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UNIVERSITY OF COLORADO BOULDER

GENERAL ATOMICS

DOT COM

Deep-Space Orbital Telecommunications

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Mission Statement

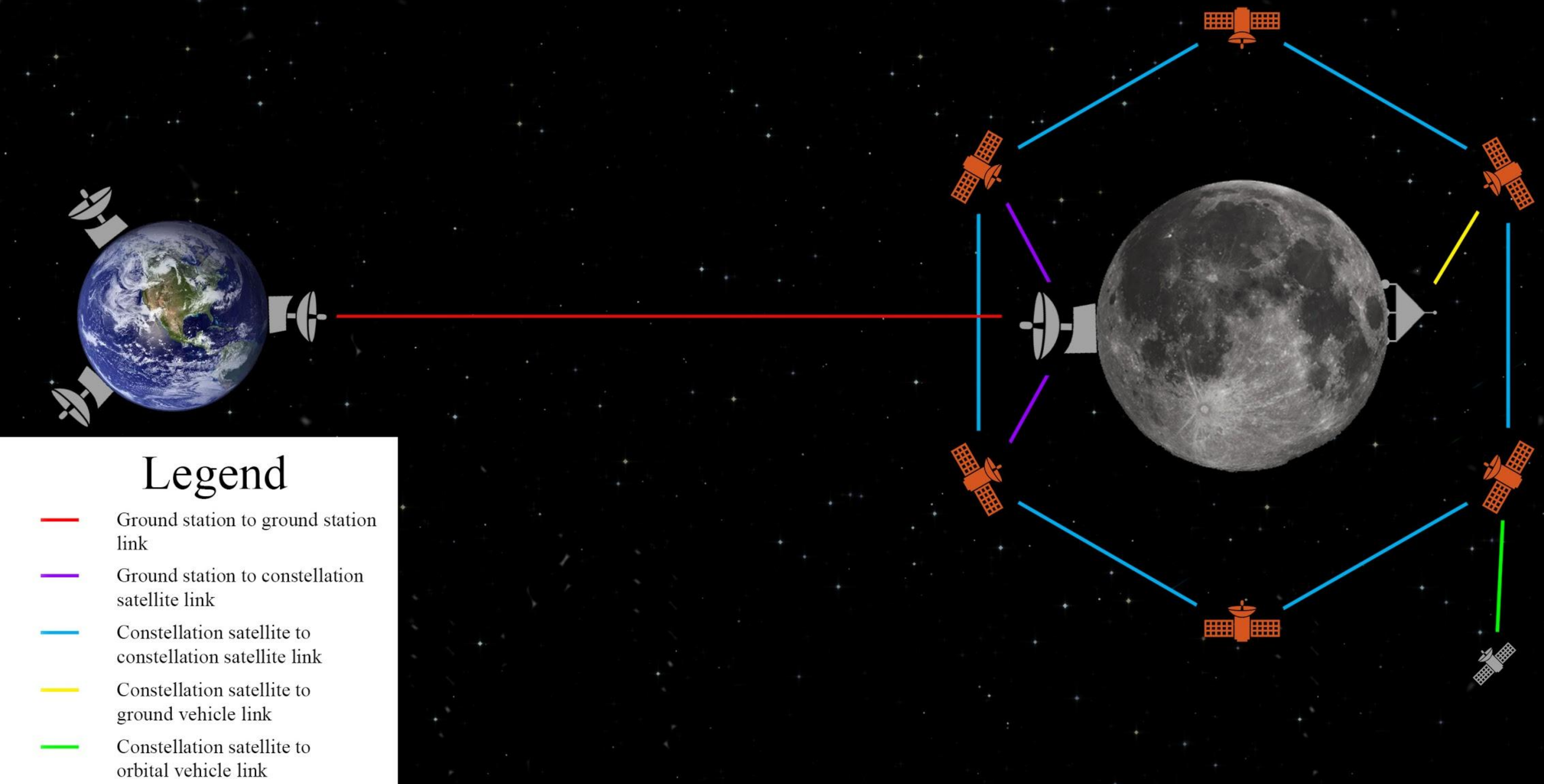
Project DOTCOM is a research-heavy **system modeling** assignment. In this, we explore the functionality and viability of a communications network architecture between the Earth and Moon. The purpose of this project is to **develop software models** to design and optimize a **Lunar communications network**, packaged through **Model-Based System Engineering.**

Table of Contents

Project Purpose & Objectives

Project Purpose & Objectives → Project Schedule → Manufacturing → Budget

System CONOPS



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Critical Project Elements

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Designation	CPE	Critical Characteristics
CPE-1	Network Protocol	Structured data transmission methodology that allows for high speed reliable communications from node to node.
CPE-2	System Link Budget	The project will meet certain data-relay rates for communication between all communication nodes.
CPE-3	Relay Stations	Allows for direct access to communications between Earth and The Moon.
CPE-4	Satellite Constellations	Construction of ideal constellation architecture around each planetary body to satisfy coverage requirements.

