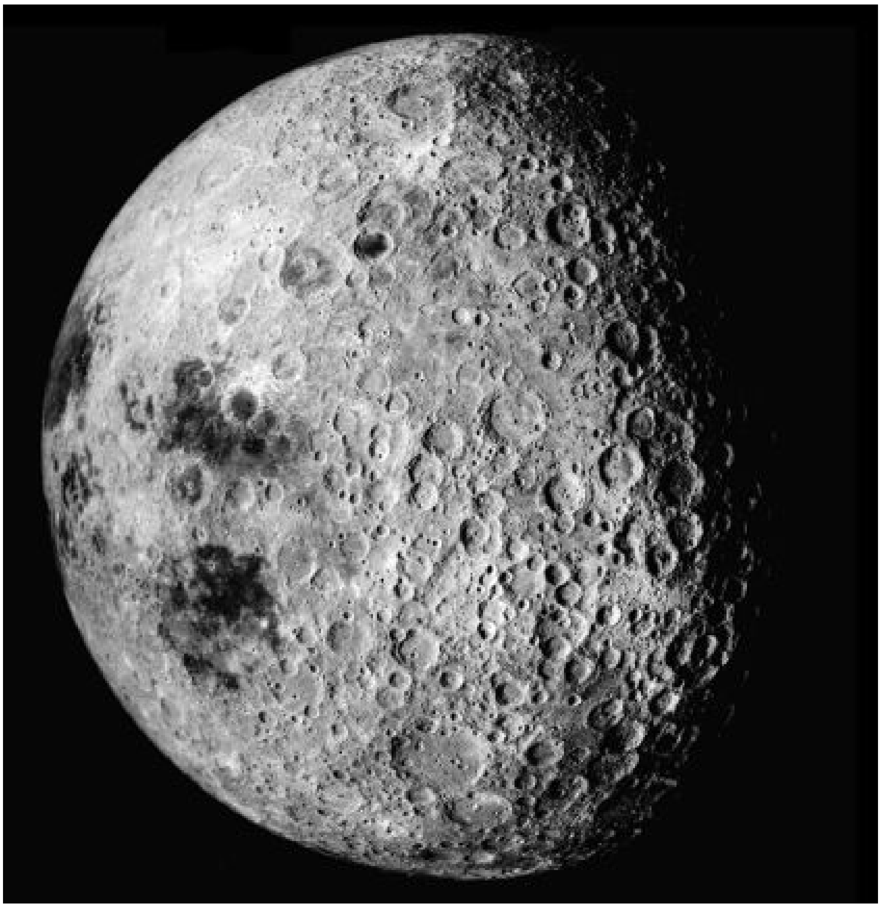
Lunar Radio Telescope

ECE 6390 – Satellite Communications

Fall 2006



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I. Introduction: the Moon

The Moon is Earth's only natural satellite. The average distance from the Earth to the Moon is 384,399 kilometers, which is about 30 times the diameter of the Earth. The Moon's diameter is 3,474 kilometers, which is about 3.7 times smaller than the Earth. The Moon makes a complete orbit about the Earth with respect to the fixed stars (its sidereal period) approximately once every 27.3 days. However, since the Earth is moving in its orbit about the Sun at the same time, it takes slightly longer for the Moon to show its same phase to Earth, which is about 29.5 days (its synodic period). Unlike most satellites of other planets, the Moon orbits near the ecliptic and not the Earth's equatorial plane.

Table1: Moon Orbital Parameters

Semi-major axis	384,399 km (0.00257 AU)
Perigee	363,104 km (0.0024 AU)
Apogee	405,696 km (0.0027 AU)
Revolution Period	27.321 582 d

The Moon is locked in synchronous rotation around the earth, meaning that it completes one rotation and one revolution about the earth at precisely equal periods (Figure 1). Thus, there is one side of the moon (called the “dark side” or “far side” of the moon) that is continuously facing away from the earth, shielded from manmade noise. (Note: there is no “dark side” of the Moon; all parts of the Moon get sunlight half the time (except for a few deep craters near the poles). Some uses of the term “dark side” in the past may have referred to the far side as “dark” in the sense of “unknown” (e.g. “darkest Africa”) but even that meaning is no longer valid today.)

Because the far side of the Moon is shielded from radio transmissions from the Earth, it is considered a perfect location for placing radio telescopes for use by astronomers. For large-scale telescopes, the 100-kilometer diameter crater Daedalus is situated near the center of the far side, and the 3-km-high rim would help to block stray communications from orbiting satellites.

