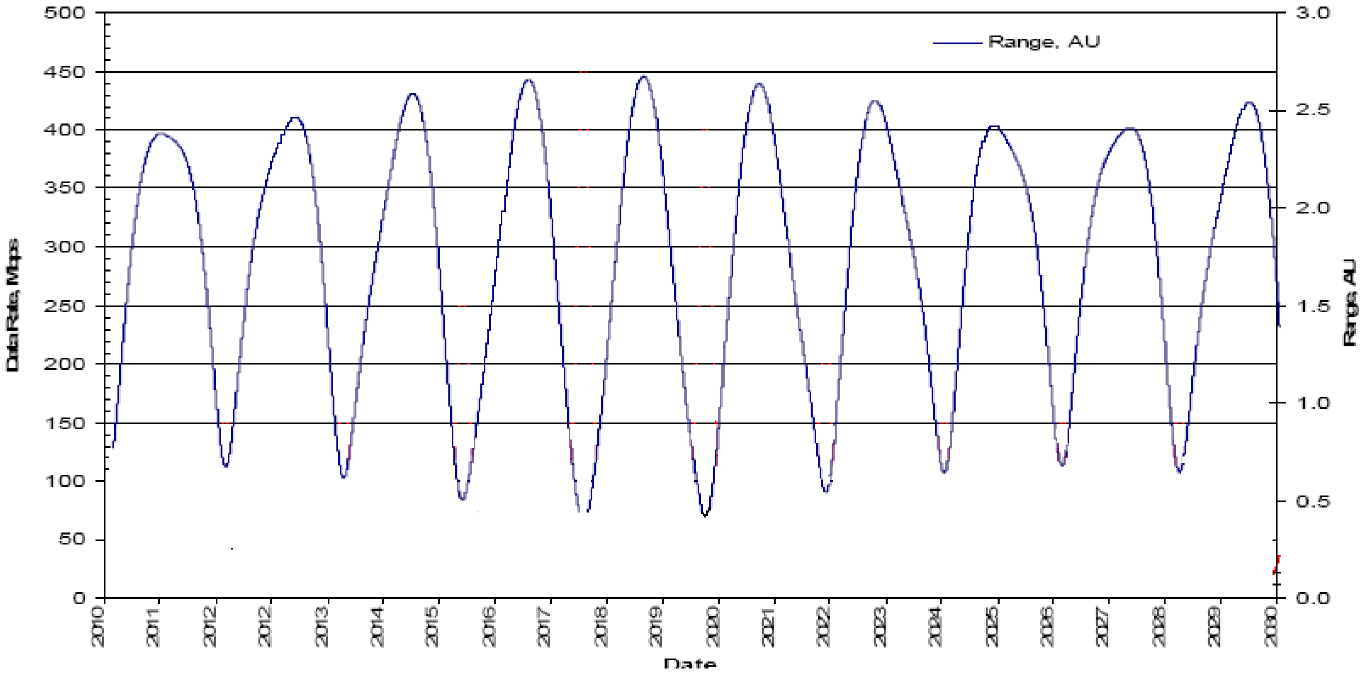

Figure 2: Realistic Earth Mars distance for the next 20 years

The variation range is approximately 56,000,000 km to 401,000,000 km.

The link is designed so that 1 Mbps is feasible at the maximum distance of 401,000,000 km

2.2 New changes in deep space communications : the use of Ka-Band

In August 2005, the Mars Reconnaissance Orbiter (MRO) was launched. To support the MRO requirements, there have been several changes implemented in NASA's Deep Space Network.

There are three DSN complexes around the world, located in Goldstone (California), Madrid (Spain) and Canberra (Australia). Each complex has one 70m (diameter) antenna, a number of 34m antennas, and one 26m antenna. The primary purpose of a deep space network is to provide communication and navigation services as well as a continuous coverage for deep space missions. The NASA DSN will be used as the Earth terminal for our project. As the DSN is connected to the internet, the Mars GPS network is available from anywhere on Earth. MRO had demonstrated that Ka-band (32 GHz) communications can be used for navigational purposes Ka-band provides two major advantages for communications and one major drawback. The first advantage is that the higher frequency provides higher gain than does the current deep space standard X-band for a same sized antenna. The second advantage is the allocated deep space bandwidth is 500 MHz, as opposed to 50 Mhz at X-band. The Ka-band spectrum allocation for deep space mission as recommended by the Space Frequency Coordination Group is as follows :

Mission Category	Mission	Uplink (forward) band (GHz)	Downlink (return) band (GHz)
A	TDRSS	None	25.5 to 27.0
A	Lunar, L2; human and robotic (SFCG)	None	37.5 to 38.0
B	Deep space robotic exploration	34.2 to 34.7	31.8 to 32.3
B	Deep space human and robotic exploration (SFCG)*.	40.0 to 40.5	37.0 to 37.5

* Includes deep-space technology demonstration in near-Earth regions.

