Satellite Communications Class Project: mm-wave Satellite Links for V2V Applications

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***Abstract*— Research and investigation into the use of 5G communications comes from a necessity of higher data speeds and less data traffic on existing frequencies. Potential applications of 5G communication include V2V networks to improve traffic and vehicle safety. 5G communication requires the use of extremely high frequency spectrums that are referred to as mm waves. Although more mm wave components are being developed for the eventual move to 5G, millimeter waves are used majorly by only operators of satellites and radar systems. This paper seeks to determine the feasibility of a satellite communications link for a potential V2V system using millimeter waves. Despite the propagation loss associated with such a high frequency, a clear-day link margin of 30db or greater is possible using the selected equipment, modulation and bandwidth detailed in this paper. However when rain is introduced, the attenuation is high enough to disrupt the signal, especially in areas with a heavy amount of rainfall such as Miami, Florida.**

Keywords—satellite, communications, millimeter wave, V2V, 5G

I. Introduction

Vehicle-to-vehicle (V2V) communications consist of a wireless communications network between automobiles that provides information regarding to the status and position of an automobile. More importantly, it can be used to determine if there are any potential traffic hazards and how to avoid them, much like the traffic collision avoidance system (TCAS) that is currently used for aircraft.

Given the criticality of the timing and availability of such a communication system, the shift to V2V implementation will require a tremendous amount of data, processing power, and high data speeds. A 5G network would not only provide a high speed of transferring data, but also a less congested frequency band for V2V systems to operate. The range of frequencies include those within the millimeter wave spectrum between 30 and 300 gigahertz.

This paper seeks to investigate and define fundamental components for a satellite communications link that operates within the mm wave spectrum.

II. Design Goals and Criteria

This section will describe the system requirements that must be met in the design of this satellite communications system as well as requirements that will be derived to define what is needed for implementation of this system.

A. System Requirements

The goal of this study is to develop a satellite communication system that operates in the W-band and V-band frequency ranges. In particular, the requirements for this communication link are as follows:

Category	Requirement
Signal	Uplink signals to the transponder shall be in the range of 81-86 GHz.
Signal	Downlink signals from the transponder to the ground transceiver shall be in the range of 71-76 GHz.
Signal	Clear-day link margin shall be at a minimum 30dB; Objective margin is 36dB
Signal	Signal shall be able to support at least 19.2 kbps data rate; Objective data rate should be 10Mbps
Space Segment	Satellite shall be in geostationary orbit over CONUS
Space Segment	Satellite shall be operational and collect data for at least 36 months; Objective duration should be 60 months.

Table 1 System Requirements

B. Derived System Requirements

A set of design parameters must be determined in order to ensure said requirements are met. These parameters are determined through research and calculation from previous studies and theory, as well as given data from the equipment used. The parameters must satisfy the derived requirements below in order to ensure the original System requirements are met.

Parameter	Description
Signal Bandwidth	The bandwidth of the signal should be at least twice the data rate to obey the Nyquist Sampling theorem
Doppler shift	The downlink and uplink clear-day link margin shall maintain values above the

	required threshold if there are any sources of Doppler shift.
Bit Error Rate	The Bit error rate (BER) of the signal shall be below 0.001
Atmospheric Attenuation	Any atmospheric attenuation due to gas shall not inhibit the required clear day link margin.

Table 2 Derived System Requirements

III. Proposed Design and Proof of Concept

The following paragraphs detail the implementations of the requirements defined in the previous sections as well as the reasoning of the selection of specific components and parameters. Equations used to calculate the design parameters are also included in this section. A fully implemented V2V network will make use of multiple satellites and ground stations, however for the purpose of this investigation the calculations will take into account only one satellite, one ground station, and one vehicle. It is the intention that the findings and calculations for this given communications link can be replicated to increase the size of the V2V network, while taking into account different elevation angles between each satellite and ground station.

A. Satellite Transceiver

The space segment of this system is designed to mirror the configuration of a VSAT star system which is characterized by a master hub or ground station in which all of the data traffic is routed through. VSAT's must communicate with each other through the master hub as illustrated by [9, fig 1].