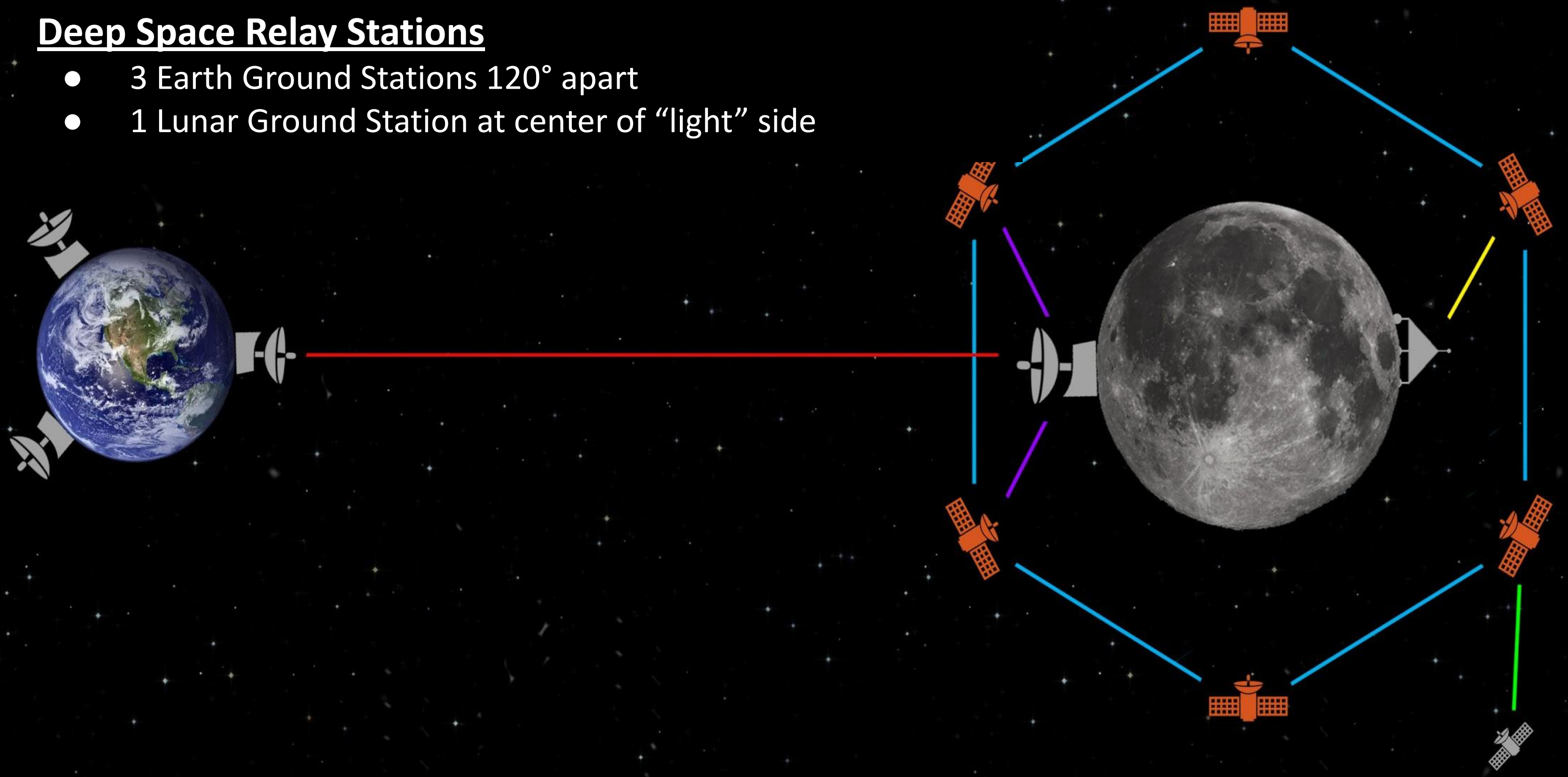
Performance Targets

Functional Requirement	Design Requirement
FR 1 Area Coverage	99% telecommunications coverage in Lunar orbit
	99% telecommunications coverage on Lunar Surface
FR 2 Endpoint Support	5+ nodes for simultaneous 'real time' communications on Lunar surface
	10+ nodes for non simultaneous (within 6 hrs) communication on Lunar surface
	10+ nodes for simultaneous 'real time' communication in Lunar orbit
	20+ nodes for non-simultaneous (within 6 hrs) communication in Lunar orbit