Note: Category A – Missions within Lunar Vicinity (< 2million km), Category B – Deep Space Missions (> 2million km)

Figure 3: Ka-band allocation

The disadvantage is a large one, namely that the weather effects in the 32 GHz frequency range are not friendly to communications. Ka-band communication links are more affected by atmosphere and weather.

Now, each of the 3 DSN complexes has at least one 34 m antenna upgraded to support Ka-band. The martian GPS network will take advantage of this improvement.

2.3 Turbo-coding/decoding

In 2003 the new CCSDS (Consultative Committee on Space Data Systems) turbo codes were implemented in the DSN. Turbo encoders are sufficiently simple that they can be implemented readily in hardware or software on a satellite. The Martian GPS network project is a great opportunity to use these codes !

The standardized turbo encoder consists of two 16-state convolutional encoders, connected with an interleaver. Code rate of 1/2 can be achieved and 3 Block lengths of 1784 through 8920 information bits are specified.

The turbo encoder embedded in the satellite will look like this :

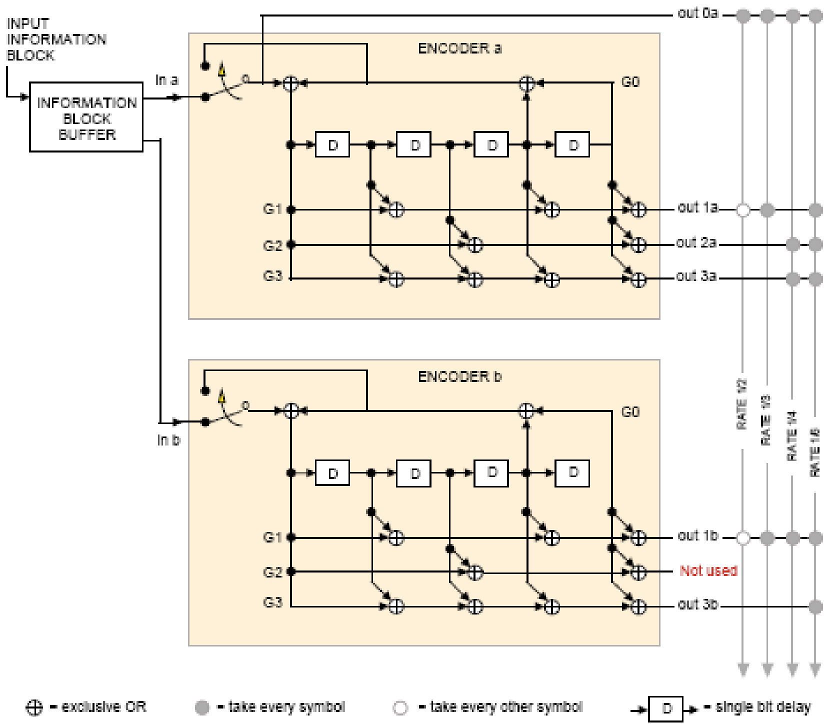

Figure 4: A standardized turbo encoder

Here is the datasheet for this turbo encoder :

http://www.sworld.com.au/pub/pce04c.pdf

Figure 5 gives the performance of some concatenated codes. It should be noted that Reed Solomon codes have the advantage of high coding gains.

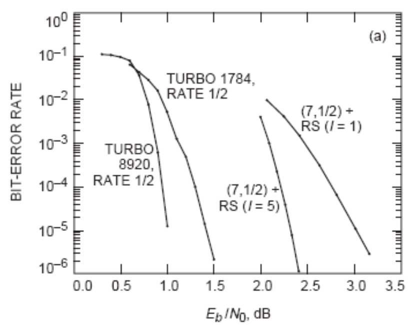

Figure 5: Performance of turbo encoder

It appears that the concatenation of (255;223) Reed-Solomon with and (rate-0.4998, length-8920) turbo code outperforms the other codes. A 1dB SNR per bit suffices to get an bit error rate of 10^{-5}. This is our choice for the error-control-coding scheme in the Earth Mars link design.