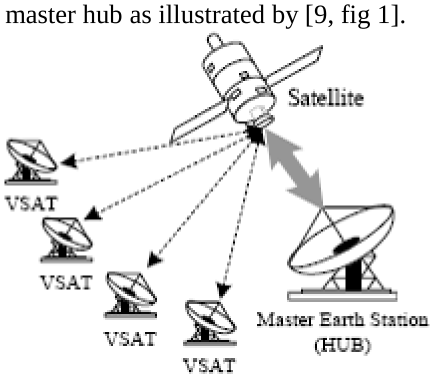


Figure 1 VSAT Star Network

In this application, the VSAT "users" are the vehicles of the V2V network. This configuration was chosen to mitigate the limited capabilities of the transmit EIRP used on each vehicle which is much more restricted than both the satellite and ground station/master hub that can contain a much higher EIRP.

The position of the satellite used in the link budget calculation will be located at 133 degrees West longitude over CONUS in a geostationary orbit. The satellite will use a custom antenna from a third party supplier that operates in the 71-86GHZ range for both receiving and transmitting signals.

The Rx/Tx chain of the satellite will consist of the following components:

- a low noise amplifier (LNA) to reduce loss in the insertion feed
- A band pass filter (BPF) to extract the correct frequency from the signal
- A mixer and local oscillator to downconvert the signal for transmission to the ground station
- A second band pass filter (BPF) to remove any unwanted frequencies after conversion frequency from the signal
- A high power amplifier (HPA) to increase the gain of the converted signal
- A low power amplifier (LPA) for additional gain and to act as a backup for the HPA

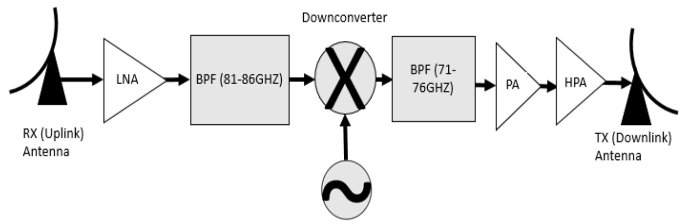


Figure 2 Satellite Rx/Tx Chain

The specific model and vendor of these components are listed in the *Budget and Timeline* section of this paper.

B. Ground Station and Vehicle

The ground station is equipped with a 13.1 meter cassegrain antenna with very high gain of 63 dbi, and is positioned at 25.82 degrees north latitude and 80.319 degrees west longitude. This position is near Miami Airport with ICAO:KZMA at an elevation of -7.882 meters. The ground station Rx/Tx chain which is very similar to the satellite transceiver consists of:

- A band pass filter (BPF) to extract the correct frequency from the signal
- a low noise amplifier (LNA) to reduce loss in the insertion feed
- A mixer and local oscillator to uoconvert the signal for transmission to the satellite.
- A power amplifier (PA) to increase the gain of the converted signal

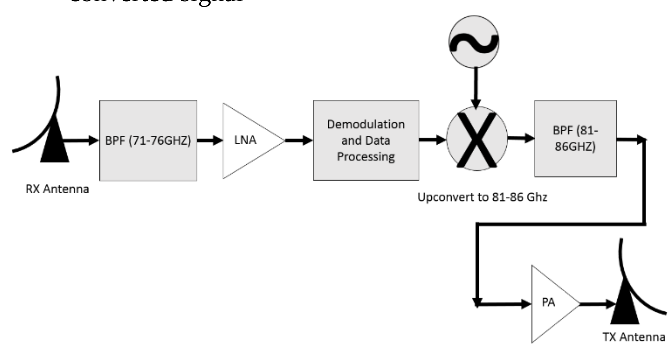


Figure 3 Ground Station Rx/Tx Chain

The location of the vehicle used in this study is assumed to be in the same location as the ground station. This location combines some of the worst conditions for transmitting and receiving data in relation to the satellite's location as well as the environmental conditions of the area. A tracking antenna will be mounted onto the vehicle with a gain of 43.8 dbi.

C. *Link Budget*

The link budget is detailed below in the following tables. Any values that were assumed for constants are listed under table 3. The equations used to determine the link budget parameters are also included in this section.

Clear day link margins for all three receivers were calculated to be greater than 30 db. To further validate the performance of this link, the received signal carrier to noise ratio (CNR) was also calculated to include rain attenuation. Unfortunately, due to the elevation of the ground station as well as the high rain conditions of the area, the CNR was significantly lower for all three receivers and would lead to unacceptable results. This is also affected by the high frequency of millimeter waves in this application.

Fortunately, gas attenuation as well as Doppler shift had very little impact to the system link budget. Doppler shift was calculated for the vehicle, by using the top speed of the fastest commercially available car with top speed of 445.63kmph [3].

