Design of an E-Band Satellite Communication System for ECE6390

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CONTENTS

I. Requirements

THE requirements for this satellite link are detailed below. Each requirement has been met or exceeded with the design decisions for each component described in detail in their section.

TABLE I
DESIGN CRITERIA

Deliverable	Threshold	Objective
Duration of Operation	3 months	6 months
Number of Ground Stations	1	Multiple
Clear-day Link Margin	30dB	36dB
Data Rate	19.2 kbps	1Mbps
Downlink Frequency	73.5 GHz	71, 73.5, 76 GHz
Uplink Frequency	83.5 GHz	81, 83.5, 86 GHz
Supplemental K-Band Beacon	Not Included	Included

II. Ground Stations

A. Uplink Location

For the Uplink, a ground station will be placed at White Sands, NM or 32.78 N, 106.32 W. This location will have a look angle of 51.8 degrees and azimuth of 177.6 degrees. The distance from the transmitter to the satellite would be 36,964 km. White sands already has a developed antenna networks, so the development and maintenance structures are already in place. The arid climate of White Sands has an average rain rate at 0.01 of 10 mm/hr. [3] This gives a loss of the melting point around 5 km above sea level or 3.7 km above the antenna. This means the rain loss would have a path of 4.7 km. Using the coefficients from the recommendation tables of ITU-R P. 838-3, the rain fade would be around 26.6 dB. [2]

B. Uplink Satillite

For the uplink ground antenna, a large dish antenna is used. This will provide high gain and directivity for the uplink. A half beam bandwidth of .1 will provide high gain but still allow 12,076 km^2 of area above the -3 dB loss. This will also produce an antenna gain of around 64dB. To produce this gain, the antenna would have to have a diameter of 6.2 meters.

C. Downlink Location

There will be three downlink locations to display collecting data across the united states. The antennas will be located at Seattle, WA, Portland, ME, and Miami, FL. These locations will test the coverage of the entire United States. The following table shows the parameters from each location.

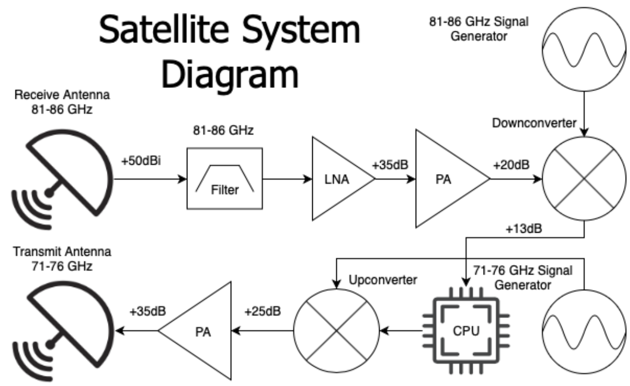
D. Downlink Antenna

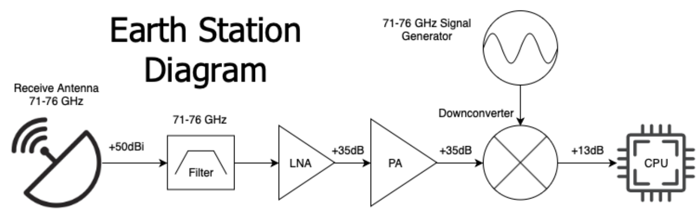
For the downlink, a phased array antenna will be used to simulate a system that could be placed on top of vehicles. The array will be comprised of four 10 cm antennas. This will produce a system with 49 dB of gain and allow the vehicle to connect from multiple orientations.

TABLE II
LOCATION DATA

Parameter	Seattle	Portland	Miami
Latitude	47.6 N	63.6 N	25.1 N
Longitude	122.3 W	70.2 W	80.2 W
Distance	38.4 km	40.2 km	37.1 km
Look angle	32.7 degrees	12.9 degrees	49.7 degrees
Azimuth Angle	157.2 degrees	217.8 degrees	227.4 degrees
Rain Rate [3]	19 mm/hr	42 mm/hr	95 mm/hr
Rain Height	3 km	5 km	4 km
Rain Loss	29 dB	84 dB	119.5 dB
T_{sky}	269 k	270K	270k

III. Communication System Overview





A. Components

1) Antenna: The antenna chosen for this satellite is a Commscope VHLPX2-80/A dish antenna. It is an 8kg dish antenna with a radius of 30cm, a beamwidth of 0.5°, and a gain of 50dBi. The satellite will have two of these antennas on-board, with one used for the uplink system and the other used for the downlink system.

