National Aeronautics and Space Administration

V-Band Communications Link Design For A Hosted Payload

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Outline

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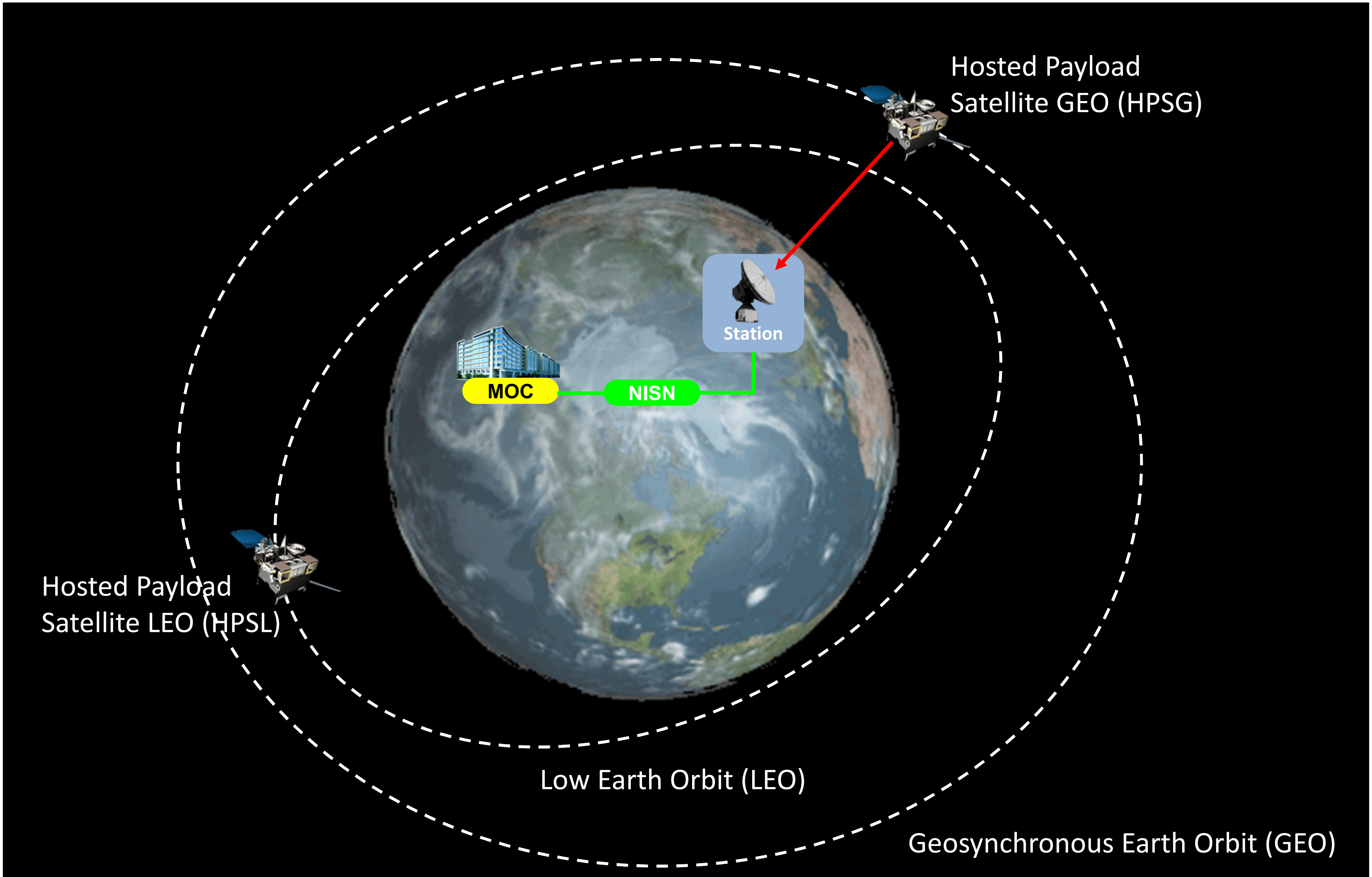
1. Introduction

Task Objectives

- Hosted Payload Study
  - Analyze commercial GEO/LEO satellite hosted payload specifications
  - Assess how NASA can use hosted payload capabilities
- V-Band Link Analysis
  - Research, analyze, and determine feasibility of high frequency communications at V-band (50-75 GHz)
  - Defining applications for high-frequency communications
  - Assessing link design and performance based on varying parameters
- V-Band Hosted Payload Application
  - Determining the size and power consumption of the associated communications payload
  - Interpreting the feasibility of implementation within the accommodation constraints of a hosted payload



SCaN SIP 2011	Hosted Payload Locations & Architecture Design for V-Band			V-band	User Missions
	Title: V-Band Architecture High-Level Operational Concept Graphic				NISN
	Figure/Table/Type: OV-1	Date: 6/21/2011	Version: 1	Figure: 1	

2. Hosted Payload Study

What is a Hosted Payload?

- Refers to the utilization of available capacity on commercial satellites to accommodate additional payloads (e.g., transponders, instruments, etc.)
- By offering "piggyback rides“ on commercial communication satellites already scheduled for launch, costumers such as government agencies can send sensors and other equipment into space on a timely and cost-effective basis.
- Concept is similar to “ridesharing” but instead partners share a satellite bus, rather than a space launch vehicle.

What is a Hosted Payload?

- Some providers offer specific hosted payload accommodations. However, many providers are open to negotiation for space onboard their satellite buses.
- For our study, based on our research, we used 10-20% of the total satellite capabilities are reserved for payload additions as a rule of thumb.

Hosted Payload Considerations

Advantages

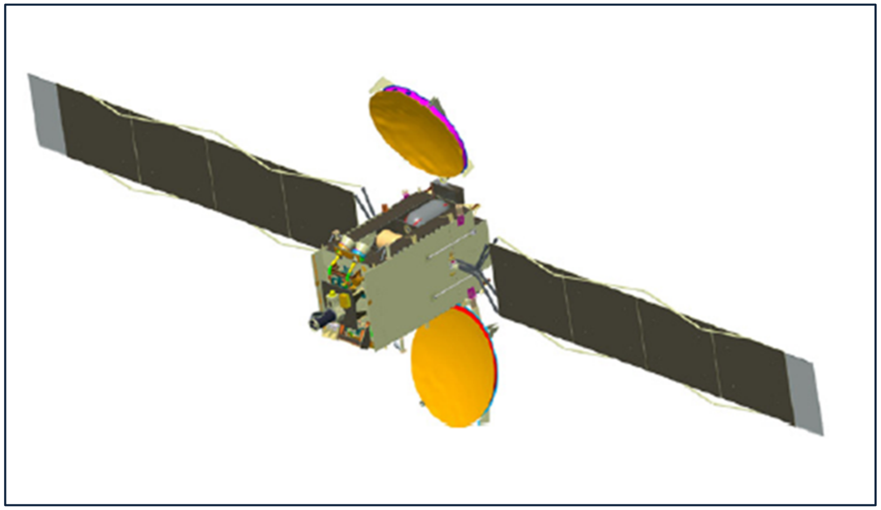
- Principal advantages
  - Faster pacing of commercial programs vs. government programs
    - ~32 months as compared to 5-7 years
  - Lower cost
    - Use of hosted payloads provides a low cost opportunity for access to higher orbit (i.e., GEO, LEO)
- Other advantages
  - Reliable and predictable launch schedule
  - Large choice of launch vehicles
  - Use of existing mission support facilities
  - Primary operator handles operations and maintenance