	Earth-Moon data rates: 500 Mbps threshold, 5 Gbps objective
FR 3 Compatibility	Network is compatible with and ensures the safety of existing and future infrastructure

Baseline Network Design

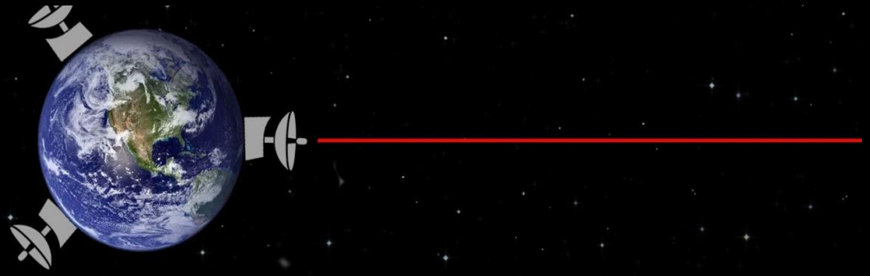
Deep Space Relay Stations

- 3 Earth Ground Stations 120° apart
- 1 Lunar Ground Station at center of "light" side



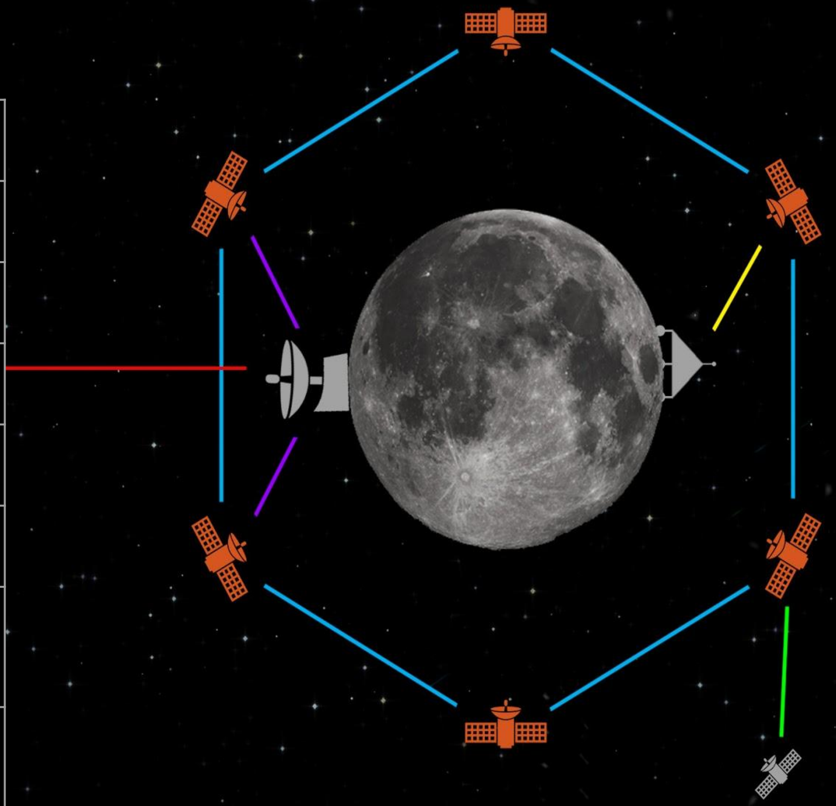
Satellite Constellation Architecture

- Walker-Delta configuration
  - ~53 deg inclination
  - 6/6/4 configuration
  - MEO equivalent altitude