TABLE III
FILTERS

Part Number	Band	50dB Rejection	VSWR
SWF-74305350-12-B1	71-76 GHz	$68 \geq f \geq 81$ GHz	1.5:1
SWF-84305350-12-B1	81-86 GHz	$78 \geq f \geq 90$ GHz	1.5:1

2) Filters: Filtering is crucial for any system because it eliminates noise and unwanted interference from all frequencies outside of the operating frequencies. Filters are passive devices that are designed with a roll-off factor indicative of how quickly in frequency the attenuation of a signal increases as it leaves the passband of a filter. Filters can be constructed to pass all frequencies above a certain point (high pass), pass only those frequencies below a certain point (low pass), or, by combining a high pass and a low pass filter, to only pass frequencies within a specified range (pass band). For our earth station we will be using a filter with a pass band of 71-76 GHz and for our satellite we will use a filter with a passband of 81-86 GHz. These filters have an out of band suppression of 50 dB and a loss of only 2dB.

3) Amplifiers: There are three types of amplifiers that could be used for this design: Low Noise Amplifiers (LNA) providing some gain with little signal distortion, Power Amplifiers (PA) providing more gain with some added noise, and High Power Amplifiers (HPA) providing the most gain to the signal, at the cost of a very high noise power. One issue not taken into account with this design is the saturated power level of the amplifier(Psat). Most amplifiers are rated for a certain level of gain and can achieve that level of gain, given that the input power level is below the saturation level of the device. In other words, an amplifier with a Psat of 20 dbm and a gain of 15 dB cannot amplify any signal with an input power greater than 5 dBm. The result would be a clipped signal in the time domain and multiple unwanted spurs and sidebands in the frequency domain. For this project we have chosen to ignore the Psat of these components and assume an infinitely linear gain. The amplifiers chosen and their specifications can be found below:

TABLE IV
OVERVIEW OF AMPLIFIERS

Part Number	Description	Frequency Range	Gain	NF
SBL-7138633540	LNA	71-86 GHz	35dB	4dB
PE15A4023	PA	70.5-76.5 GHz	25dB	4dB
FMAM4024	PA	80.5-86.5 GHz	20dB	4dB

4) Mixers: Analog Devices provides the mixers we have chosen for this design. Their mixers offer not only integrated oscillators for easy up/downconversion, but also internal amplifiers providing gain to the signal. These mixers are examples of what are known as Single Sideband Mixers (SSB) because the output of the device is only the carrier and either the upper or lower sideband depending on the model. Unfortunately, the Noise Figures for the models operating from 71-76 GHz are prohibitively large.

TABLE V
OVERVIEW OF MIXERS

Part Number	Description	Frequency Range	Gain	NF
ADMV7310	Upconverter	71-76 GHz	35dB	28dB
ADMV7410	Downconverter	71-76 GHz	13dB	28dB
ADMV7320	Upconverter	81-86 GHz	33dB	5dB
ADMV7420	Downconverter	81-86 GHz	10dB	5dB

5) Miscellaneous: These parts were all chosen in order to meet the SNR requirements of our communication system. In addition, when choosing components, compatibility between components was also taken into account. Each of these components utilizes a WR-12 waveguide connector for efficient transmission of the signal between modules. The estimated loss for these waveguides is 1.97 dB per meter.

B. System Temperature

All of these components together have an effect on the system temperature of our satellite. Calculating the system temperature was performed using the equation for Noise Figure:

$$NF = 10\log_{10}(1 + \frac{T_e}{T_o}) \quad (1)$$

where T_e is the system temperature and T_o is 290K. For the satellite system, those temperatures can be found in the table below. Using those temperatures, the system temperature for the satellite receiver and transmitter subsystems can be found. The equation for the earth station receiver system is