Disadvantages

- Limitations on payload mass, volume, and power
- Adherence to commercial satellite development and deployment schedules
  - Strict procurement, construction, and launch schedules (Government schedules are typically much longer)
- Coverage is restricted to position of commercial satellite

STAR Bus

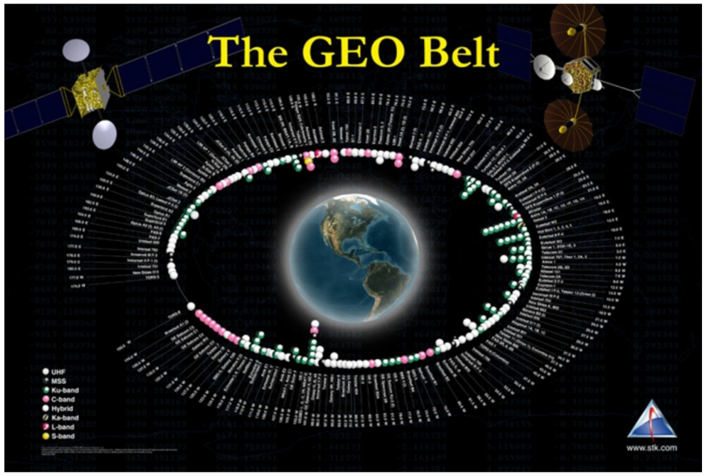
- Payload Mass Capability:
  - Approx. 60kg, depending on size of primary payload
  - 430 kg total payload mass
- Available Payload Volume:
  - Approx. 25” x 30” x 28”
- Orbit: GEO
- Available Payload Power:
  - Dependent on specific host spacecraft
- Payload Interface:
  - Orbital’s SPI Modem interface
  - MIL-STD-1553 bus



An Earth-staring remote sensing hosted payload on the nadir deck of a STAR 2.4 bus

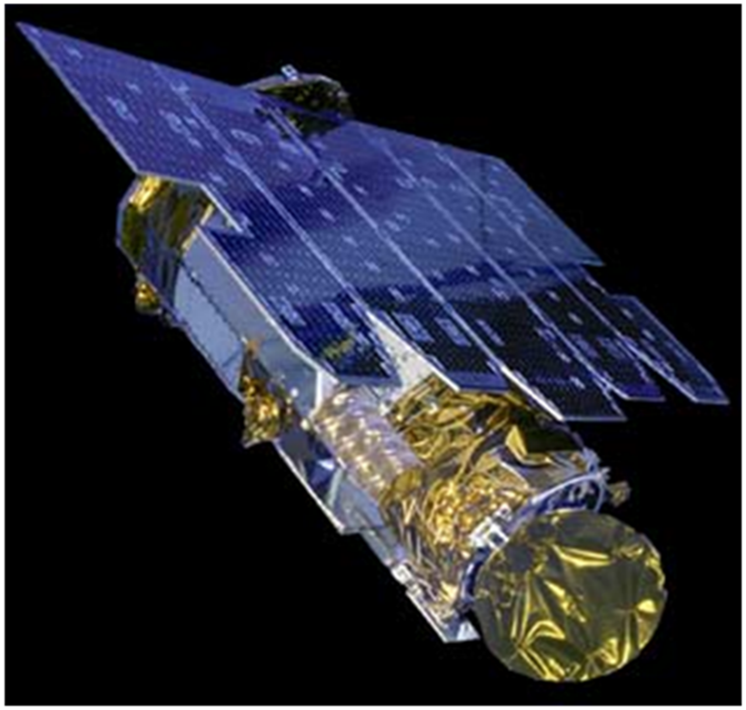
GEO Specifications Summary

- GEO Satellites
  - Average Weight: 2966 kg
  - Power: 5.66 kW
  - Average Dimensions: 40.7 m x 12.4 m x 11.8 m
- Hosted Payloads
  - Weight: 296 – 592 kg
  - Power: 0.566-1.132 kW
  - Estimated Payload Dimensions
    - Length: 4.07 – 8.14 m
    - Width: 1.24 – 2.48 m
    - Height: 1.18 – 2.36 m



LEOStar Bus

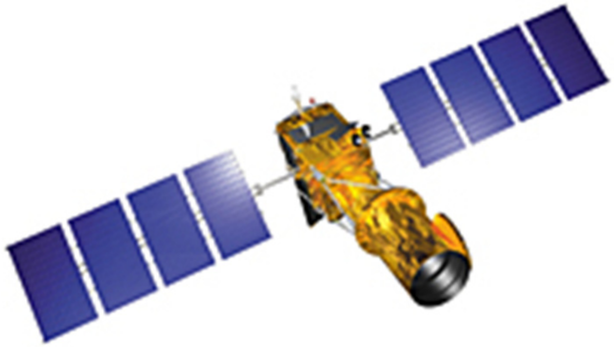
- Payload Mass Capability:
  - ≤101 kg
- Bus dimensions:
  - 95.2 cm x 160 cm
- Orbit: LEO (450-1000 km)
- Available Payload Power:
  - 110 W
- Payload Interface:
  - MIL-STD 1553B/RS-422
  - CCSDS



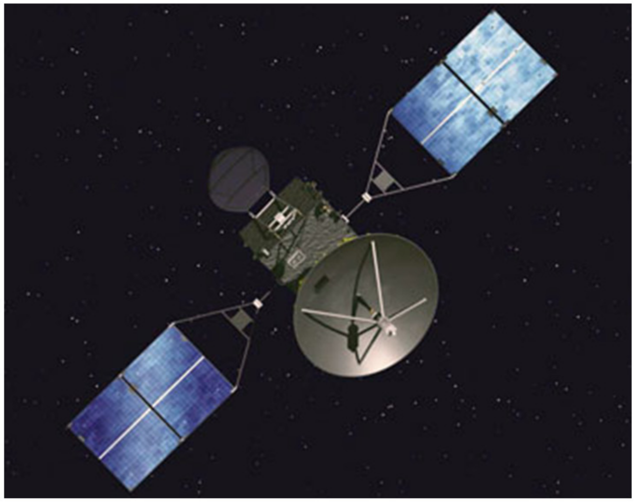
OrbView-3, which uses the LEOStar bus

LEO Specifications Summary

- LEO Satellites
  - Average Weight: 1405 kg
  - Power: 4.5 kW
  - Average Dimensions: 1.75 m x 1.7 m x 1.8 m
- Hosted Payloads
  - Weight: 140 – 280 kg
  - Power: 0.45 – 0.9 kW
  - Estimated Payload Dimensions
    - Length: 0.175 – 0.35 m
    - Width: 0.17 – 0.34 m
    - Height: 0.18 – 0.36 m