The link margin for both the satellite and ground station hub was initially unaffected by a data rate of 9.5 Mbps. However this needed to be adjusted to 180kbps due to the low link margin received by the satellite from the vehicle which is the weakest link in the system.

CONSTANTS		
Earth radius	6367500	m
GEO orbital altitude	35786000	m
GEO orbital altitude + Earth's radius	42153500	m
Boltzmann's constant	1.38065E-23	J/K
Speed of light	300000000	m/s

Table 3 Link Budget Constant Values

SIGNAL PARAMETERS		
Maximum Data rate	180	kbps
Uplink Frequency (worst)	86	GHz
Uplink Wavelength	0.003488372	m
Downlink Frequency (worst)	76	GHz
Downlink Wavelength	0.003947368	m
Uplink Frequency with **max doppler shift** from	86.00003548	GHz
Uplink Frequency with **min doppler shif**t from moving vehicle	85.99996452	GHz
Uplink Wavelength **max doppler shift**	0.003488371	m
moving vehicle	76.00003136	GHz
Downlink Frequency with **min doppler shift** from	75.99996864	GHz
Downlink Wavelength **max doppler shift**	0.003947367	m
Signal bandwidth	360000	Hz
Max BER of BPSK	0.001	
Minimum Required C/N	6.82	db

Table 4 Link Budget Signal Parameters

GROUND STATION PARAMETERS		
Ground station latitude	25.82	degrees North
Ground station longitude	80.319	degrees West
Ground station altitude	-7.882	m
Ground transmit power	25	dB
Ground antenna gain	63	dBi
Ground antenna noise temp	76	K
Received Power	-92.54123901	db
Noise Power	-154.2280094	db
C/N received (clear sky)	61.68677038	db
Clear Day Link margin of Ground Station	54.86677038	db
C/N received (rain)	-69.25804161	db

Table 5 Link Budget Ground Station Parameters

SATELLITE PARAMETERS		
Satellite longitude	133	degrees West
Sat transmit power	13	dBW
Sat antenna gain	54	dBi
Sat antenna noise temp	200	K
Received Power from Ground station	-81.63356231	dbW
Received Power from Vehicle	-112.8335659	dbW
Noise Power	-150.0258454	db
C/N received from vehicle (clear sky)	68.39228305	dbw
C/N received from vehicle (clear sky)	37.19227946	dbw
Clear Day Link margin of satellite and vehicle	30.37227946	db
C/N received from vehicle (rain)	-95.7410476	db

Table 6 Satellite Parameters for Link Budget

GROUND VEHICLE PARAMETERS		
Ground station latitude	25.82	degrees North
Ground station longitude	80.319	degrees West
Ground station altitude	-7.882	m
Ground transmit power	13	dB
Ground antenna gain	43.8	dBi
Ground antenna noise temp	62	K
Received Power	-111.7412426	db
Noise Power	-155.1122284	db
C/N received (clear sky)	43.37098583	db
Clear Day Link margin of vehicle	36.55098583	db
C/N received (rain)	-87.57382616	db

Table 7 Vehicle Parameters for Link Budget

SIGNAL ATTENUATION AND PATH LOSS		
Path length (d)	39044874.83	m
Elevation angle	25.22002836	deg
Uplink path loss	222.9630219	dB
Downlink path loss	221.8893247	dB
Uplink path loss (with high end of doppler shift from vehicle)	222.9630255	dB
Downlink path loss (with high end of doppler shift from vehicle)	221.8893283	dB
Atmospheric attenuation due to rain @ 76 GHz	130.944812	dB
Atmospheric attenuation due to rain @ 86 GHz	132.9333271	dB
Atmospheric attenuation due to gas @ 76 GHz	0.651914278	dB
Atmospheric attenuation due to gas @ 86 GHZ	0.6705404	dB

Table 8 Calculated path loss and other link budget values

A BPSK digital modulation scheme was selected for both uplink and downlink carrier signals. The minimum required C/N in our link margin was calculated for a BER of 0.001 using the following equation:

$$P_e\, BER = Q\left(\sqrt{\frac{2C}{N}}\right) \qquad (1)$$

The actual CNR also needed to be calculated by determining the received power and noise power at each station. This was done for the

- the uplink between the vehicle and satellite,
- the uplink between the ground station and satellite
- the downlink between the satellite and the ground station
- the downlink between the satellite and vehicle