TABLE VI
SATELLITE COMPONENT TEMPERATURES

Part Number	Description	Noise Figure	Temperature
VHLPX2-80/A	Antenna	N/A	190K
SWF-74305350-12-B1	Filter	2dB	107.02K
SBL-7138633540-1212-E1	LNA	4dB	438.45K
FMAM4024	PA	4dB	438.45K
ADMV7420	Mixer	5dB	627.06K

$$T_s = T_{\text{ant}} + T_{\text{filter}} + T_{\text{LNA}} + \frac{T_{\text{PA}}}{G_{\text{LNA}}} + \frac{T_{\text{mix}_{down}}}{G_{\text{LNA}} \times G_{\text{PA}}} \quad (2)$$

and the equation for the satellite receiver is

$$T_s = T_{\text{ant}} + T_{\text{filter}} + T_{\text{LNA}} + \frac{T_{\text{PA}}}{G_{\text{LNA}}} + \frac{T_{\text{mix}_{down}}}{G_{\text{LNA}} \times G_{\text{PA}}} \quad (3)$$

which when solved gets a Satellite system temp of 780.3795K and a Earth Receiver temperature of 780.38K. Since the antenna, filters, and LNA had almost identical noise temperatures, the system temperatures were very similar. Overall, the system temperature was greatly affected by the first few components in our system, which is why it was critical to use an LNA near the beginning of the RF chain.

C. Digital System

The main criteria in any digital system is the BER (Bit Error rate). For the un-coded system, the desired BER is on the order of 10^{-3}. An appropriate SNR must be chosen to match this bit error rate. The equation for finding the BER is the Q function. In MATLAB this is a built in function called

```
BER = qfunc(t)
```

1) Modulation: The appropriate modulation is QPSK which balances a higher data rate due to 2 bits/symbol and decreasing the bit error rate. Having higher density modulations will increase the number of bits per symbol but will adversely affect the bit error rate. Due to the large latency (round trip time) the signal has due to the large distance, the bit error rate should be minimized. If an error occurs, then the high latency will cause a large delay for the packet to get re-transmitted.

2) BER: To hit the goal of 10^{-3} BER, the q function must be solved by finding a SNR that meets that criteria. Using QPSK the argument of the Q function is

$$Q(\sqrt{2 * SNR}) \tag{4}$$

using MATLAB the command becomes

```
BER = qfunc(\sqrt{2*SNR})
```

where SNR was guessed and checked until the order of the BER was 10^{-3}.

After using guess and check, the linear SNR found was 4.7 which has a BER of $1.1 * 10^{-3}$. In db, the SNR is 6.72 dB.

3) Symbol Rate: The goal data rate is 1Mbps. Using the modulation technique of QPSK our symbol rate is less than the data rate. For QPSK, the data rate is related to the symbol rate by:

$$R_b = 2 * R_s \tag{5}$$

which means that

$$R_s = 1Mbps/2 = .5MBaudps \tag{6}$$

4) Bandwidth: Using the symbol rate of .5MBaudps the bandwidth can be found using the relationship of:

$$B_w = R_s(1+\alpha) \tag{7}$$

where B_w is the bandwidth, R_s is the symbol rate and α is the roll of factor.

Based on our filter design, our $\alpha = .5$. Therefore our bandwidth:

$$B_w = .5MBaudps(1+.5) = 750KHz \tag{8}$$

5) Shannon Limit: Aggregating all the information together, Shannon's limit will determine if this link is feasible. The Shannon's limit equation is

$$C = B_w log_2(1+SNR) \tag{9}$$

plugging in the bandwidth found above and the minimum SNR needed to satisfy the BER, the Capacity (C) is found to be $2.09Gbps$. Since that is the capacity which cannot be achieved, an $\%80$ factor is taken to show the achievable data rate based on the capacity. The achievable data rate is $1.673Gbps$ which is still above our desired data rate. Therefore our digital system is feasible.

6) Minimum CNR: From the minimum SNR, the minimum CNR of the link can be calculated. Since the system used QPSK the relationship (in linear) is

$$SNR * 2 = CNR \tag{10}$$

therefore

$$CNR = 2 * 4.7 = 9.4(linear) \tag{11}$$

$$CNR = 10log_{10}(9.4) = 9.73dB \tag{12}$$

7) Summary: Table VII shows the summary of data from this section.