The coding and decoding structure for both links (uplink and downlink) is illustrated here

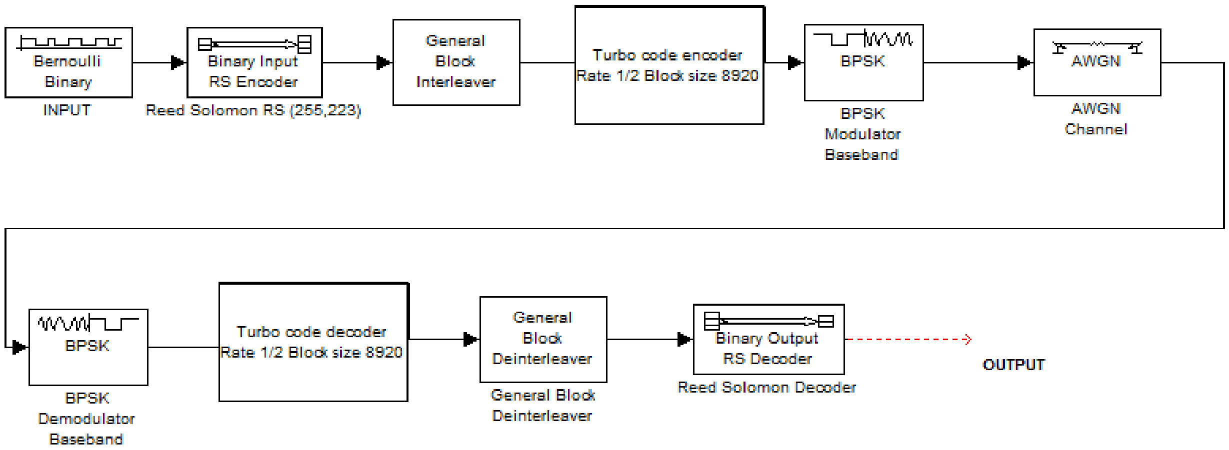

Figure 6: Coding and decoding structure

The link design for each case is initiated with the worst case scenario from the furthest distance. Three of the 18 satellites (one per constellation) orbiting Mars will have the capability to communicate with Earth. These 3 hub satellites are chosen so that there is always one facing Earth.

2.4 Uplink Budget

The table shows the various parameters used to compute Earth to Mars link budget. A frequency of 34.45 GHz was chosen for this link to be consistent with the DSN specifications. The signal to noise ratio of 17 dB guarantees an nearly error-free communication.

Uplink data & budget		
D_b	Actual bit rate	1 Mbps
	Reed-Solomon coding rate	223/255
	Turbo code coding rate	1/2
	Physical bit rate	2.287 Mbps
	Modulation	BPSK
	Roll-off factor	0.5
B	bandwidth	3.43 Mhz
D_b/B	actual spectral efficiency	0.29 bps/Hz
T	Physical noise temperature	25 K
B	Atmospherical noise temperature (99.9% of the time)	$100K$
N	Noise power	-142.28 dBW
f	frequency	34.45 GHz
λ	wavelength	0.00870 m
r	maximum distance	4.01×10^{11} m
	maximum pathloss	-295.25 dB
P_t	Transmit power	30 dBW
	DSN antenna diameter	34 m
G_t	DSN antenna gain	81 dBi
η	satellite antenna efficiency	0.8
d	satellite antenna diameter	3 m
G_r	satellite antenna gain	59.09 dBi
P_r	Received Power	-125.16 dBW
C/N	Carrier to Noise ratio	17.12 dB
$P_b(e)$	Probability of error	~ 0

2.5 Downlink budget

When the distance between Earth and Mars reduces to its minimum, there is an increase in the link margin to about 17 dB that allows one to trade among the given trade space as: (1) increasing the downlink data rate or (2) applying power conservation methods on the satellite.