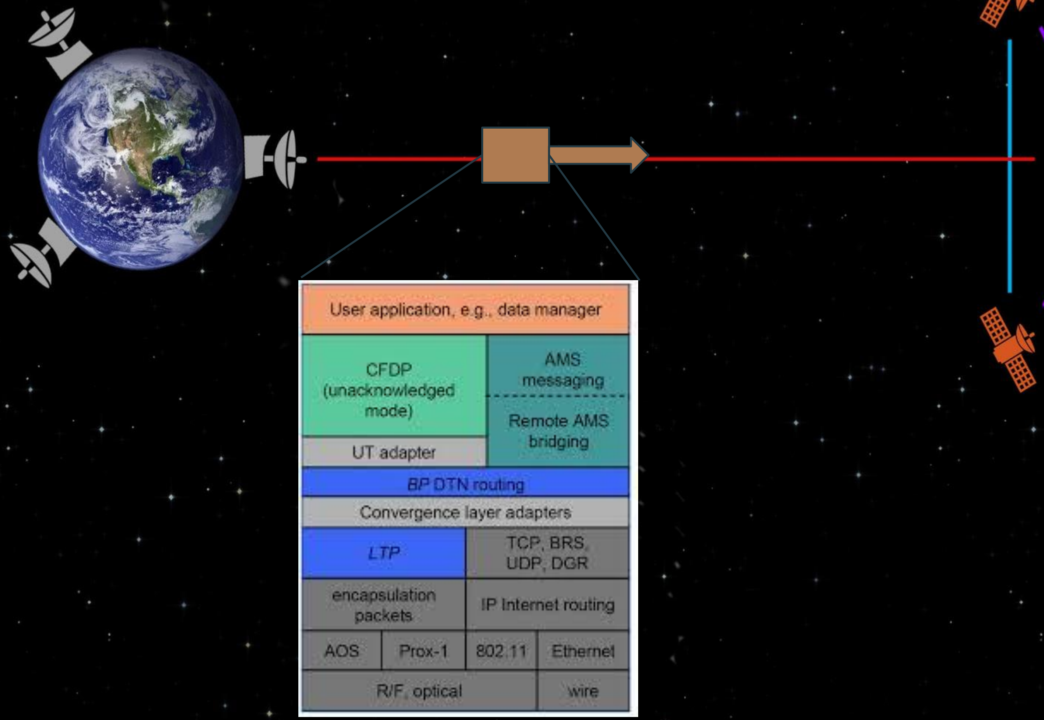
Inter-Constellation Satellite Link Budget

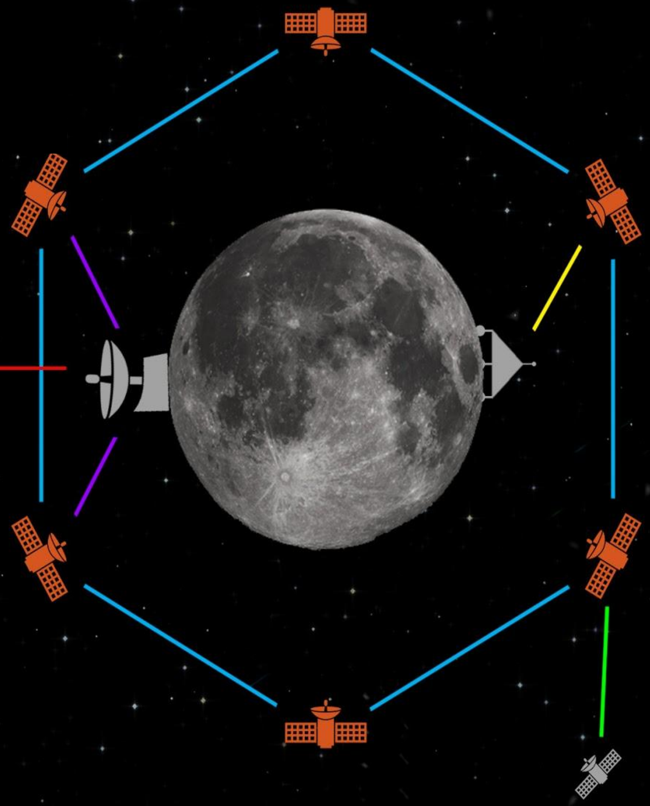
Link Parameters	Value
Max Range (km)	11,024 km
Frequency (GHz)	26
Antenna Size (D)	1 m
Transmit Power (W)	30 W
Data Rate (Mbps)	500
Receive System Noise Temperature (K)	700 K
Required Eb/No (dB) [BPSK Modulation, BER = 10^-7]	11 dB
Required Design Margin	3 dB