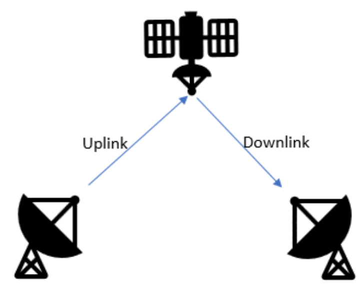
TABLE VII
DIGITAL SYSTEM SUMMARY

CNR$_{min}$	9.73 dB
SNR$_{min}$	4.7 dB
Symbol Rate	500KBaudps
Data Rate	1Mbps
Bandwdith	750KHz
Modulation Scheme	QPSK
BER	$1.1 * 10^{-3}$
Roll off factor	.5

IV. LINK BUDGET

The Link Budget consists of two different subsystems, the uplink and the downlink. Both components are critical in effectively sending a signal from the transmitting ground station to receiving it at another point on either. The difficulty of this problem is due to communicating via a bent pipe satellite that is stationed in GEO orbit. Many issues arise due to problems such as losses due to propagation, atmospheric disturbances etc. Most of the issues are due to the distance of propagation.

Both subsystems are governed by similar properties and equations. Therefore the equations below are applicable to both the uplink and downlink.



A. SNR Calculation

1) Overview: The important number for calculating the viability of the link is based on the SNR. The SNR determines the strength of the desired signal compared to the relative noise that gets added based on many factors.

The equation for SNR is

$$SNR = \frac{P_r}{N} = \frac{P_t G_t G_r}{Noise * Losses} \tag{13}$$

where P_t is the power transmitted by the system, G_t is the directivity due to the transmitting antenna, G_r is the directivity due to the receiving antenna, Noise is the receiver system noise and the Losses are losses like path loss, atmospheric absorption, cable losses etcs. Due to the nature of the data, it is actually easier to perform the calculations in the dB scale. There the power received equation becomes:

$$P_r = P_t + G_t + Gr - L_p - L_o \tag{14}$$

where L_p is the path loss, L_o stand for all other losses. All the values are in dB.

The equation for the Noise in dB becomes:

$$N = k + T_s + B \tag{15}$$

where k is the Boltzmann's constant, T_s is the system temperature in dB and B is the bandwidth of the signal in dB

2) P_r calculation: The most important calculation is calculating the power received on the receiver from the transmitter. Looking at equation 14 there are 5 terms that deal with the power received. Below are the first 3 with the losses described afterwards:

P_r corresponds to the power transmitted. This number is mostly limited on the satellite since the ground station have access to large power grids. Therefore when selecting a P_t for the ground station, we desire to make it as large as possible based off the electrical grid. For the satellite this number is much more limited since the power system usually runs off a battery and solar energy.

G_t corresponds to the directivity of the transmitting antenna. To determine the directivity (which is proportional to the gain) we use the formula:

$$G = 10log_{10}(Ef * (\frac{\pi D}{\lambda})^2) \tag{16}$$

where Ef is the efficient of the aperture, D is the diameter of the dish and λ is the wavelength of the signal.

G_r follows the same properties as G_t

3) Losses: There are many losses to consider. The losses cause the transmitted signal to attenuate and reduce in power as it propagates towards the satellite. Losses are due to factors such as the distance of the propagation, the current weather, cable losses, etc.

Given the large distance the signal needs to propagate, the path loss is the main driver for signal attenuation. The equation for path loss is:

$$L_p = 20log_{10}(\frac{\lambda}{4\pi R}) \tag{17}$$

where λ is the wavelength of the transmitted signal and R is the distance from the ground station to the satellite.

TABLE VIII
OTHER LOSSES

Losses	Value (dB)
$L_{clearsky}$	$0.2dB$
$L_{rainsky}$	$3dB$
L_{edge}	$3dB$
L_{misc}	$0.4dB$

Other losses to take into consideration are seen in the table above where $L_{clearsky}$ represents the loss of the signal on a clear day, $L_{rainsky}$ represents the loss of the signal on a rainy day, L_{edge} represents the loss due to the edge beam, L_{misc} represents all other losses due to cables, etc...

4) Noise: The Noise of the system is due to the hardware components in the receiver as well as the bandwidth of the signal. The equation for the Noise is given by 15. The first term k is the Boltzmann's constant which is -228.6 dB. T_s is the receiver system temperature. It is calculated by adding up the contributions of each components noise to the overall system noise temp. The equation for our system is given by:

$$T_s = T_{ant} + T_{LNA} + \frac{T_{PA}}{G_{LNA}} + \frac{T_{downConverter}}{G_{LNA}G_{PA}} \tag{18}$$

where all the gains are converted to linear scale and the temperatures are in kelvin.

In most cases, the temperature noise of a device is not provided. Instead it provides the noise figure. The noise figure can be used to find the temperature noise of the system via:

$$T_{out} = T_{in}(NF - 1) \tag{19}$$

where T_{in} is the starting temperature which we set to 290K. NF must be converted to linear scale before being used in equation 19.