This value can be found as received power under the table for each station's parameters. Received power was calculated using the following equation:

$$P_R = P_T + G_T + G_R - 20log\left(\frac{4\pi d}{f/_c}\right) - L_{atm} \qquad (2)$$

In Equation (2) Pt represents the transmitted power, Gt is the gain of the transmitting antenna, Gr is the gain of the receiving antenna, f is the frequency of the signal, c is the speed of light in a vacuum, and Latm is the loss in signal due to atmospheric attenuation. This was calculated with and without rain as seen in the parameter tables. Received noise power was calculated using:

$$P_N = 10log(kTB) \qquad (3)$$

Pn represents the received noise power in dbW with the boltzman constant k, bandwidth B, and noise temperature of the receiving antenna in kelvin for T. Finally, the CNR for each station is given by:

$$\frac{C}{N} = P_R - P_N \qquad (4)$$

The Rain attenuation values in Table 8 were calculated based on the model provided by ITU document [4] which consists of taking the product of the specific attenuation due to rain and the effective path length between the transmitter and receiver. The specific attenuation value is obtained from equation 5 using frequency dependent coefficients with $R_{0.01}$ representing the point rainfall rate for the location of the ground station for 0.01% of an average year. Such coefficients were determined by [6] after extensive research into the subject matter.

$$\gamma_R = k(R_{0.01})^{\alpha} \qquad (5)$$

The ground station location $R_{0.01}$ value was determined to be 95 as part of zone N, given by the rainfall rates detailed in ITU recommendation [5]. The values for coefficients κ and α are listed below

kh @ 76GHZ	1.1185
ah @ 76GHZ	0.7199
kh @ 86GHZ	1.2398
ah @ 86GHZ	0.7006

Table 9 Rain Attenuation Coefficients

Gaseous attenuation was calculated based on models from ITU [7]. This model presents the total zenith attenuation due to water vapor and dry air (oxygen) in the atmosphere, both of which are primarily responsible for gaseous attenuation of the W/V band frequencies. The method for predicting this gaseous attenuation is presented in equation 6, where the specific attenuations are obtained from the chart in [7, figure 4]

$$A = \frac{A_O + A_W}{\sin\varphi} \qquad (6)$$

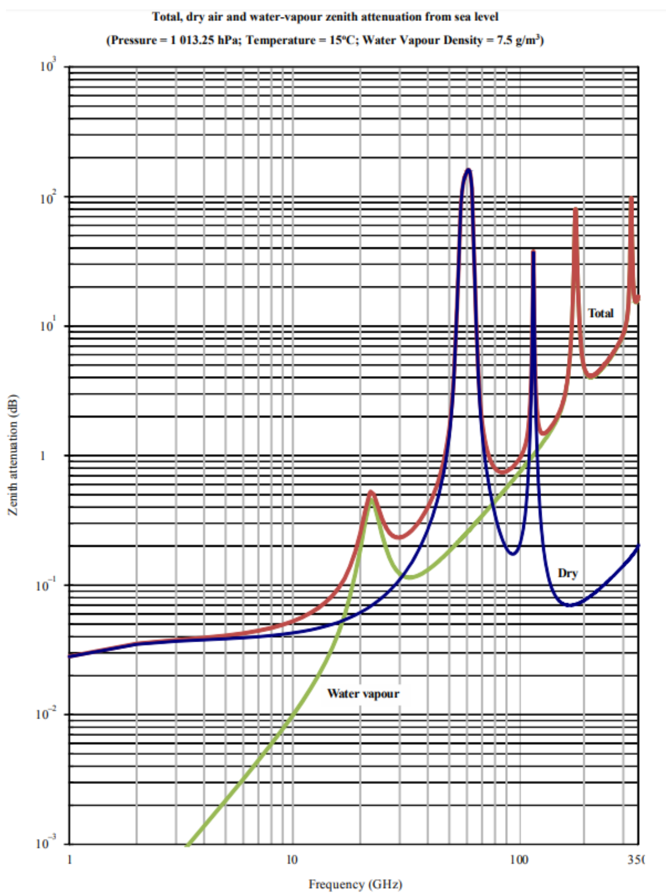


Figure 4 Zenith Attenuation from ITU-R P.676-11

D. Space Segment Propulsion System

Once the satellite is launched, various forces acting on the satellite will pull it out of orbit over time. In order to maintain a geostationary orbit of the satellite, a pair of gas jets will be installed on each axis of the satellite in both directions in order to control pitch, roll, and yaw. This will ensure the satellite remains in a circular orbit on the equatorial plane by engaging a gas jet on the required axis and thereby changing its velocity. The opposite gas jet will be engaged to stop this motion. According to Pratt [8], a GEO satellite deviates from its orbit a an average rate of 0.85° per year. Corrections will therefore made every 3 weeks to mitigate this error. The same as jets will also be used to maintain the correct attitude of the satellite antennae towards CONUS.