Downlink data & budget		
D_b	Actual bit rate	1 Mbps
	Reed-Solomon coding rate	223/255
	Turbo code coding rate	1/2
	Physical bit rate	2.287 Mbps
	Modulation	BPSK
	Roll-off factor	0.5
B	bandwidth	3.43 Mhz
D_b/B	actual spectral efficiency	0.29 bps/Hz
T	Physical noise temperature	40 K
B	Atmospherical noise temperature (99.9% of the time)	$100K$
N	Noise power	-142.17 dBW
f	frequency	32.05 GHz
λ	wavelength	0.009354 m
v_{Earth}	Earth velocity	29.784 km/s
v_{Mars}	Mars velocity	24.129 km/s
$v_{satellite}$	Satellite velocity	1.4247 km/s
f_D	Doppler shift estimation	757 kHz
r	maximum distance	4.01×10^{11} m
	maximum pathloss	-294.63 dB
P_t	Transmit power	18 dBW
η	satellite antenna efficiency	0.8
d	satellite antenna diameter	3 m
G_t	satellite antenna gain	59.09 dBi
	DSN antenna diameter	34 m
G_r	DSN antenna gain	81 dBi
P_r	Received Power	-138.54 dBW
C/N	Carrier to Noise ratio	3.64 dB
$P_b(e)$	Probability of error	~ 0

2.6 Pulse shape

To meet the requirements of the DSN, pulse shaping is necessary to make sure that negligible power is out of our allocated band. The raised cosine pulse is known to have a limited bandwidth. Below is the power spectrum of a raised cosine pulse with roll off factor 0.50.

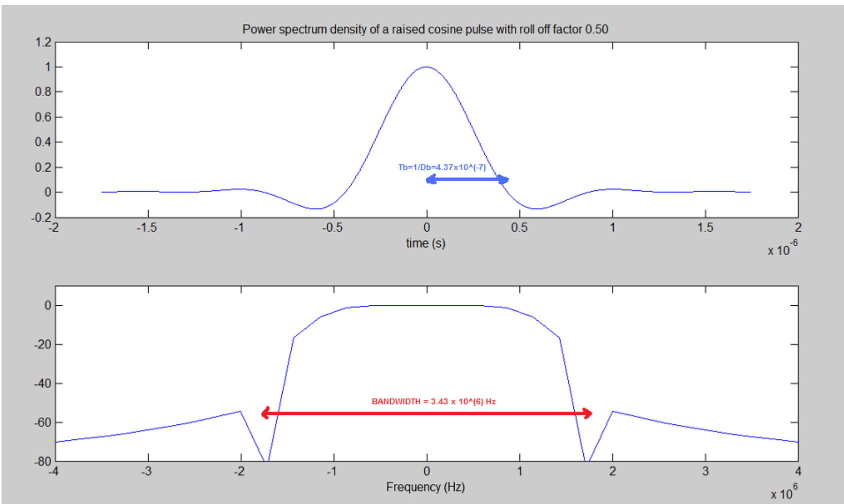

Figure 7: Pulse shaping

3. Mars Orbit to Mars receiver Link Design

- The quality of this link mostly relies on the Gold code :