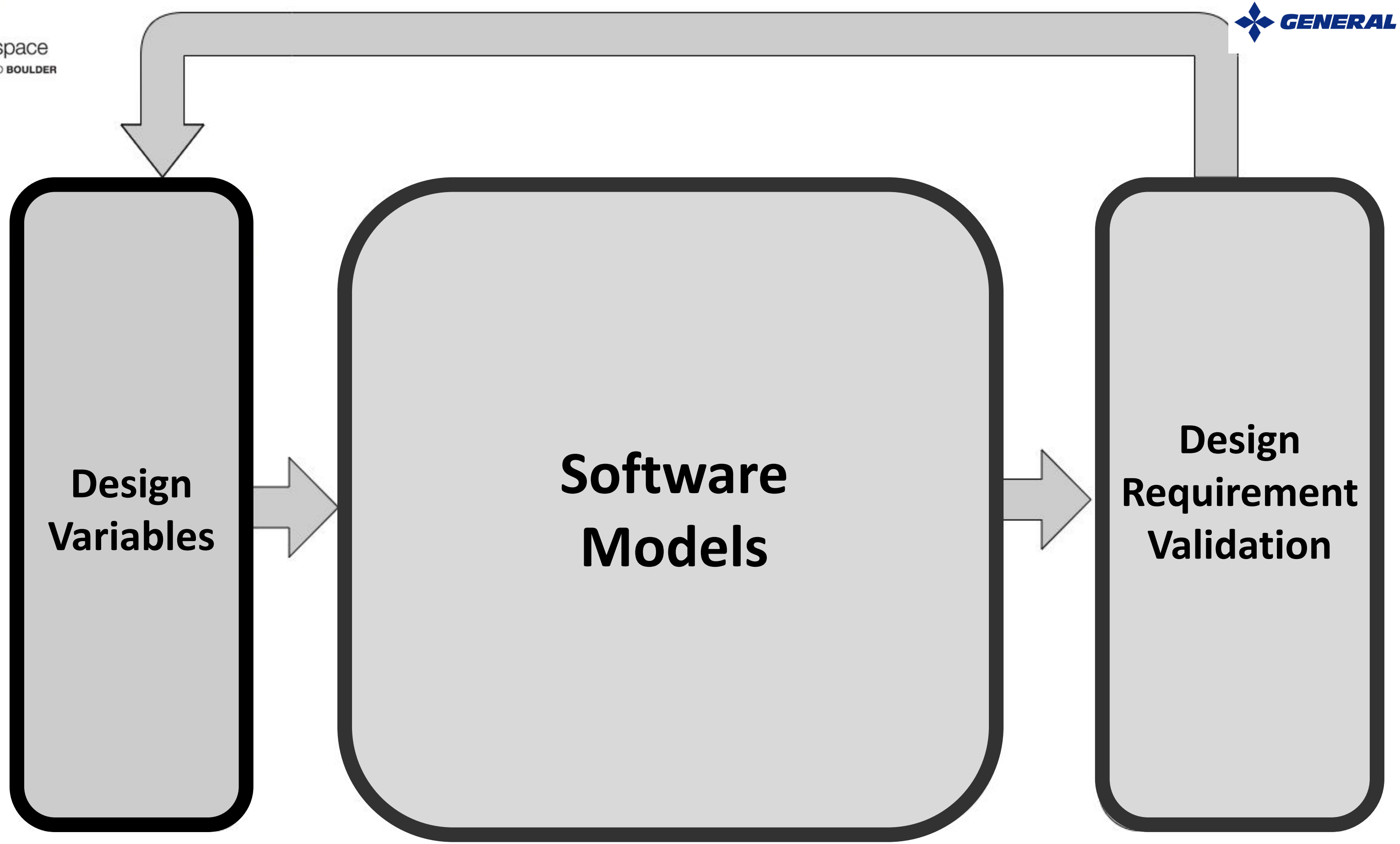


Network Protocol

- Interplanetary Overlay Network (NASA JPL)
  - Implements Delay Tolerant Networking (DTN)