LEO Star Bus in Orbit



Future Satellite Launches

Satellite Provider	Satellite Bus	Orbit	Satellite Name	Orbital Slot	Launch Date
Orbital Sciences	STAR	GEO	SES-3	103° West	2nd Quarter 2011
Orbital Sciences	STAR	GEO	SES-2	87° West	3rd Quarter 2011
Astrium	EuroStar E3000	GEO	Astra 1N	19.2° East	2nd Quarter 2011
Astrium	EuroStar E3000	GEO	Astra 2F	28.2° East	4th Quarter 2012
Astrium	EuroStar E3000	GEO	Astra 2E	28.2° East	1st Quarter 2013
Astrium	EuroStar E3000	GEO	SES-6	319.5° East	1st Quarter 2013
Astrium	EuroStar E3000	GEO	Astra 5B	21.5° East	2nd Quarter 2013
Astrium	EuroStar E3000	GEO	Astra 2G	28.2° East	1st Quarter 2014
Space Systems / Loral	LS 1300	GEO	SES-4	338° East	2nd Quarter 2011
Space Systems / Loral	LS 1300	GEO	QuetzSat-1	77° West	3rd Quarter 2011
Space Systems / Loral	LS 1300	GEO	Ses-5 / Sirius 5	5° East	4th Quarter 2011
Thales Alenia Space	Spacebus 4000	GEO	W3C	7° East	3rd Quarter 2011
Orbital Sciences	LEOStar	LEO	NuSTAR	TBD	2012
Orbital Sciences	LEOStar	LEO	GEMS	TBD	2014

Potential Applications of Hosted Payloads

- Propagation Analysis
- Technology Demonstration
  - i.e., Internet Routing in Space
- Added Capacity in Space
- Space Situational Awareness
  - i.e., Collision Avoidance, Debris Monitoring, Nuclear Detection, Radiation Assessment, Streaming and still imagery
- Sensor Package and Instrumentation
  - i.e., Hyper-Spectral Sounding, Ocean Color Analysis, Ozone Mapping, Earth Staring, and Weather Tracking
- Others…

3. V-Band Communications Link Design & Analysis

What is V-Band?

- V-Band is an arbitrary designation of a high frequency range approximately between 50-75 GHz
- Although V-Band frequencies are allocated by NTIA, no operational licenses have been issues yet.
- V-Band is also highly attenuated by atmosphere and rain

V-Band Considerations

Advantages

- Increased data rate capabilities for satellite-to-ground communications for shorter download time
- Smaller antennas for higher frequency bands reduce the mass on payload
- High frequency transmissions are less likely to be distorted due to interference and low population of users in higher frequency bands
- The higher the data rate, the higher the level of public interest and engagement. Higher rates allow for high-res images, high-def video, etc…

Disadvantages

- Space-Ground Communications
  - Atmospheric Absorption
    - Increased rain attenuation
    - Resonance of oxygen molecules
    - Increased humidity attenuation
  - Requires more transmission power
- Not suitable for emergency communications due to atmospheric variability
- Need a more precise attitude control system on the flight platform due to the pointing requirements of the narrow beamwidth

Link Design Process

Define Requirements for Each Link →

1. Identify Communications Requirements
2. Specify Alternate Communications Architectures
3. Determine Data Rates For Each Link
4. Design and Size Each Link
5. Document Reasons For Selection

Design Each Link →

1. Select Frequency Band
2. Select Modulation and Coding
3. Apply Antenna Size, Beamwidth Constraints (if any)
4. Estimate atmospheric, rain absorption
5. Estimate Received Noise, Interference Powers
6. Calculate Required Antenna Gains and Transmitter Power

Size the Communications Payload Subsystem

1. Select Payload Antenna Configuration
2. Calculate Antenna Size
3. Estimate Antenna Mass
4. Estimate Transmitter Mass and Power
5. Estimate Payload Mass and Power

What is a Link Budget?

- A link budget analysis is an analysis of gains and losses within an RF link.
- Gains and losses of the components/factors in the RF path are computed and summed
  - Result is an estimate of the end-to-end system performance in the real world
  - This must be done to determine if a sufficient signal strength will be received to meet data rate requirements

Link Budget

- Link Budget Analysis can be performed for both the downlink and uplink, but the parameters used in the calculation varies including:
  - Uplink power amplifier gain and noise factors
  - Transmit Antenna Gain
  - Receiver Antenna and Amplifier Gains and Noise Factors
  - Atmospheric Attenuation Factors
  - Slant range and corresponding space loss over a distance

Equations for Link Budget

$$E_b/N_0 = EIRP + L_s + L_a + G_r + 228.6 - 10\log T_s - 10\log R$$

- *E_b/N_o= Energy per bit to noise power spectral density ratio*
- *EIRP = Equivalent Isotropic Radiated Power (dB)*
- *L_s = Space Loss (dB)*
- *L_a = Atmospheric Losses (dB)*
- *G_r = Receiver Gain (dB)*
- *T_s = System Noise Temperature (K)*
- *R = Data Rate (bps)*

Space Mission Analysis and Design

Equations for Link Budget

- **$EIRP = P_t + L_t + G_t$**
- **$L_s = 147.55 – 20logS – 20logf$**
- **$G_t = G_{pt} + L_{pt}$**
- **$G_{pt} = 44.3 – 10log(Θ^2)$**
- **$L_{pt} = -12(e_t/Θ)^2$**
- **$G_r = G_{pr} + L_{pr}$**
- **$G_{pr} = -159.59 + 20logD_r + 20logf + 10logN$**
- **$L_{pr} = -12(e_r/Θ)^2$**
- **Θ = 21/fD [f in GHz]**

- *EIRP = Equivalent Isotropic Radiated Power (dB)*
  - *P_t = Transmit Power (dB)*
  - *L_l = Line Loss (dB)*
- *L_s = Space Loss*
  - *S = Propagation Path Length(km)*
  - *F = Frequency(Hz)*
- *G = Antenna Gain (dB)*
- *L = Antenna Loss*
- *D = Antenna Diameter (m)*
- *e = Antenna Pointing Loss (deg)*
- *Θ = Antenna Beamwidth (deg)*
- *N = Antenna Efficiency(% - Decimal)*
- *f = Frequency (Hz)*
- *$_r$ = Receiver*
- *$_t$ = Transmitter*
- *$_p$ = Peak Gain*