  Generators for Gold code of length $2^{13} - 1 = 8191$

$$\boxed{g_1(x) = 1 + x + x^5 + x^6 + x^7 + x^9 + x^{10} + x^{12} + x^{13}}$$

$$\boxed{g_2(x) = 1 + x + x^3 + x^4 + x^{13}}$$

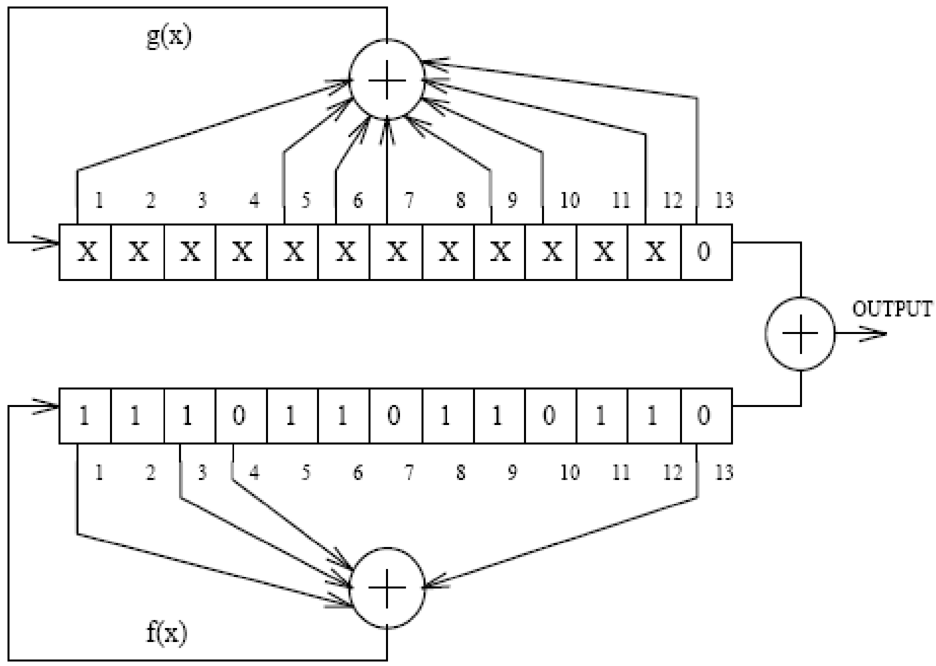

Figure 8: A length 8191 Gold code

Our simulation shows that the autocorrelation of this Gold code is nearly perfect (SIMULINK)