A telemetry, tracking, command, and monitoring (TTC&M) system will be established between the satellite and ground station hub for controlling the gas jets. The TTC&M system will also implement sensors to monitor voltage, current, and temperature of all subsystems on the satellite, as well as the pressure of the gas jet tanks and attitude of the antennae.

E. *Space Segment Power System*

The satellite must be able to transmit signals of strength near 20 watts and be able to power all subsystems for at least 36 months. To do so, the satellite will obtain its electrical power through solar cells with enough area to account for loss of the solar cell efficiency at end of life (EOL). The angle of incidence between the solar cells and sun will be maintained using the on-board propulsion system to be as efficient as possible without compromising orbit trajectory or antenna attitude.

The power system will also be comprised of 3 lithium ion batteries and a power system control asic. Power obtained by the solar cells will be used to charge the batteries for situations where solar power is unavailable. The switching between these two sources of power to the satellite will be handled by the power system control ASIC.

IV. Safety and risk Management

In respect to V2V, an adequate link margin must be established to ensure that users will be able to send and receive vehicle data in time to avoid any potential hazards. Therefore, the parameters chosen for calculating link budget were representative of a worst case scenario in order to determine the bare minimum requirements that would be needed to establish a safe link margin. For instance, the ground station and vehicle where chosen to be in a location that had a combination of the worst rain fall in CONUS while also being in a highly populated area that is on the eastern most part of CONUS. The speed of the vehicle chosen matched that of the fastest commercially available automobile, thereby having the most impact to the Doppler shift. The highest frequency for the downlink and uplink signals were selected in order to maximize the amount of propagation loss as well as atmospheric attenuation. Furthermore, the polarization coefficients used for rain attenuation where chosen to be vertical instead of horizontal.

To ensure proper operation and extended lifecycle while in orbit a TTC&M system will be implemented as mentioned earlier. Aside from control of the onboard gas jets, the satellite will also receive additional commands from the ground station when necessary. These commands include, powering on/off of each subsystem, change of each subsystem's operating mode, deployment of solar cell arrays and protective covers, and uploading of computer programs. Such commands would take priority in any processes that are running on the on-board computer. Dedicated personnel will be assigned to monitor the satellite through the TTC&M system.

Normal operation of the TTC&M will make use of the signal link that has been established in this paper for the W and Vbands. A ku-band antenna and auxiliary rx/tx chain will also be installed onto the satellite in the event that there is a failure with the default antenna. The BER of this link will be in the order of 10^{-5}. Commands and telemetry will be communicated through this link exclusively.

The ground station hub antenna is built to withstand 100% relative humidity and rain up to 4 in/hr and is still operational under 60mph winds. While being able to survive 210 mile per hour winds. Additional ground station hubs will be constructed in varying locations in the event that the weather conditions are extreme in one area.

Development of the space segment will also be subjected to extensive design reviews, audits, and tests at all levels to expose any additional potential risks that must be mitigated.