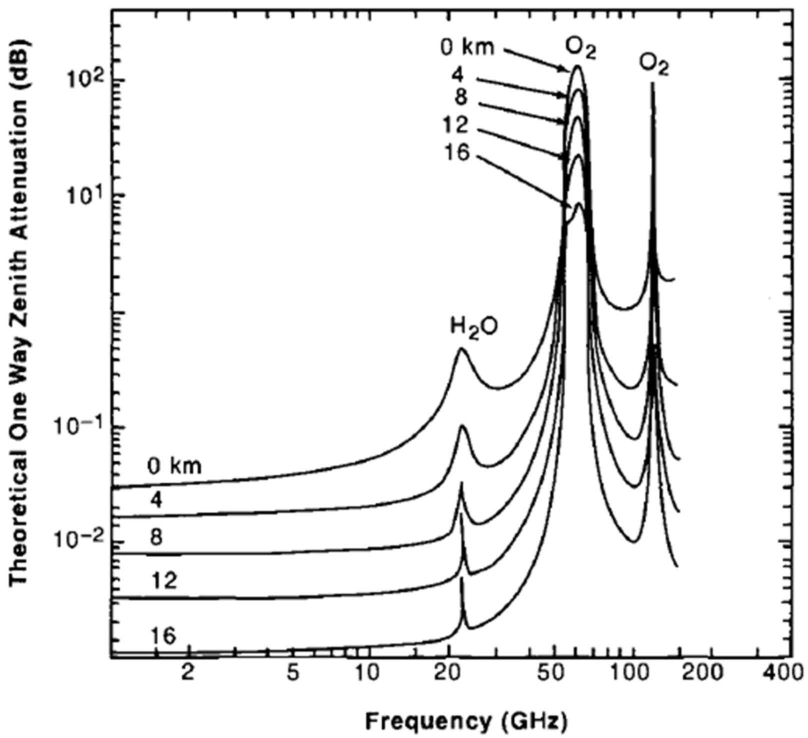
Space Mission Analysis and Design

Types of Atmospheric Absorption

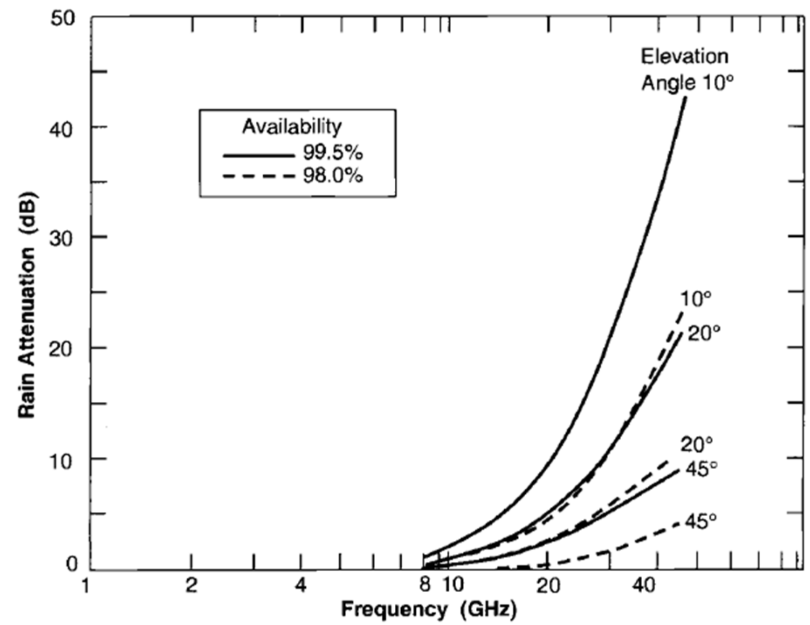
- **Refraction**
  - Slight shift apparent elevation of a satellite depending on atmospheric pressure and water vapor content.
  - Causes off-pointing of receiver antenna.
- **Depolarization**
  - Occurs when the shape of the raindrops causes a signal to be differentially absorbed, causing a rotation or change in the signal's polarization.
  - Results in power loss at the receiving antenna.
- **Reflection/Multipath**
  - Occurs when a signal is partially reflected
- **Rain Attenuation**
  - Occurs when water droplets diffuse/absorb the RF radiation in a satellite signal
  - Effect is proportional to the rain intensity
- **Molecular Attenuation**
  - Attenuation by oxygen molecules and water vapor in the atmosphere
  - The large absorption band at ~60 GHz make these frequencies attractive for inter-satellite communications (using atmosphere to shield against interference from Earth)

Attenuation Graphs

Atmospheric Attenuation



Rain Attenuation



Space Mission Analysis and Design

V-Band Application

Fixed Parameters:

- f: 50-75 GHz
- L_l: -6 dB
- L_s: Calculate for GEO
- L_a: Assume -9 dB (3 dB atmosphere + 6 dB rain loss for 98% availability at >45° elevation angle, SMAD)
- e_t and e_r: Assume 3 dB loss
- T_s: 300 K (ref. SDO)
- BER: < $5x10^{-9}$
- Modulation: BPSK
- E_b/N_0 Required:
  - 2.8 dB (ref. SDO using BER, Modulation, and Encoding chosen)

Input Parameters:

- P_t: 2.5 W – 20W
- D_t: 0.05 m – 0.50 m
- D_r: 1 m – 5 m
- Bit Rate: 150 Mbps – 350 Mbps

Calculated Parameters:

- EIRP, L_{pt}, L_{pr}

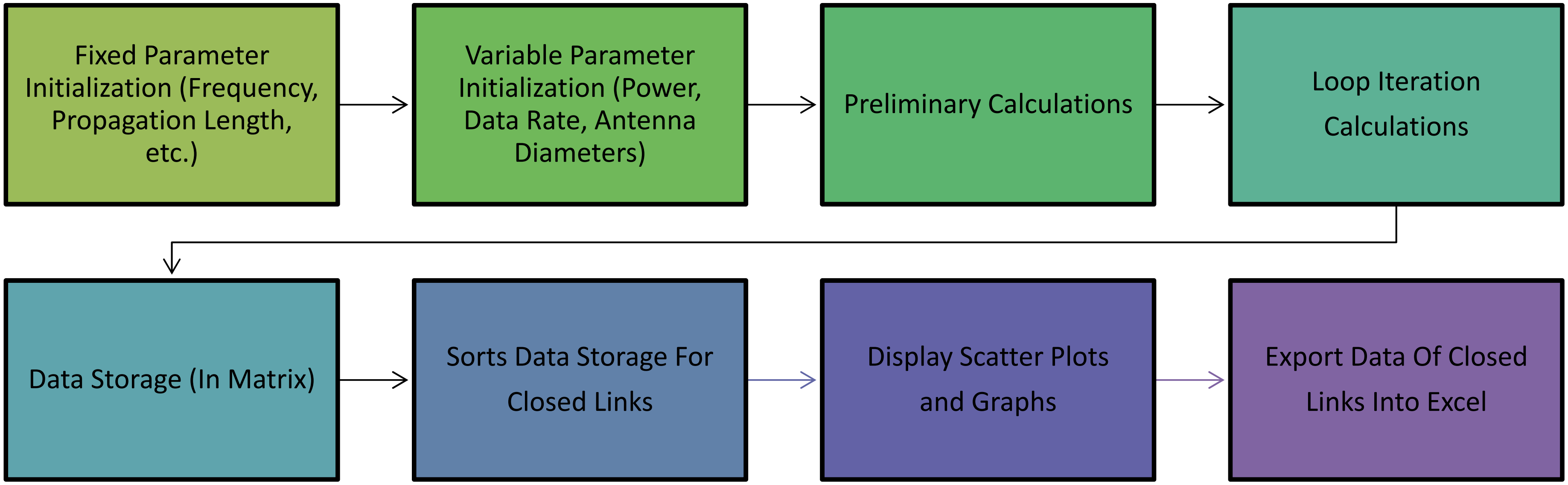
Link Margin: 6 dB

Simple Link Budget Calculator

Parameter	Symbol	Units	A	B	C	D	E	F	G
Inputs									
Frequency	f	GHz	50	50	55	60	65	70	75
Transmitter Power	P	dBW	3.979400087	6.989700043	6.989700043	6.989700043	6.989700043	6.989700043	6.989700043
Data Rate	R	bps	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08	1.50E+08
Transmitter Antenna Diameter	dt	m	0.25	0.5	0.5	0.5	0.5	0.5	0.5
Transmitter Antenna Pointing Offset	et	deg	0	0	0	0	0	0	0
Receive Antenna Diameter	dr	m	1	3	3	3	3	3	3
Receive Antenna Pointing Offset	er	deg	0	0	0	0	0	0	0
Antenna Efficiency	N	% (decimal)	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Transmitter Line Loss	Ll	dB	-9	-9	-9	-9	-9	-9	-9
Propagation Path Length	S	km	36000	36000	36000	36000	36000	36000	36000
Atmospheric Propagation and Polarization Loss	La	dBkm	-6	-6	-6	-6	-6	-6	-6
System Noise Temperature	Ts	K	300	300	300	300	300	300	300
Required Eb/No	(Eb/No)reqd	dB	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Implementation Loss	L	dB	-3	-3	-3	-3	-3	-3	-3
Outputs									
Transmitter Antenna Beamwidth	theta t	deg	1.68	0.84	0.763636364	0.7	0.646153846	0.6	0.56
Receive Antenna Beamwidth	theta r	deg	0.42	0.14	0.127272727	0.116666667	0.107692308	0.1	0.093333333
Peak Transmitter Antenna Gain	Gpt	dB	39.79381437	45.81441428	46.64226798	47.3980392	48.09328132	48.73697499	49.33623946
Transmitter Pointing Loss	Lpt	dB	0	0	0	0	0	0	0
Transmitter Antenna Gain	Gt	dB	39.79381437	45.81441428	46.64226798	47.3980392	48.09328132	48.73697499	49.33623946
Peak Receive Antenna Gain	Gpr	dB	51.79302698	61.33545208	62.16330578	62.919077	63.61431912	64.25801279	64.85727726
Receive Antenna Pointing Loss	Lpr	dB	0	0	0	0	0	0	0
Receive Antenna Gain	Gr	dB	51.79302698	61.33545208	62.16330578	62.919077	63.61431912	64.25801279	64.85727726
Space Loss	Ls	dB	-217.5554501	-217.5554501	-218.3833038	-219.139075	-219.8343171	-220.4780108	-221.0772753
Equivalent Isotropic Radiated Power	EIRP	dB	34.77321445	43.80411432	44.63196803	45.38773924	46.08298137	46.72667504	47.3259395
Eb/No	Eb/No	dB	-14.92133381	3.651991158	4.479844862	5.235616079	5.930858204	6.574551872	7.173816339
Carrier-to-Noise Density Ratio	C/No	dB	66.83957878	85.41290375	86.24075745	86.99652867	87.6917708	88.33546446	88.93472893
Margin	M	dB	-20.72133381	-2.148008842	-1.320155138	-0.564383921	0.130858204	0.774551872	1.373816339
Bit Error Rate	BER		#NUM!	3.44E-03	1.38E-03	6.06E-04	2.86E-04	1.44E-04	7.60E-05

With the use of Microsoft Excel, we were able to create a simple link budget calculator, utilizing the link budget equations.