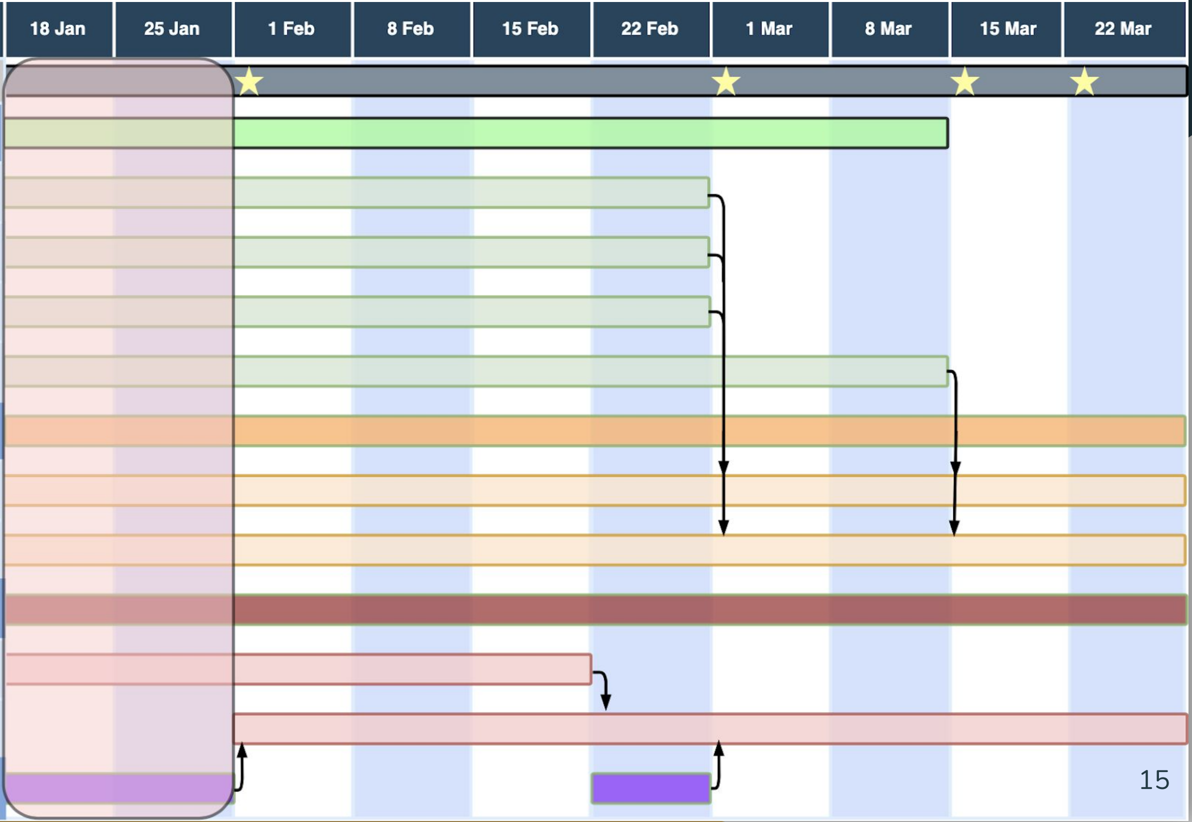

Design Variables
Software Models
Design Requirement Validation

Project Schedule

Project Purpose & Objectives → **Project Schedule** → Manufacturing → Budget

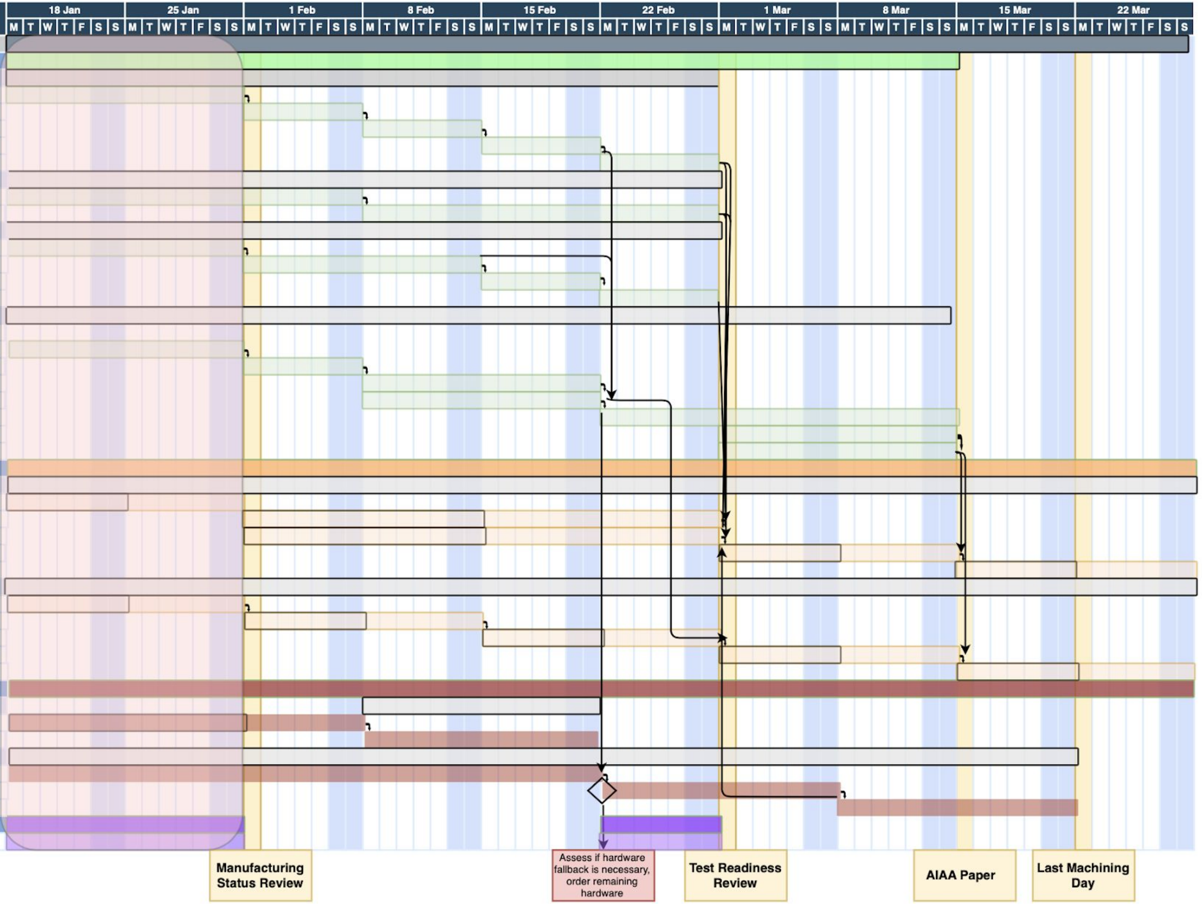
Schedule Overview

Task Name	Duration	Start	ETA
Complete Project Execution	70 days	01.18.21	03.28.21
System Architecture	56 days	01.18.21	03.14.21
Relay Stations	42 days	01.18.21	02.28.21
Link Budget	42 days	01.18.21	02.28.21
Constellation Architecture	42 days	01.18.21	02.28.21
Network Protocol	56 days	01.18.21	03.14.21
MBSE Modeling	70 days	01.18.21	03.28.21
Structural Modeling	70 days	01.18.21	03.28.21
Behavioral Modeling	70 days	01.18.21	03.28.21
Hardware	70 days	01.18.21	03.28.21
Manufacturing	35 days	01.18.21	02.21.21
Network Demonstration	56 days	01.31.21	03.28.21
Purchases	21 days	01.18.21	02.28.21