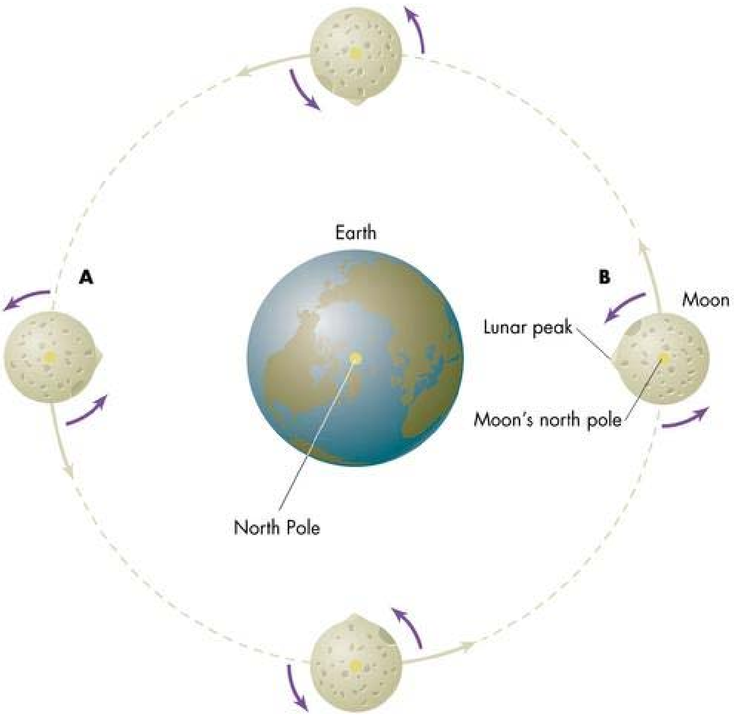


Figure1: Synchronous rotation of moon around the earth

II. Satellite Orbits

Our goal is to build a radio observatory that makes continuous measurements of the spectrum between 1.000-4.000 GHz at the far side of the moon, located in the crater Daedalus. This data must be relayed back to earth without loss through one or more satellites in a communication network.

One idea for designing the orbit of the relay satellites would be to launch two satellites in moon-synchronous orbits; one satellite will be facing the far side of the moon, and therefore collects the data from the moon-based dish. This satellite will constantly be in front of the moon-based dish. Since the moon-based dish is large enough (a diameter of 300m), the satellite will not block the terrestrial signals traveling towards the antenna. The same dish antenna is used to transmit data to the first satellite.

The other satellite will also be placed in moon-synchronous orbit, and it will be used to collect the data from the first satellite and relay it back to earth.

The Moon makes a complete orbit about the Earth with respect to the fixed stars (its sidereal period) approximately once every 27.3 days. Therefore, for a moon-synchronous orbit we have:

$$T = 2\pi \frac{R^{3/2}}{\sqrt{GM_{moon}}}$$

T =27.3 days=655 hours, and 12 minutes=2358720 seconds

Mass of the moon= 7.3477×10^{22} kg (0.0123 Earths)

$\Rightarrow GM_{moon} = 6.672\times10^{-11}\times7.3477\times10^{22} = 4.9024\times10^{12}$

$\Rightarrow R = 88403\,km$ Radius of a moon-synchronous orbit

The second satellite is located 90° from the first satellite with respect to the Moon’s center. Therefore, the Earth will always be in the line of sight of the second satellite.

The deep space network satellites can be used to receive the information sent from the second satellite to earth. DSN currently consists of three deep-space communications facilities placed approximately 120 degrees apart around the world. This strategic placement permits constant observation of spacecraft as the Earth rotates, and helps to make the DSN the largest and most sensitive scientific telecommunications system in the world.

As data is received from outer space by the moon-based dish, the dish transmits it to the first satellite using a higher frequency as an uplink. The first satellite then transmits the data to the second satellite which transmits it back to earth and to one of the deep space network antennas. At each satellite location, one of the DSN satellites will be in the line of sight for the second satellite to transmit data to.

One problem would be that the second satellite is receiving information from the first satellite and sending it to earth in a completely different direction (Figure 2). The first satellite has almost the same problem to a lower extent. It receives data from the moon and sends it to the second satellite in a different direction. In order to solve this issue, we use two antennas for each satellite, one to receive data and the other to relay it back in a different direction. The two antennas will have low mutual effects. First, because they are operating at different frequencies (uplink and downlink) and second because they are pointing to different directions. The high-gain antennas have very low side-lobe levels; and they won't interfere with each other.

For each satellite, one antenna points towards the direction of the other satellite in order to have maximum gain in that direction. Since the relative position of satellites 1 and 2 remains the same, these antennas could point to fixed directions. The first satellite has its other antenna pointing towards the moon since it is receiving data from the moon. The second satellite has its other antenna pointing towards the earth. This antenna should have a reconfigurable pattern to transmit data to earth, since its view angle of the DSN antennas changes as the satellite rotates in its orbit. Both satellites have an elliptical orbit around the earth, and are considered High-earth orbit (HEO) satellites.