The last term B of the Noise equation is the bandwidth of the signal. The largest the Bandwidth the larger the Noise.

V. LINK BUDGET CALCULATIONS

The tables below show a summary of all the calculations based off the modulation, ground station data, satellite components, etc...

TABLE IX
EARTH STATION TRANSMITTER

Component	Info
Antenna Gain	64dBi
Uplink Frequency	$83*10^9$
Uplink Bandwidth	$18*10^6$
Power Transmit	300W

TABLE X
SATELLITE

Component	Info
CNR_{minUp}	9.73 dB
Distance	36,000km
Antenna Gain	50dBi
Downlink Frequency	$73*10^9$
Downlink Bandwidth	$.75*10^6$
T_{system}	780.638
G_{system}	165dBi
L_{margin}	36dB

TABLE XI
RECEIVERS

Component	Info
$CNR_{minDown}$	9.73 dB
Antenna Gain	49dBi
T_{system}	709.163K
L_{margin}	36dB

The data was simulated in MATLAB with custom scripts [4]. The scripts allowed plugging in different parameters and weather conditions based on the numbers above and the losses based off Table VIII.

The first part of the calculation was calculating the $\frac{C}{N}_{uplink}$. The numbers for the equations below come from the tables above.

A. Overall System Gain

For the satellite system, the overall system gain can be found by adding the gains of all the components in the RF chain and subtracting all of the sources of noise from passive devices such as filters.

For the Earth Station receiver:

$$\mathrm{G_{Antenna}} + G_{\mathrm{Filter}} + G_{\mathrm{Mix}} + G_{\mathrm{LNA}} + G_{\mathrm{PA}} (20)$$

$$= 49\mathrm{dBi} - 2\mathrm{dB} + 13\mathrm{dB} + 35\mathrm{dB} + 25\mathrm{dB} = \mathbf{120}\mathrm{dB} \quad (21)$$

For the satellite receiver:

$$G_{\mathrm{Antenna}} + G_{\mathrm{Filter}} + G_{\mathrm{LNA}} + G_{\mathrm{PA}} + G_{\mathrm{Mix}} \quad (22)$$

$$= 50\mathrm{dBi} - 2\mathrm{dB} + 35\mathrm{dB} + 20\mathrm{dB} + 13\mathrm{dB} \quad (23)$$

$$\text{Total Satellite Gain} = \mathbf{116}\mathrm{dB} \quad (24)$$

B. Clear Sky Calculations

1) Uplink Calculation:

$$\frac{C}{N}_{uplink} = \frac{P_{r satellite}}{N} \quad (25)$$

For the P_r at the satellite for the uplink:

$$P_r = P_{tGS}[dB] + G_{GS} + G_{satellite} - L_{pathloss} - L_{extra} \quad (26)$$

The path loss is:

$$L_{pathloss} = 20log_{10}\left(\frac{.003614}{4\pi 36,000,000}\right) = -221.984[dB] \quad (27)$$

All the extra losses in the system:

$$L_{extra} = L_{misc} + L_{clearsky} + L_{edgebeam} \quad (28)$$

$$L_{extra} = 0.4[dB] + 0.2[dB] + 3[dB] = 3.6[dB] \quad (29)$$

Calculation for the power received at the satellite

$$P_r = 10log_{10}(300) + 64 + 50 - 221.984 - 3.6 \quad (30)$$

$$P_r = -86.8128[dB] \quad (31)$$

Calcluation for the Noise of the satellite system

$$N = k[dB] + T_{system}[dB] + B[dB] \quad (32)$$

$$N = -228.6 + 10log_{10}(638.64) + 10log_{10}(.75 * 10^6) \quad (33)$$

$$N = -141.797[dB] \quad (34)$$

The $\frac{C}{N}$ calculation

$$\frac{C}{N}_{uplink} = -86.8128 - (-141.797) = 54.9842[dB] \quad (35)$$

now adding in the clear fade margin of 36 dB our CNR becomes

$$\frac{C}{N}_{uplink} = 54.9842[dB] - 36[dB] = 18.9842 \quad (36)$$

2) Downlink Calculation:

The downlink occurs from the Satellite to our receiver. For this system we are testing receiving on a car. Thus the P_r is the power reciecved by the car.