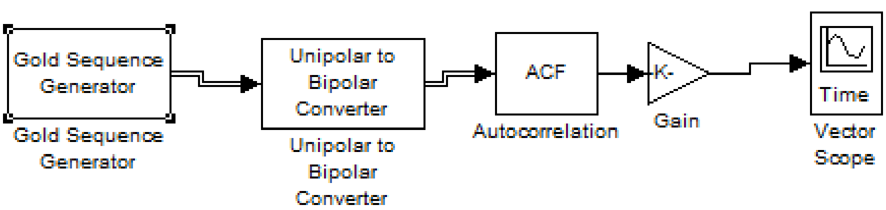

Figure 9: Simulation for autocorrelation

Processing gain is

$$\boxed{M = 10\log(8191) = 39.13dB}$$

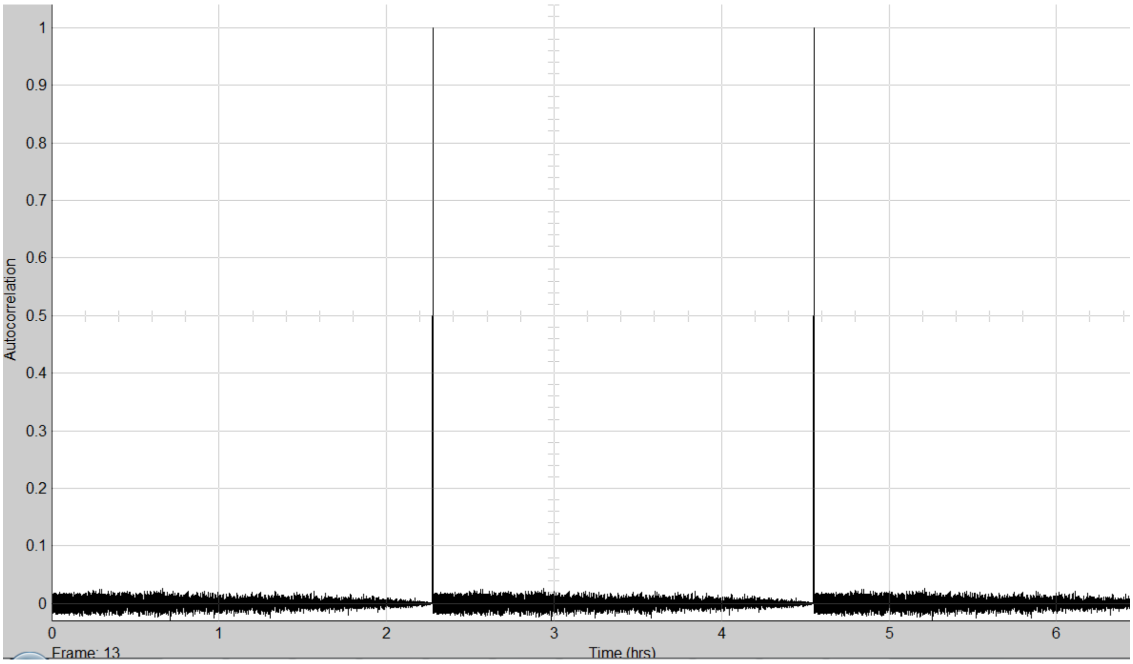

Figure 10: autocorrelation

MPS facts		
D_b	Bit rate	50 bps
D_c	Chip rate	409550 chip/s
L	Gold code length	8191 chip
M	Processing gain	39.13 dB
	Modulation	BPSK
B	Bandwidth	$\sim 1Mhz$
T	Physical noise temperature (Upward looking on Mars)	9 K
B	Antenna noise temperature	176 K
N	Noise power	$2.553 \times 10^{-15}W$
V	Maximum number of visible satellites	8
I	Interference power	$4.2 \times 10^{-17}W$
N+I	Overall interference	$2.595 \times 10^{-15}W$
N+I	Overall interference (dB)	-145.86 dB
f	frequency	2.23 GHz
λ	wavelength	$0.1345m$
$v_{satellite}$	satellite velocity	1.4247 km/s
f_D	Doppler shift estimation	10.59 kHz
r	distance	$R = 17708.5km$
	pathloss	-184.37 dB
Θ_{HPBW}	required HPBW (Jacob's work)	17.68°
G_T	required gain	20.23 dBi
η	antenna efficiency	0.8
d	antenna diameter	0.49 m
P_T	transmit power	4.92 dBW
G_r	Receive antenna gain in the worst case	-13 dBi
P_r	Received Power	-172.22 dBW
$(C/N)_{spread}$	Spread Carrier to Noise ratio	-26.36 dB
$(C/N)_{despread}$	Despread Carrier to Noise ratio	12.77 dB
	Link margin	1 dB
$(C/N)_{despread}$	Despread Carrier to Noise ratio	11.77 dB
$P_b(e)$	Probability of errorQ $\sqrt{2\frac{S}{N}}$	2.0653e-008

- At the bit rate of 50 bit/s this means one error every 11 days.

The overall MPS CDMA system has been simulated with Matlab/Simulink given the conditions we derived above.