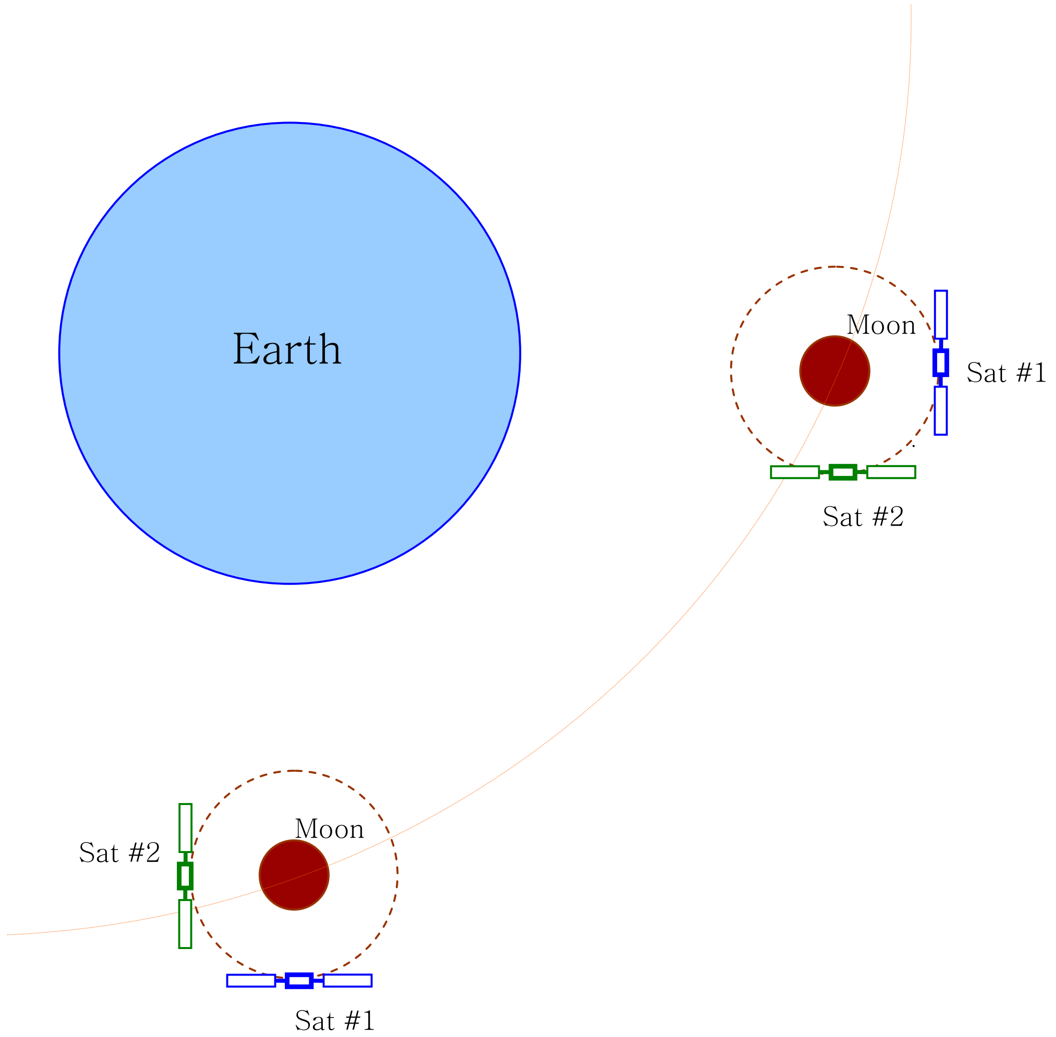


Figure 2: Satellite Configuration- Objects not drawn to scale

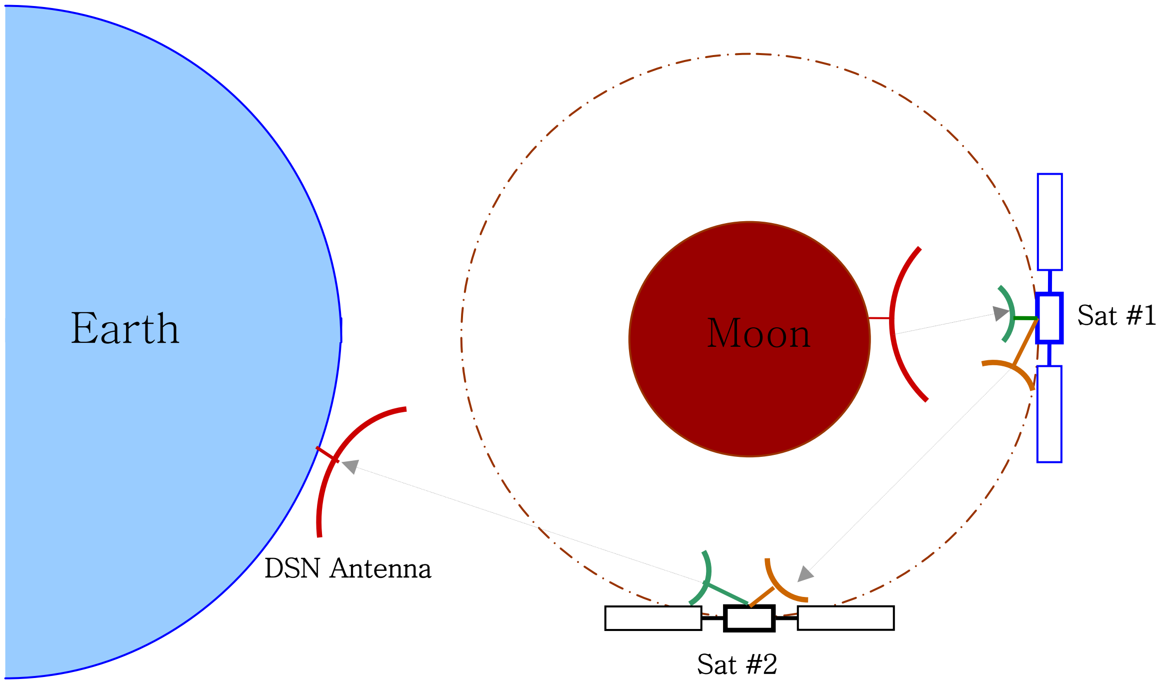


Figure 3: Antenna Arrangements- Objects not drawn to scale

III. Data Processing

The signal we receive from the outer space is in the range of 1-4GHz. This gives us a bandwidth of 3GHz. The sampling rate should therefore be at Nyquist rate:

Sampling Frequency $= 3 \times 2 = 6 \frac{Gsymbols}{\sec}$.

We use 8 levels of quantization for each symbol, using 3bits/symbol. This gives us a bit rate of $6 \times 3 = 18 \frac{Gbits}{\sec}$.

We also choose to use $\mathbf{1/2}$ rate turbo coding for error detection.

Real bit rate$=18 \times 2 = 36 \frac{Gbits}{\sec}$.

Since this number of bits per second requires a relatively large bandwidth, we choose to use 16-QAM as our modulation technique. 16 QAM uses 1 symbol per 4 bits, therefore we have:

Final symbol rate $= \frac{36}{4} = 9 \frac{Gsymbols}{\sec}$.

This will lead to a bandwidth of 9GHz for the communication system.

A raised cosine pulse with $\alpha = 0.4$ is used as the pulse shape based on our previous experiences (homework #5).

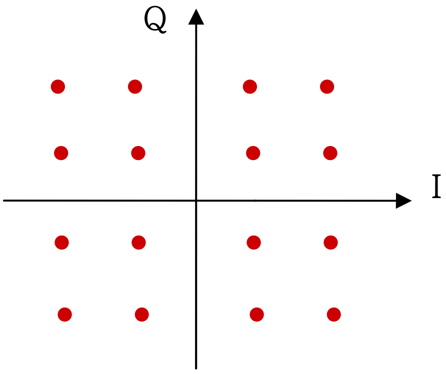


Figure 4: Signal Constellation for 16-QAM Modulation Scheme

IV. Link Analysis

1) Satellite to Earth Link