The $\frac{C}{N}_{downlink}$ can be calculated in a simliar way.

$$\frac{C}{N}_{downlink} = \frac{P_{r car}}{N} \quad (37)$$

Equation for power received: Note L_{extra} is the same as the uplink (3.6 db)

$$P_r = P_{tsat}[dB] + G_{Sat} + G_{car} - L_{pathloss} - L_{extra} \quad (38)$$

Calculation for path loss:

$$L_{pathloss} = 20log_{10}\left(\frac{.00411}{4\pi 36,000,000}\right) = -220.834[dB] \quad (39)$$

Equation for the system noise

$$N = k[dB] + T_{system}[dB] + B[dB] \quad (40)$$

$$N = -228.6 + 10log_{10}(709.1635) + 10log_{10}(.75 * 10^6) \quad (41)$$

$$N = -141.342[dB] \quad (42)$$

Calculation for the minimum power received given our minimum $\frac{C}{N}$ with the clear day margin added

$$P_{rmin} = N + \frac{C}{N}_{min} + L_{margin} \quad (43)$$

$$P_{rmin} = -141.342 + 9.73 + 36 \quad (44)$$

$$P_{rmin} = -95.612[dB] \quad (45)$$

Calculation for the power transmit given our minimum power received

$$P_{tsat} = Pr_{sat} - G_{Sat} - G_{Car} + L_{pathloss} + L_{extra} \quad (46)$$

$$P_{tsat} = -95.612 - 50 - 49 + 220.835 + 3.6; \quad (47)$$

$$P_{tsat} = 29.83[db] \quad (48)$$

3) Total CNR:

Using the uplink and the downlink CNR, the total CNR with the fade margin included is:

$$\frac{C}{N}_{total} = \frac{1}{\frac{1}{\frac{C}{N}_{Up}} + \frac{1}{\frac{C}{N}_{Down}}} \quad (49)$$

$$\frac{C}{N}_{total} = 79.1347[dB] \quad (50)$$

4) Summary: Clear day with margin:

Table XII shows the summary of the CNR data for the clear day with the fade margins. Looking at the table, each link and the total total are above the minimum CNR needed with the fade margin. Therefore it will work in the clear day situation plus conditions that add up to 36dB losses such as rain.

TABLE XII
CLEAR DAY SNR CALCLUATIONS WITH MARGIN

CNR_{up}	18.9842 dB
CNR_{down}	9.73 dB
CNR_{total}	9.24 dB

C. Rain Attenuation

The calculations above for the clear day included the fade margin to support average rainy/bad conditions. The calculations in this section, use the data from above but remove the link margin and calculate the actual CNR for rain day conditions. This will show the true feasibility of the link on rain day conditions. We determined many receiver locations and defined the rain data in table II. The below calculations are for our uplink location of White Sands NW, and a downlink receiver in Seattle. To test for the worse case, assume that it is raining in both locations and thus rain attenuation occurs on both links.

1) Uplink Calculation: The Uplink calculations are the same except for the addition of extra loss and noise due to a higher sky temperature and rain attenuation. Numbers will be reused from the clear sky calculations. For the uplink which is in White Sands, NM, the rain attenuation is 26.6dB.

$$P_r = P_{rclear} + L_{rain} = -86.8128 - 26.6 = -113.413[dB] \quad (51)$$

For the Noise calculations a new equation is needed to find the new system temperature based on the new sky temperature due to the rain.

$$L_a = L_{clear} + L_{rain} = 0.2 + 26.6 = 26.8[dB] \quad (52)$$

$$T_{skyrain} = T_{skyclear}(1 - \frac{1}{L_a}) \quad (53)$$

$$T_{skyrain} = 270(1 - \frac{1}{10^{\frac{26.8}{10}}}) = 269.4359K \quad (54)$$

$$T_s = 269.435 + 673.36 = 942.795K \quad (55)$$

$$N = -228.6 + 10log_{10}(780.638) + 10log_{10}(.75 * 10^6) \quad (56)$$

$$N = -140.925 \text{ [dB]} \quad (57)$$

$$\frac{C}{N}_{uplink} = -113.413 - (-140.925) = 27.5119[dB] \quad (58)$$

2) Downlink Calculation: The Downlink calculations are the same except for the addition of extra loss and noise due to a higher sky temperature and rain attenuation. Numbers will be reused from the clear sky calculations. For the downlink, the calculations will be performed for Seattle