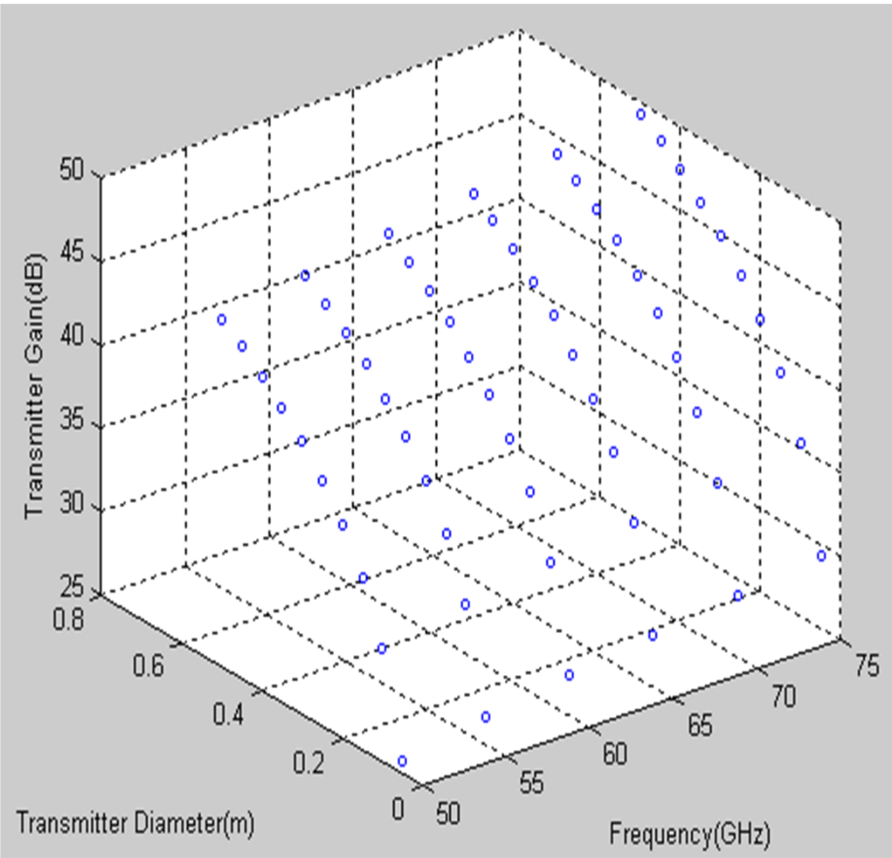
MATLAB Script



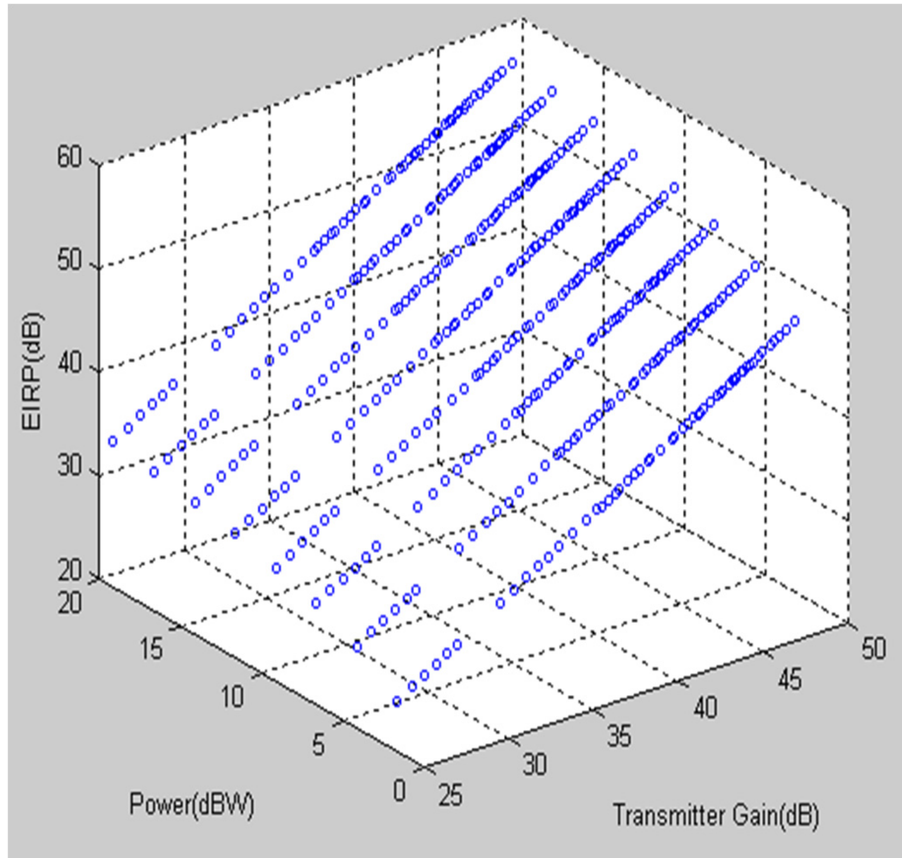
- MATLAB is a software that allows the user to type code to systems of equations based on the outputs desired.
- By using MATLAB, we have created a calculation program to determine a number of different outputs depending on the user's known inputs.