V. Business Considerations

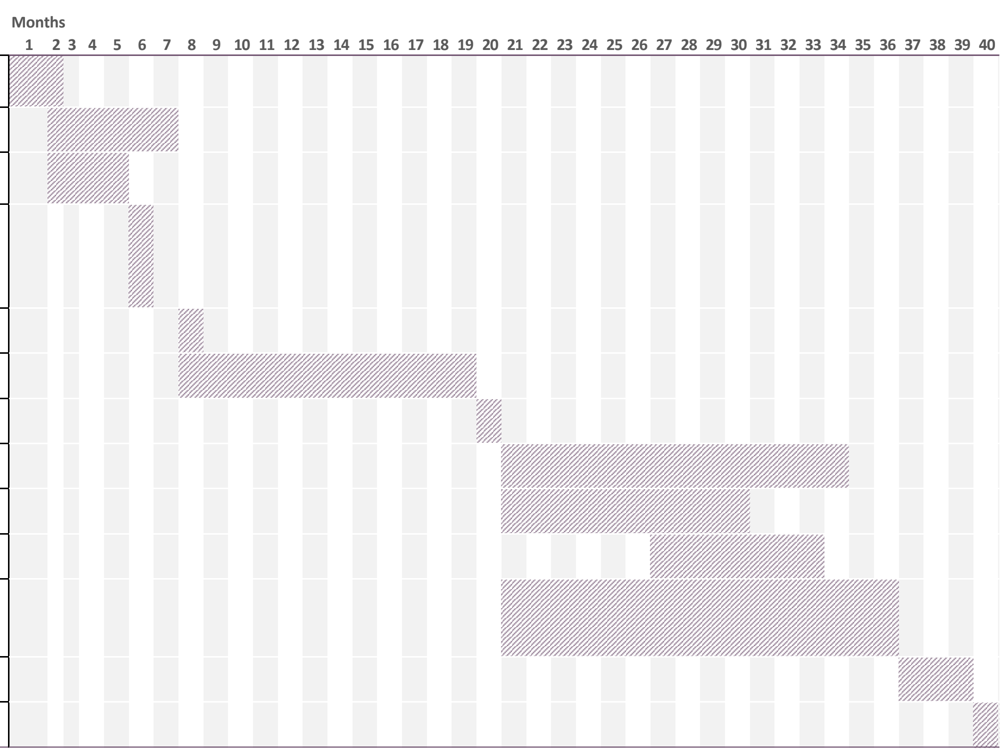
A. Predicted Budget

The chart below lists the cost estimate of the minimum required parts and labor to build and verify this satcom system. This does not include maintenance costs as well as launch costs.

Part Description	Part Number	Vendor	Cost	Quantity	Total Cost	Website
13.1 Meter Cassegrain Antenna	n/a	General Dynamics	$20,000	2	$40,000	https://gdmissionsystems.com/products/satcom-technologies/antennas/large-fixed-antennas/13-1-meter-
BPF 71-76 GHZ	FIB-12-RE030	millitech	$2,500	1	$2,500	http://www.millitech.com/MMW-FilterFerrite-FIB.htm
Ground station LNA	LNA-12-02690	millitech	2,700	2	$5,400	http://www.millitech.com/MMW-Amplifier-LNA.htm
mixer 60-90 GHZ frequency range	MXP-12	millitech	3,500	2	$7,000	http://www.millitech.com/MMW-MixerDetector-MXP.htm
BPF 81-86GHZ	FIB-10-RW210	millitech	2,950	1	$2,950	http://www.millitech.com/MMW-FilterFerrite-FIB.htm
Power Amplifier	AMP-12-41020[5]	millitech	4,000	1	$4,000	http://www.millitech.com/MMW-Amplifier-AMP.htm
Satellite MM wave Antenna	HRP3-800	mWave	6,000	2	$12,000	https://www.mwavellc.com/60-to-110-ghz-antenna/custom-millimeter-wave-antennas-60-110ghz/
Satellite BPF 81-86GHZ	FIB-10-RW180	millitech	$2,650	1	$2,650	http://www.millitech.com/MMW-FilterFerrite-FIB.htm
Satellite BPF 71-76 GHZ	GDV-10	millitech	3,300	1	$3,300	http://www.millitech.com/MMW-Sources-GDV.htm
LPA	AMP-12-02280/02290	millitech	3,976	1	$3,976	http://www.millitech.com/MMW-Amplifier-GaNAMP.htm
HPS	AMP-12-20020/20010	millitech	4,200	1	$4,200	http://www.millitech.com/MMW-Amplifier-GaNAMP.htm
Solar panels	n/a	Isis	600	20	$12,000	https://www.isispace.nl/product/custom-solar-panels/
Labor	**Number of Staff**	**Rate per hour**	**Max Time in months**		**Total Cost**	
Research and Development	10	$70	40		$4,480,000	
TTC&M Staff	20	$47	60		$9,024,000	
				Grand total	$13,603,976	

B. Projected Timeline

ACTIVITY	PLAN START	PLAN DURATION
Requirements Gathering	1	2
Proof of Concept	2	6
Modeling and Simulation	2	4
Risk Identification and Management	6	1
Bid Proposal	8	1
Subsystem Design	8	12
Requirements Review	20	1
Launch System Planning and	21	14
Equipment Procurement	21	10
Integration and build	27	7
Subsystem Testing and Debugging	21	16
Final Testing	37	3
Oribtal Launch	40	1



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