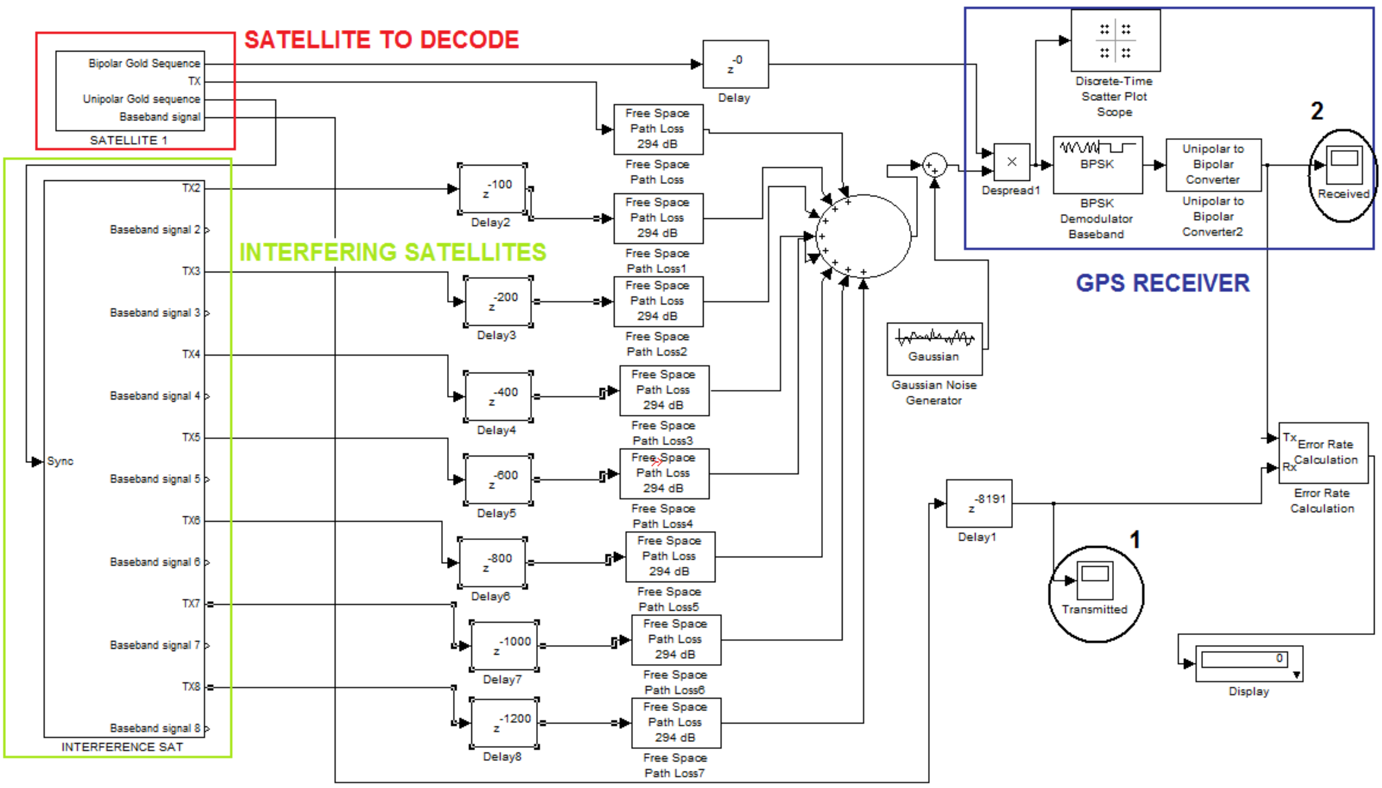

Figure 11: MPS CDMA

Scopes 1 and 2 have been compared and it appears that the MPS receiver is able to recover the data transmitted by the satellite 1. If the delay of the Gold code at the despread operation matches the propagation delay of satellite i, then it decodes the data sent by the satellite i.