We start from the downlink equation from the second satellite to earth, since it is more straight-forward. We know that the DSN dishes receive data at a frequency of 32.05GHz. We also know that DSN dishes have a diameter of 34m and a noise temperature of $T_N = 20°K$.

$$\left(\frac{C}{N}\right)_R = P_T + G_T + G_R - 20\log_{10}(r) - 20\log_{10}(\frac{4\pi}{\lambda}) - 10\log_{10}(N)$$

$f = 32GHz \Rightarrow \lambda = 0.00938\,m$

Earth antenna: $D = 34m$, $\eta = 0.94$ ➔ $Gain = 80.86dBi$

For the second satellite we consider two dish antennas: One with a diameter of 1m and the other one with a diameter of 2m. Since the DSN antenna provides a very high gain, we will use the smaller antenna for the satellite-earth link. We assume an efficiency of 0.8 for each antenna.

Satellite antenna: $D = 1\,m$, $\eta = 0.8$ ➔ $Gain = 49.53dBi$

To calculate the antenna distance to earth, we assume the worst case scenario where the second satellite is farthest from earth. The second satellite orbits the earth in an elliptical orbit. We first find the apogee for this orbit:

$$apogee = \sqrt{apogee(moon)^2 + R(moon - synchronous)^2} = 415220km$$

$$R_{\max} = \sqrt{apogee(satellite)^2 - R_{Earth}^2} = 415170km$$

Figure 5 shows the maximum distance from satellite 2 to earth.