For the Noise calculations a new equation is needed to find the new system temperature based on the new sky temperature due to the rain.

$$L_a = L_{clear} + L_{rain} = 0.2 + 29 = 29.2[dB] \quad (59)$$

$$T_{skyrain} = T_{skyclear}(1 - \frac{1}{L_a}) \quad (60)$$

$$T_{skyrain} = 270(1 - \frac{1}{10^{\frac{29.2}{10}}}) = 269.66 \quad (61)$$

$$T_s = 269.66 + 709.16350 = 978.824 \quad (62)$$

$$N = -228.6 + 10log_{10}(978.824) + 10log_{10}(.75 * 10^6) \quad (63)$$

$$N = -139.942 \quad (64)$$

The minimum Power received by the ground station to satisfy the CNR minimum:

$$P_{rmin} = N + P_{rminclear} + L_{rain} = -139.942 + 9.73 + 29 = -101.212[dB] \quad (65)$$

Calculation for the power transmit given our minimum power received

$$P_{tsat} = Pr_{sat} - G_{Sat} - G_{Car} + L_{pathloss} + L_{extra} \quad (66)$$

$$P_{tsat} = -101.212 - 50 - 49 + 220.835 + 3.6 \quad (67)$$

$$P_{tsat} = 24.2227[db] \quad (68)$$

$$\frac{C}{N}_{uplink} = -101.212 - (-139.942) = 38.7297[dB] \quad (69)$$

3) Total CNR: Using the uplink and the downlink CNR with rain attenuation, the total CNR is:

$$\frac{C}{N}_{total} = \frac{1}{\frac{1}{\frac{C}{N}_{Up}} + \frac{1}{\frac{C}{N}_{Down}}} \quad (70)$$

$$\frac{C}{N}_{total} = 21.1281[dB] \quad (71)$$

4) Summary: Rainy Day: Table XIII shows the summary of the CNR data for a rainy day. Looking at the table, each link and the total total are above the minimum CNR needed. Therefore the link will work in conditions where it rains in both White Plains, NW and Seattle. Since the link is enough over the dB limit, more rainy conditions can be supported.

TABLE XIII
RAINY DAY SNR CALCLUATIONS

CNR_{up}	27.5119 dB
CNR_{down}	21.1281 dB
CNR_{total}	20.22dB

D. System Summary

As shown above, our system works both for a clear day and a rainy day in Seattle. Unfortunately in locations with a very high rain attenuation like Miami, we cannot provide reliable connection all the time. During peak storm conditions the link may degrade to the point of becoming unusable. Though, under normal circumstances the link will work.

VI. PROPULSION SYSTEM

A. Launch System

To launch our system to a geosynchronous orbit, we will use the SpaceX *Falcon 9* rocket. The *Falcon 9* can carry a weight of 8,300kg, which is plenty of power to get the satellite into orbit. The cost of this launch will be $62 million.

B. On board Propulsion

To assist in maintaining a geosynchronous orbit, the satellite will be equipped with Krypton Ion thrusters. These thrusters are a highly efficient system that is capable of producing small impulses for corrective maneuvering.

VII. Power System

A. Solar Panel

Photovoltaic is proposed for the power source for the satellite. Potential types of solar cells and their performance is shown in the table below. [16], [17], [18], [19], [20] These parameters are calculated with Air Mass (AM) 1.5. Note that the satellite will receive the solar radiation with AM 0 (more solar radiation than AM 1.5), and under this condition, the net power supply would be bigger than shown. Although the perovskite type shows the best power-to-weight and cost-to-power ratio, there are many reports about degradation under thermal cycle and Ultra Violet (UV) irradiation. Based on robustness on space radiation (proton, electron beam, and heavy ions) and on thermal cycles reported for Triple Junction(thin film) and CIGS, we chose CIGS as satellite power sources since it has better power-to-weight and cost-to-power ratio than the triple junction.

Reliability under thermal cycle between -55C and 125C is also important. CIGS have shown no degradation under 100 cycles of temperature variation shown above[21]. Therefore CIGS has enough lifetime for our proposed system (5-10 years).

Based on the requirement of transmit power of about 10 dBW (shown in table XI), margin up to 3 W will be generated by photovoltaic. Based on the maximum power output, which is shown in Table XIV, the cell area of 250 cm2 was calculated. The corresponding weight would be 2.56 g. The corresponding price would be $4.5 for CIGS solar panel.