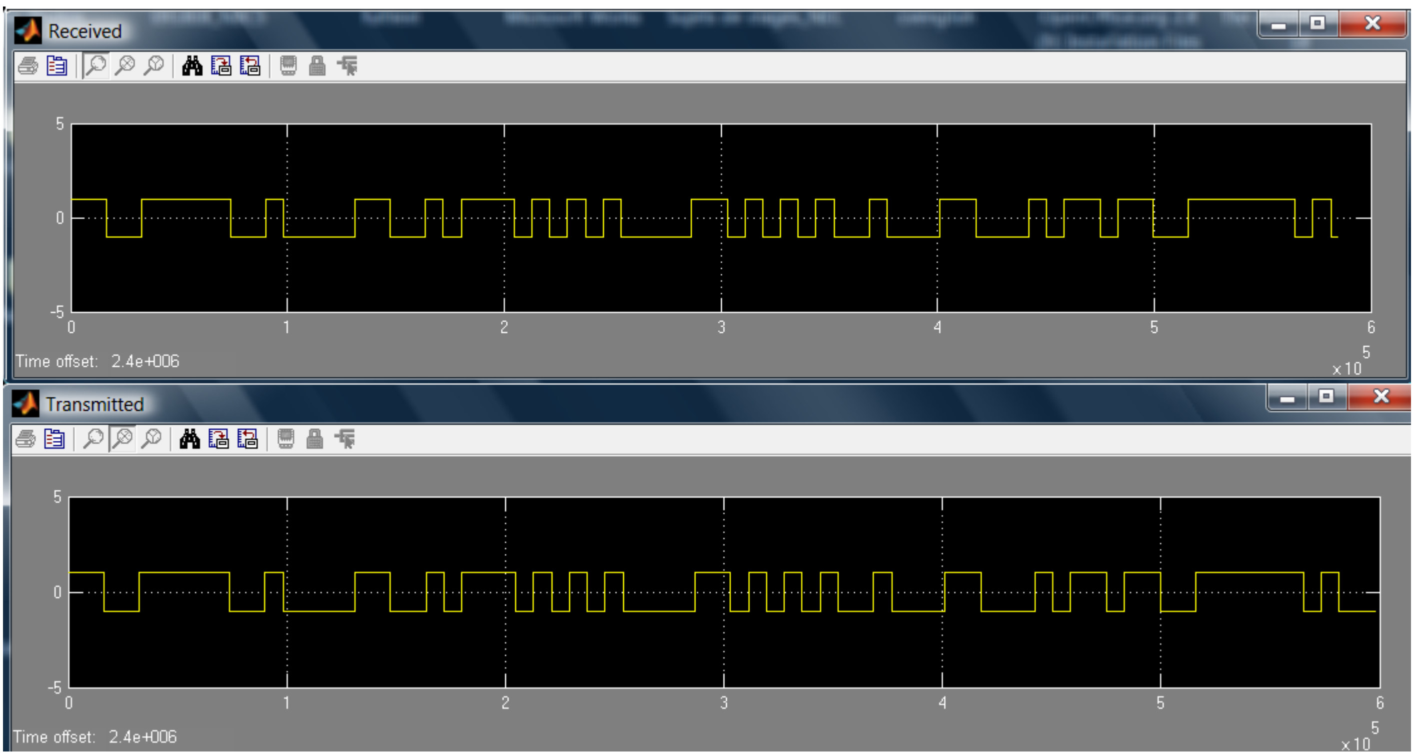

Figure 12: Transmitted and received signals

The simulation run was too slow to simulate a significant number of data bit because one instruction period was a chip period only. However the bit stream at the receiver has always been error-free compared to the transmitted data stream.

4. Satellite to Satellite Link Design

The 3 hub satellites will be able to relay the signal received from Earth using X-band. Each satellite will communicate with the adjacent satellites of the same constellation.

The single conversion transponder (bentpipe) could be used

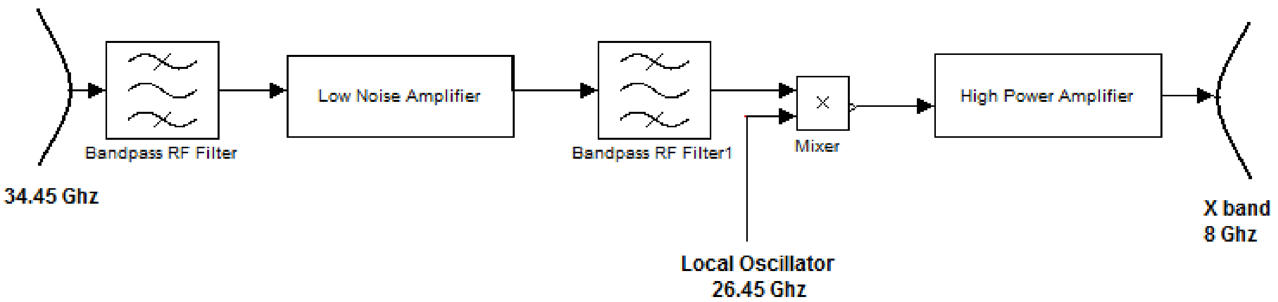

Figure 13: Bent pipe transponder

Link Budget for inter-satellite link		
P_T	Hub Satellite Transmit Power	5 dBW
d	Antenna diameter	0.6 m
η	Antenna efficiency	0.8
λ	wavelength	0.0375 m
G_T	Hub Satellite antenna gain	33.06 dBi
G_R	Receive antenna gain	33.06 dBi
$20\log_{10}\frac{\lambda}{4\pi}$	pathloss	-50.50 dBi
$20\log_{10}\frac{1}{r}$	pathloss	-146.02 dBi
Total		$P_r = -130.41 dBW$
B	Bandwidth	$3.43 \times 10^6 Hz$
T	Noise temperature	50 K
$10\log_{10}(kTB)$	Noise power	$P_r = -146.26 dBW$
C/N	Carrier to Noise ratio	15.85 dB

5. References

1. Changes in deep space network to support the Mars Reconnaissance Orbiter (Jeff B. Berner, Alaudin M. Bhanji, and Susan C. Kurtik) 2006

2. Deep Space Ka-Band Link Management and Mars Reconnaissance Orbiter: Long-Term Weather Statistics Versus Forecasting (FARAMAZ DAVARIAN, SHERVIN SHAMBAYATI, AND STEPHEN SLOBIN) 2004

3. Key telecommunications technologies for increasing data return for future Mars exploration (C.D. Edwards Jr, R. DePaulab) 2007

4. High Capacity Communications from Martian Distances part 1(Hemali Vyas, Leonard Schuchman, Richard Orr, Dan Williams, Michael Collins) 2006

5. The Implementation of a Multiplexing Gold Code Generator using a Xilinx Logic Cell Array (Steven J. Merrileld and John C. Devlin)

6. Turbo-Decoder Implementation for the Deep Space Network (K.Andrews, V.Stanton, S.Dolinar, V.Chen, J.Berner, and F.Pollara)2002

7. Satellite Communications (Thimothy Pratt, Charles Bostian, Jeremy Allnutt) $2^{nd} edition$

8. ECE 6390 G.Durgin class notes