Data Graphs

Frequency vs. Transmitter Diameter vs. Transmitter Gain

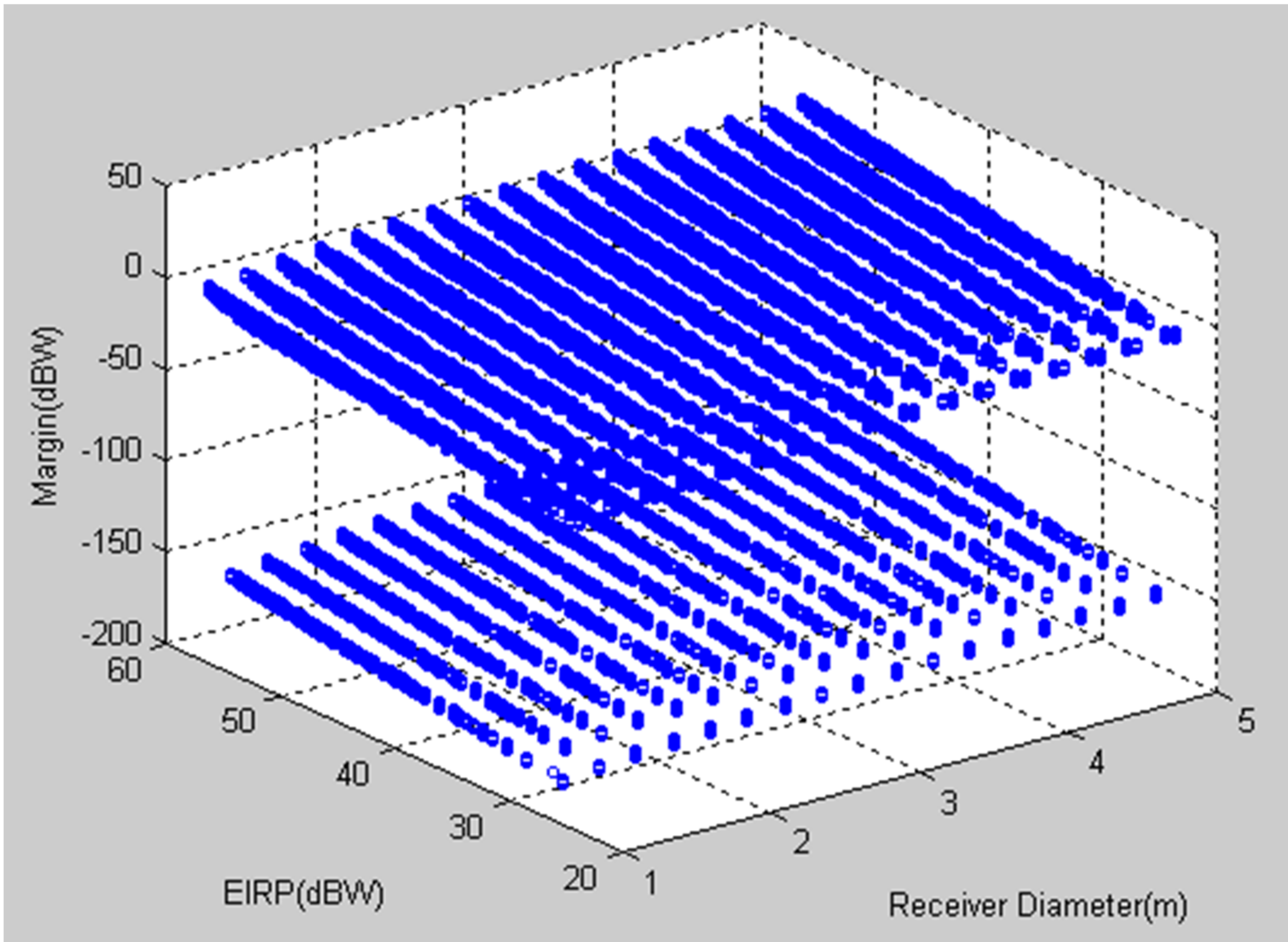


Transmitter Gain vs. Transmitter Power vs. EIRP



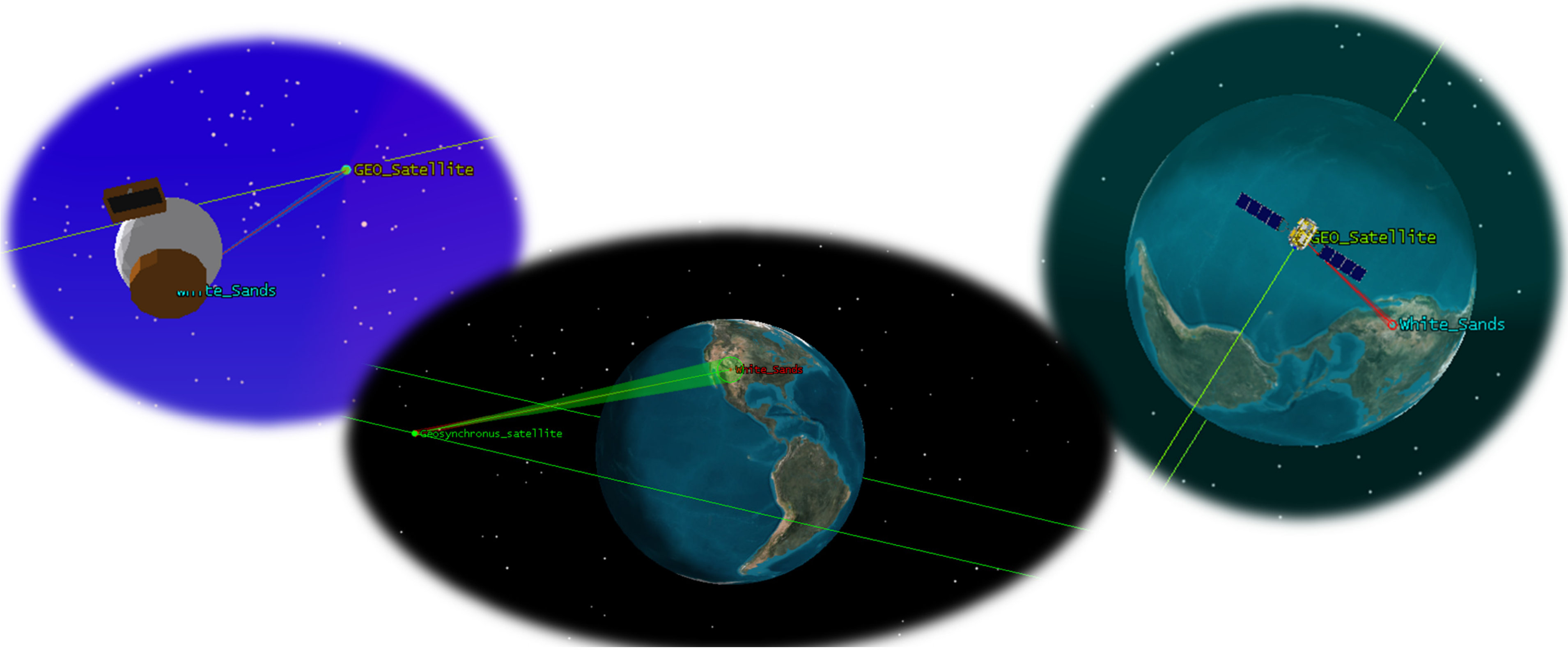
Data Graphs

Receiver Diameter vs. EIRP vs. Link Margin



STK Simulations

- Satellite Tool Kit (STK) is a software tool that allows the user to input the parameters while the equations are calculated by the software.
- To verify the results, we used the MATLab data to simulate the entire scenario in STK in a static environment.
- To provide a dynamic study of the environment for the link.



Static Environmental Losses
STK Results – MATLab Verification

Inputs:	Frequency (GHz)	Power (W)	Transmitter Diameter (m)	Receiver Diameter (m)	Data Rate (mbps)	*Outputs:*	EIRP (dBW)	Eb/No (dB)	BER
	50	2.5	0.5	5	150		43.748	1.7574	4.17E-02
	50	5	0.5	5	150		46.759	4.7677	7.17E-03
	50	7.5	0.5	5	150		48.52	6.5286	1.36E-03
	50	10	0.5	5	150		49.769	7.778	2.67E-04
	50	12.5	0.5	5	150		50.738	8.7471	5.41E-05
	50	15	0.5	5	150		51.53	9.5389	1.11E-05
	50	17.5	0.5	5	150		52.199	10.2084	2.32E-06
	50	20	0.5	5	150		52.779	10.7883	4.87E-07
Max Data Rate of 236mbps at 5W for an Eb/No of 2.8									
	50	2.5	0.5	5	150		43.748	1.7574	4.17E-02
	50	5	0.5	5	300		46.759	1.7574	4.17E-02
	50	10	0.5	5	600		49.769	1.7574	4.17E-02
	50	20	0.5	5	1200		52.779	1.7574	4.17E-02
As Data Rate Doubles, Power Doubles									
	50	2.5	0.5	3	150		43.748	-2.6791	1.49E-01
	50	5	0.5	3	150		46.759	0.3312	7.09E-02
	50	7.5	0.5	3	150		48.52	2.0921	3.60E-02
	50	10	0.5	3	150		49.769	3.3415	1.89E-02
	50	12.5	0.5	3	150		50.738	4.3106	1.01E-02
	50	15	0.5	3	150		51.53	5.1024	5.47E-03
	50	17.5	0.5	3	150		52.199	5.7719	2.99E-03

Additional Constant Inputs:

- System Noise Temperature: 300 K
- Encoding Gain: 3 dB
- Line Loss: -6
- Modulation: BPSK
- Atmospheric Loss: 9 dB
- Parabolic Antenna
- Transmitter and Receiver Pointing Offset: Total 3 dB loss