TABLE XIV
POWER SYSTEMS

Parameters	Triple junction InGaP, GaAs, Ge	Triple junction (thin film) InGaP, GaAs, InGaAs	CIGS Cu(In,Ga) Se2	Perovskite CH3NH3PbI3
PCE(percent)	28	41	10	16
Pmax (mW/cm2)	35	38	12	20
Price(USD)	300 /W	380 /W	1.5 /W	0.5 /W
SAP Energy Density	70 W/kg	150 W/kg	1170 W/kg	1750 W/kg
Flexibility	Low	High	High	High
Mass	High	Low	Low	Low

B. Battery

A Lithium ion rechargeable battery is chosen for the power storage in the satellite due to its high robustness to space radiation and to thermal cycles with having the least memory effect and highest performance to our knowledge. Specifically, an 6Ah Space Cell manufactured by Eagle Pitcher Technologies, LLC. was chosen. The details are shown in Table XV. One manufactured batteries are used, and the total weight is 222g.

TABLE XV
SPECIFICATIONS

Part Number	LP-33330
Operating Voltage	3.0-4.1 V
Beginning of Life Capacity/Energy	6 Ah @ 20°C
maximum dimensions	3.0”W x 2.0”L x 1.0”H
Specific Energy	105 Whr/kg
Operating Temp	-5 to 35°C
Survival Temp. (non- op)	-15 to 40 °C

VIII. Radiation

To reduce radiation effects we need shielding to protect our components. We determined that a reliable radiation per year is 9,375 rad/year [1]. This means we need 5.5mm of aluminum shielding [1]. This will wrap all the electronics for our satellite. To determine the weight the size of the satellite needs to be determined. Based on internal components and adequate space for parts we found that an appropriate inner volume of approximate $1m^3$ is appropriate. To calculate the weight we know that aluminum is $2.7\frac{g}{cm^3}$. Therefore we need the volume of aluminum needed. To determine that we use the fact that we need $1m^3$ of internal space and add 5.5mm to find the outer volume:

$$V_{aluminum} = V_{outer} - V_{inner} \tag{72}$$

$$V_{outer} = 1005.5^3[mm^3] \tag{73}$$

$$V_{inner} = 1000^3[mm^3] \tag{74}$$

therefore

$$V_{aluminum} = 1005.5^3 - 1000^3 \tag{75}$$

$$V_{aluminum} = 1.65 * 10^7[mm^3] \tag{76}$$

$$V_{aluminum} = 16,590.9[cm^3] \tag{77}$$

using the fact that aluminum is $2.7\frac{g}{cm^3}$

$$Weight = 2.7[\frac{g}{cm^3}] * 16,590.9[cm^3] \tag{78}$$

$$Weight = 44,795g \tag{79}$$

$$Weight = 44.8kg \tag{80}$$

The aluminum plating adds 44.8kg of weight which we add to the total weight budget

IX. Doppler Shift

The Doppler shift will negligibly affect our system since the satellite is in GEO stationary orbit. From the Earth Transmit station to the satellite there is zero Doppler shift since both systems are moving perpendicularly to each other and at the same angular velocity. From the satellite to the car, due to the distance the satellite is from earth the signal the non-orthogonal component will be very small. Therefore the effect of the Doppler shift will be negligible.

X. Feasibility

Size, weight, and power (*SWaP*) are important parameters to consider for each component in our system. Table XVI lists the SWaP for the components used in our satellite system.

TABLE XVI
SIZE, WEIGHT, POWER, AND PRICE

Component	Size (m^3)	Weight (kg)	Power (Watts)	Price (USD)
Filter	8.7E-6 m^3	0.011 kg	N/A	$1,700
LNA	2E-5 m^3	0.045 kg	1.2 W	$3,600
PA	1.57E-5 m^3	0.055 kg	8.4 W	$11,201.50
Mixer(down)	4.19E-7 m^3	0.012 kg	1 W	$154.28
Mixer(up)	6.56E-7 m^3	0.012 kg	5 W	$327.11
PA	1.57E-5 m^3	0.055 kg	8.4 W	$10,766.99
Shielding	1.6591E-2 m^3	44.8 kg	N/A	N/A
Solar Cells	0.250 m^3	0.256 kg	1 W	$4.50
Batteries	0.039 m^3	0.222 kg	1000 Wh	$20
Total	0.3056 m^3	45.468kg	25 W	$1,142,262.77

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