$N = kT_{sys}B = -112.04\,dbW$

$T_{sys} = 20 + 30 = 50°K$

We assume $T_N = 20°$ for the DSN antenna and $T_{RF} = 30°$ for low-noise amplifier.

We then replace these values in the link budget equation to find:

$$\left(\frac{C}{N}\right)_R = P_T + 7.5253dB$$

If we were using Turbo-coding with BPSK, $\left(\frac{C}{N}\right)_R = 0$ would be sufficient to get $BER = 10^{-6}$. Since we are using 16-QAM, we should allow for a higher level of $\left(\frac{C}{N}\right)$ in order to get the same performance. We approximate a required $\left(\frac{C}{N}\right) = 7$ for this purpose. We also consider rain attenuation and possible alignment errors and leave a margin for that (details explained in the chart below). Overall,

$\left(\frac{C}{N}\right)_R = 17.5253$ seems sufficient for all design margins and error possibilities.

This gives us $P_T = 10 Watts$ which is low enough to use in a satellite.

The following chart summarizes the link budget calculations for the satellite-earth link

Satellite to Earth Link Budget

	Units	**Value**
Frequency	GHz	32
Wavelength	m	0.00938
Diameter (Satellite Antenna)	m	1
Satellite Antenna Efficiency		0.80
Gain (Satellite Antenna)	**dBi**	**49.53**
Diameter (DSN Antenna)	m	34
DSN Antenna Efficiency		0.94
Gain (DSN Antenna)	**dBi**	**80.86**
Max Distance	km	415,170
Propagation loss	**dB**	**234.9047**
Noise Temperature (blackbody)	K	20
Noise Temperature (Satellite LNA)	K	30
Bandwidth	GHz	9.00
Noise Power	**dBW**	**-112.04**
Required C/N (w/ Turbo Coding and 16QAM)	dB	7
Possible Alignment Error	dB	3
Design Margin	dB	2
Extra C/N Margin	dB	5.5253
Final C/N	dB	17.5253
Signal Power Transmitted	**Watts**	**10**