Dynamic Environmental Losses STK Results

Links	A (50 GHz)		B (55 GHz)		C (60GHz)		D (65 GHz)		E(70Ghz)		F(75GHz)	
Components	T	R	T	R	T	R	T	R	T	R	T	R
Antenna Size (m)	0.5	5	0.5	5	0.5	5	0.5	5	0.5	5	0.5	5
Power (W)	3.54813		3162.28		$1.12202*10^{20}$		446.684		1.99526		1.41254	
Free Space Loss (dB)	-217.7863		-218.6141		-219.3699		-220.0651		220.7088		-221.3081	
Atmospheric Loss (dB)	-1.2716		-31.4971		-197.7897		-24.498		-1.5219		-0.7529	
EIRP (dBW)	51.269		81.597		247.853		74.548		51.692		50.791	
Eb/No (dB)	12.2649		12.367		12.33		12.3168		12.4364		12.3044	
BER	$3.229566*10^{-9}$		$2.138712*10^{-9}$		$2.486046*10^{-9}$		$2.622741*10^{-9}$		$1.60811*10^{-9}$		$2.756888*10^{-9}$	

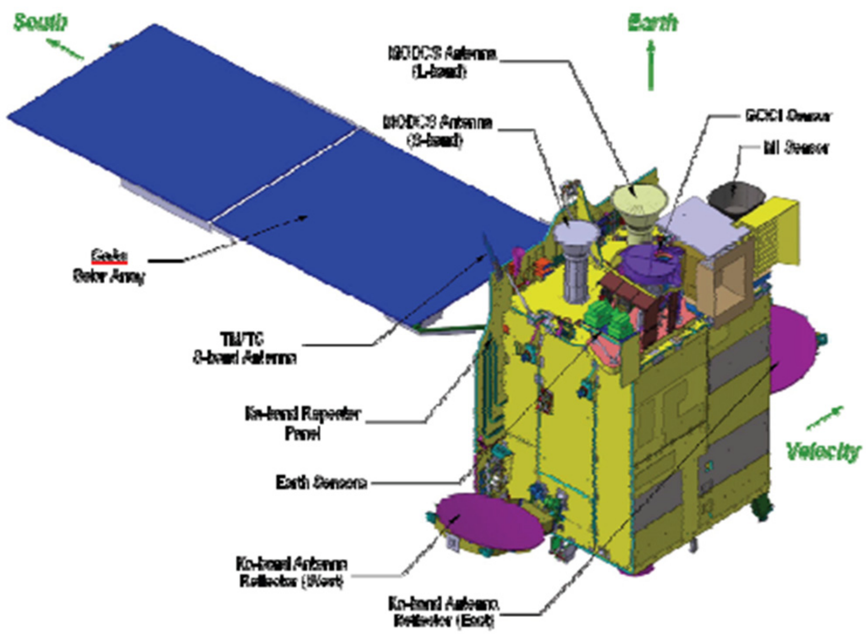
T = Transmitter, R= Receiver

V-Band Analysis Summary

- Due to the extent of the atmospheric attenuation with V-Band, the feasibility of utilizing the frequency band on a hosted payload between 58-62 GHz is impractical.
- When constrained by hosted payload parameters, the power needed to transmit at these frequencies while keeping a sensible size ground station is unreasonable.
- At 50 and 75 GHz, the atmospheric attenuation is low enough for a transmission from space to ground with a high data rate. However, when using the rain model the loss increases such that the links do not close.

Future Work

- Research components of a Communications Payload
- Design Communications Payload for V-Band



COMS Payload: A Ka-Band Communications Payload Representation

Questions?

References

- Books:
  - Digital Communications Fundamentals and Applications
    - By: Bernard Sklar
  - Introduction to Satellite Communications
    - By: Bruce R. Elbert
  - Space Mission Analysis and Design
    - By: Wiley J. Larson and James R. Wertz
- Mentors:
  - Eric Knoblock, Systems Definition & Communications, DSE
  - David Avanesian, Systems Definition & Communications, DSE
  - Charles Niederhaus, Systems Definition & Communications, DSE
  - David Bittner, Systems Definition & Communications, DSE

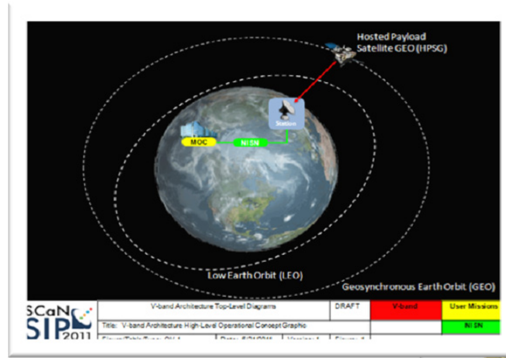
V-Band Communications Link Design For A Hosted Payload

Task Description:

Research, analyze, and determine feasibility of high frequency communications at V-band (50-75 GHz) to be accommodated on a hosted payload.

This task includes:

- Assessing link design and performance based on varying parameters
- Research commercial GEO/LEO satellite bus developers
- Determine the feasibility of implementation within the accommodation constraints of a hosted payload



Student Information

- Anthony Zunis, University of Akron, Sophomore, Electrical Engineering and Applied Mathematics, SCaN SIP Intern
- Deboshri Sadhukhan, University of Akron, Freshman, Electrical Engineering, SCaN SIP Intern
- John Alexander, Ohio University, Freshman, Electrical & Computer Engineering, SCaN SIP Intern

Mentors

- Eric Knoblock, Systems Definition & Communications, DSE
- David Bittner, Systems Definition & Communications, DSE

Support

- David Avanesian, Systems Definition & Communications, DSE
- Charles Niederhaus , Systems Definition & Communications, DSE

Schedule for V-Band:

Communications Specifications:

- Define Applications, Requirements, and Link Parameters - **7/5/11**

Communications Design:

- Analyze/Design Communication Links - **7/15/11**
- Size and Design Communications Payloads - **7/21/11**

Final Presentation:

- Finalize and Document Analysis and Design- **7/29/11**
- Final Presentation at Symposium - **8/4/11**

Schedule for Hosted Payload:

Hosted Payload Specifications:

- Document Hosted Payload Accommodation Specifications - **7/5/11**

Communications Design:

- Provide accommodation data for link and payload designs - **7/25/11**

Final Presentation:

- Finalize and Document Analysis - **7/29/11**
- Final Presentation at Symposium - **8/4/11**

Verification of Three Programs

	Excel	MATLab	STK
Modulation	BPSK	BPSK	BPSK
Frequency (GHz)	50	50	50
Transmitter Power (dBW)	1	1	1
Transmitter Diameter (m)	2	2	2
Receiver Diameter (m)	10	10	10
EIRP (dBW)	52.85561411	52.85561411	52.81
C/No (dB*Hz)	110.9219784	110.9107786	110.598383
Eb/No (dB)	29.16106585	29.15986602	28.8375
BER	1.11x10^-14	1.11399x10^-14	1.00x10^-30