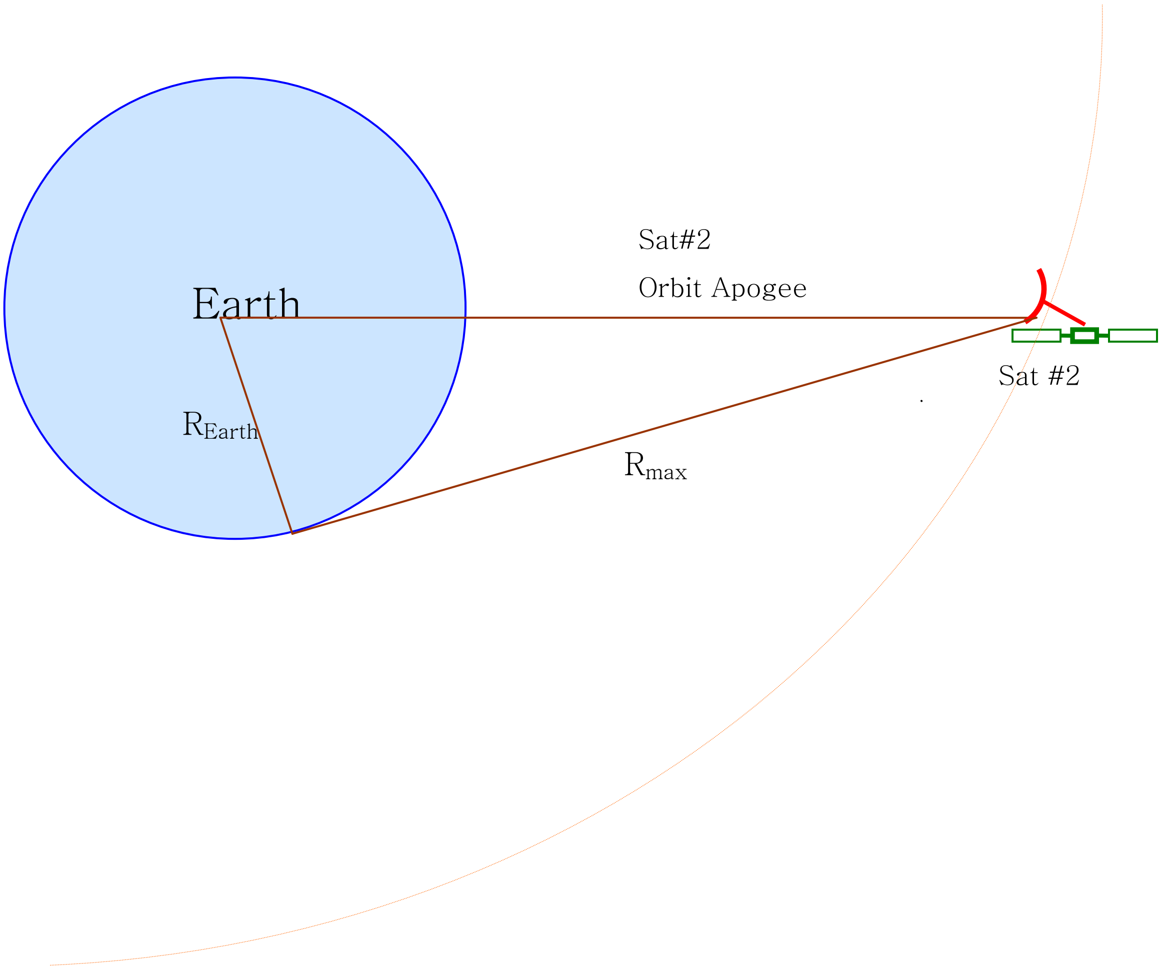


Figure 5: Maximum distance between Sat#2 and Earth antenna- Objects not drawn to scale

2) Satellite to Satellite Link

The most important factor in this link is power. We will use a frequency of 45GHz to transmit data from the first satellite to the second satellite. The path loss at this high frequency will be compensated by the high gains of the dish antennas. Also the distance between the antennas is not large compared to the earth-moon distance, so the path loss will not be significant.

In both satellites we will use 2m diameter antennas to get higher gains. (We leave the 1m diameter antennas for communication with the earth and the moon).

$f = 45GHz \Rightarrow \lambda = 0.0067m$

Satellite antennas: $D = 2m$, $\eta = 0.8$ ➔ $G_T = G_R = 58.473dBi$

Distance between satellites: $R = \sqrt{2} \times r = 125020km$

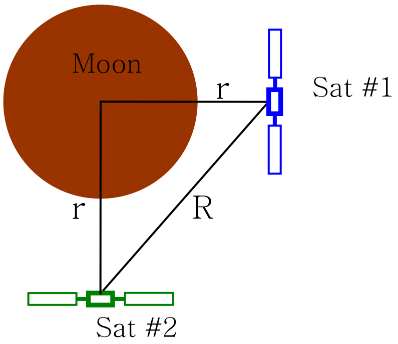


Figure 6: Distance calculation between the two satellites

$$N = kT_{sys}B = \text{-}112.495\ dbW$$

$$T_{sys} = 15 + 30 = 45°K$$

We assume $T_N = 15°$ for the black body noise temperature and $T_{RF} = 30°$ for low-noise amplifier. Replacing these values in the link budget equation we get:

$$\left(\frac{C}{N}\right)_R = P_T + 2.03dB$$

Considering 7dB for the $\left(\frac{C}{N}\right)$ required for 16 QAM modulation used with turbo coding, 3dB margin for possible alignment error and about 2dB design margin, we consider $\left(\frac{C}{N}\right)_R = 12$ to be an acceptable ratio for $BER = 10^{-6}$. This will give us $P_T = 10dB = 10Watts$ which is an acceptable power for the satellite antennas. Details of the link are explained in the chart below.

Satellite to Satellite Link Budget

	Units	**Value**
Frequency	GHz	45
Wavelength	m	0.0067
Diameter (Satellite Antenna)	m	2
Satellite Antenna Efficiency		0.80
Gain (Satellite Antenna)	**dBi**	**58.473**
Distance	km	125,020
Propagation loss	**dB**	**227.40**
Noise Temperature (blackbody)	K	15
Noise Temperature (Satellite LNA)	K	30
Bandwidth	GHz	9.00
Noise Power	**dBW**	**-112.495**
Required C/N (w/ Turbo Coding and 16QAM)	dB	7
Possible Alignment Error	dB	3
Design Margin	dB	2
Final C/N	dB	12
Signal Power Transmitted	**Watts**	**10**

3) Moon to Satellite Link

The T_N used for satellite antenna will change in the link budget equations.

Average black body temperature of the moon: $T_N = 274.5°K$. The LNA noise temperature is again considered to be $T_{RF} = 30°$.

$$N = kT_{sys}B = \text{-}104.1916 \ dbW$$

We will use a carrier frequency of 25GHz.

$$f = 25GHz \Rightarrow \lambda = 0.012m$$

Moon antenna:

$$D = 300m, \ \eta = 0.9 \Rightarrow G_T = 97.444dBi$$

Satellite antenna:

$$D = 1m, \ \eta = 0.8 \Rightarrow G_R = 47.39dBi$$

Distance between moon and satellite (moon-synchronous orbit): R=88,403 km

Replacing the values in the link budget equation, we find:

$$\left(\frac{C}{N}\right)_R = P_T + 29.69dB$$

If we only use 4 watts of transmitted power (6.02 dBW), we could have a $\left(\frac{C}{N}\right)$ of 35.71dB. This is sufficient to account for all possible additional errors.

Moon to Satellite Link Budget

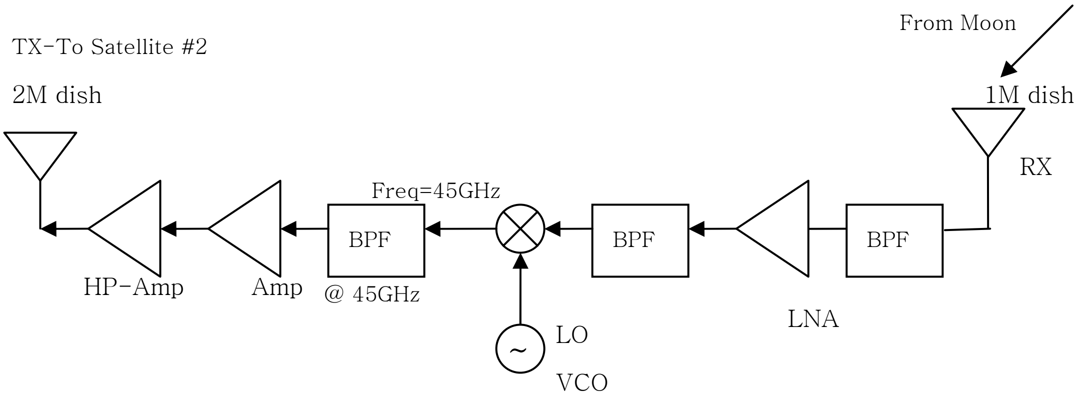
	Units	**Value**
Frequency	GHz	25
Wavelength	m	0.0120
Diameter (Satellite Antenna)	m	1
Satellite Antenna Efficiency		0.80
Gain (Satellite Antenna)	**dBi**	**47.39**
Diameter (Moon Antenna)	m	300
Moon Antenna Efficiency		0.9
Gain (Moon Antenna)	**dBi**	**97.444**
Distance	km	88,403
Propagation loss	**dB**	**219.33**
Noise Temperature (blackbody)	K	274.5
Noise Temperature (Satellite LNA)	K	30
Bandwidth	GHz	9.00
Noise Power	**dBW**	**-104.1916**
Required C/N (w/ Turbo Coding and 16-QAM)	dB	7
Possible Alignment Error	dB	3
Design Margin	dB	2
Extra C/N Margin	dB	23.71
Final C/N	dB	35.71
Signal Power Transmitted	**Watts**	**4**

Challenges:

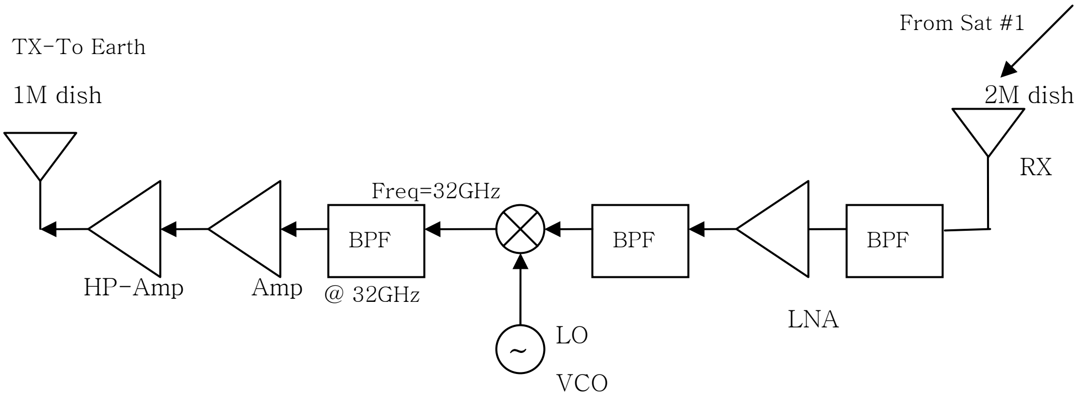
As shown in previous calculations, the bandwidth required to transmit the signal is almost 9GHz. The challenge here is to find LNA and other electronic circuitry for the required bandwidth. As we go to higher frequencies, it is easier to find wideband circuitry. This is one reason to use the Ka band (25-45GHz) for transmission.

V. System Design

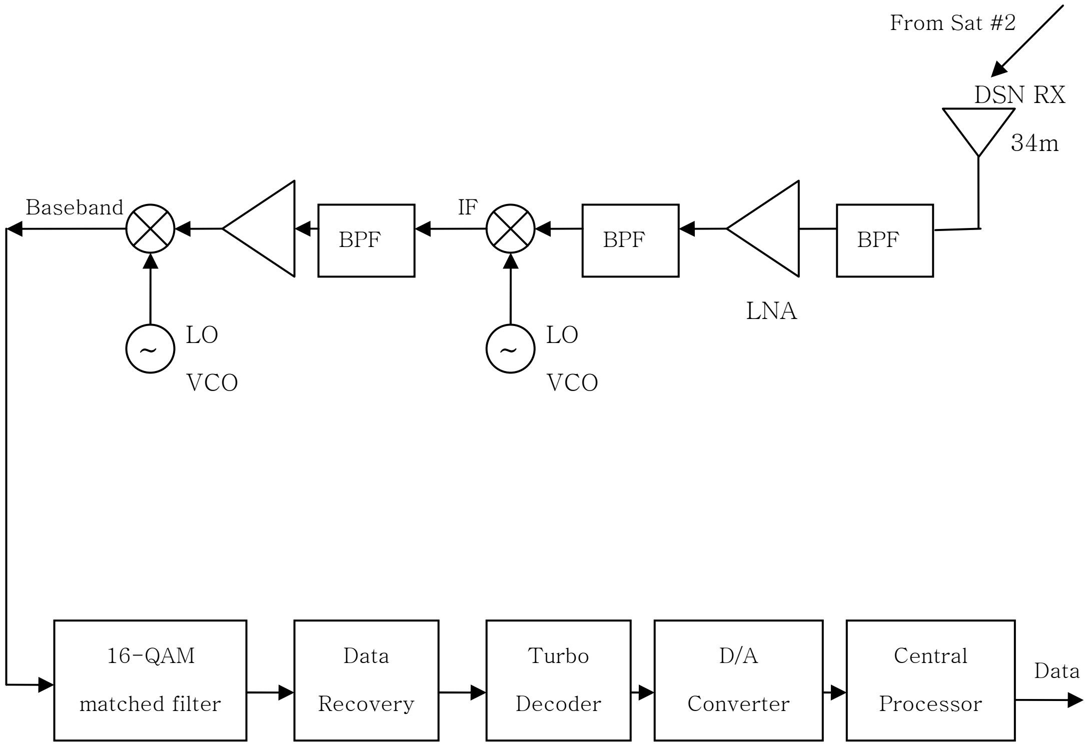
1) Satellite #1 Transceiver Design



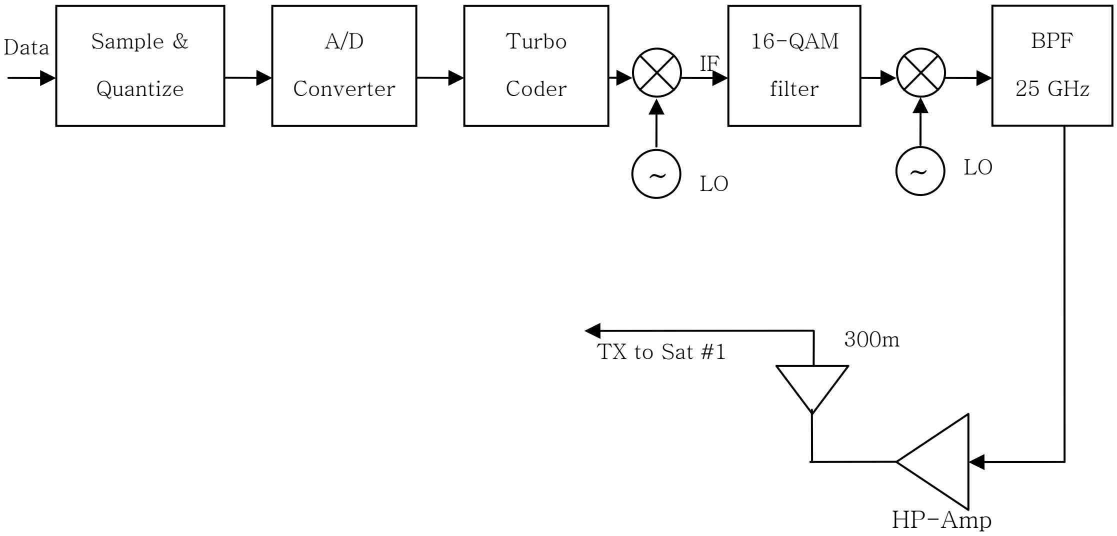
2) Satellite #2 Transceiver Design



3) Earth System Design



4) Moon System Design



VI. Cost Analysis

Each satellite costs approximately $150 million to build and launch into orbit, and $1 million per watt to transmit. The cost for this project will be as follows:

Item	**Count**	**Cost (Millions)**	**Total (Millions)**
Satellite	2	$150	$300.00
Moon-Satellite#1	4 Watts	$1/Watt	$4.00
Satellite#1-Satellite#2	10Watt	$1/Watt	$10.00
Satellite#2-Earth	10Watt	$1/Watt	$10.00
		Total	$324.00

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