Detailed Schedule

#	Task Name	Duration	Start	ETA
1	Complete Project Execution	70 days	01.18.21	03.28.21
2	**System Architecture**	56 days	01.18.21	03.14.21
3	Relay Stations	42 days	01.18.21	02.28.21
4	Earth's Atmospheric Conditions	14 days	01.18.21	01.31.21
5	Relay Station Determination	7 days	01.31.21	02.07.21
6	Existing Relay Station Locations	7 days	02.07.21	02.14.21
7	Relay Station Placement	7 days	02.14.21	02.21.21
8	Model Verification	7 days	02.21.21	02.28.21
9	Link Budget	42 days	01.18.21	02.28.21
10	RF Link Budget	21 days	01.18.21	02.07.21
11	Laser Link Budget	21 days	02.07.21	02.28.21
12	Constellation Architecture	42 days	01.18.21	02.28.21
13	Constellation Geometry Output	14 days	01.18.21	01.31.21
14	Network Connection Windows	14 days	01.31.21	02.14.21
15	Surface Coverage Verification	7 days	02.14.21	02.21.21
16	Orbital Coverage Verification	7 days	02.21.21	02.28.21
17	Network Protocol	56 days	01.18.21	03.14.21
18	Network Capacity Single Flow Model	0 days	---	---
19	Network Capacity Multiple Path Model	7 days	01.18.21	01.31.21
20	Network Capacity Variable Connections Model	7 days	01.31.21	02.07.21
21	Network Capacity Latency Assumptions Update	14 days	02.07.21	02.21.21
22	Network Capacity Discreet Data Packages Experimentation	14 days	02.07.21	02.21.21
23	Network Capacity Model Hardware Verification	7 days	02.21.21	02.28.21
24	Architecture Optimization via Network Capacity Model	14 days	02.28.21	03.14.21
25	DTN DevKit Network Architecture Emulation	14 days	02.28.21	03.14.21
26	**MBSE Modeling**	70 days	01.18.21	03.28.21
27	Structural Modeling	70 days	01.18.21	03.28.21
28	Data Type Enumeration	14 days	01.18.21	01.31.21
29	Block Definition Modeling	14 days	01.31.21	02.14.21
30	Internal Block Modeling	14 days	02.14.21	02.28.21
31	Dependency Modeling	14 days	02.28.21	03.14.21
32	Parametric Modeling	14 days	03.14.21	03.28.21
33	Behavioral Modeling	70 days	01.18.21	03.28.21
34	Use Case Modeling	14 days	01.18.21	01.31.21
35	State Machine Modeling	14 days	01.31.21	02.14.21
36	Requirements Tracing	14 days	02.14.21	02.28.21
37	Sequence Modeling	14 days	02.28.21	03.14.21
38	Activity Modeling	14 days	03.14.21	03.28.21
39	**Hardware**	56 days	01.31.21	03.28.21
40	Manufacturing	14 days	02.17.21	02.21.21
41	CAD Model	7 days	02.07.21	02.14.21
42	3D Print Casting	7 days	02.14.21	02.21.21
43	Network Demonstration	56 days	01.31.21	03.28.21
44	Single Node ION Implementation	21 days	01.31.21	02.28.21
45	Dual/Multi-Node Network	14 days	02.28.21	03.14.21
46	Prescribed Latencies and Bundle File Sizes Implemented	14 days	03.14.21	03.28.21
47	**Purchase**	14 days	01.18.21	01.31.21
48	Hardware	14 days	01.18.21	01.31.21



Week 14:

Senior Design Symposium

Week 15:

Spring Final Review

College of Engineering Expo

Week 16:

Spring Final Review

Project Final Report

Final Check Our Form

Manufacturing

Project Purpose & Objectives → Project Schedule → **Manufacturing** → Budget

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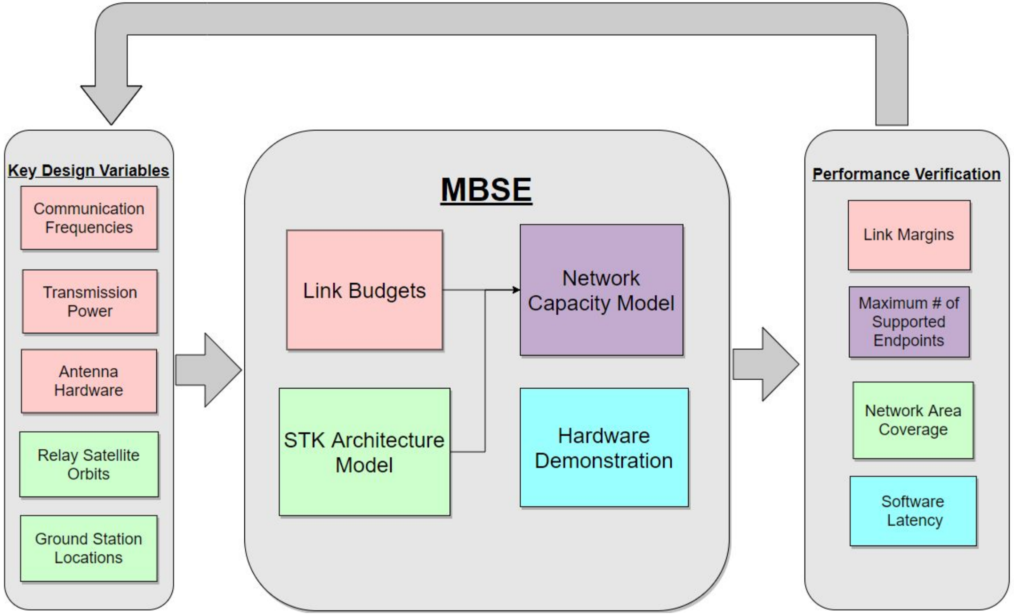
Manufacturing Tasks

To be **manufactured:**

1) STK Architecture Model
2) Network Link Budgets
3) Network Capacity Model
4) MBSE System Model

To be **purchased:**

5) Hardware Demonstration



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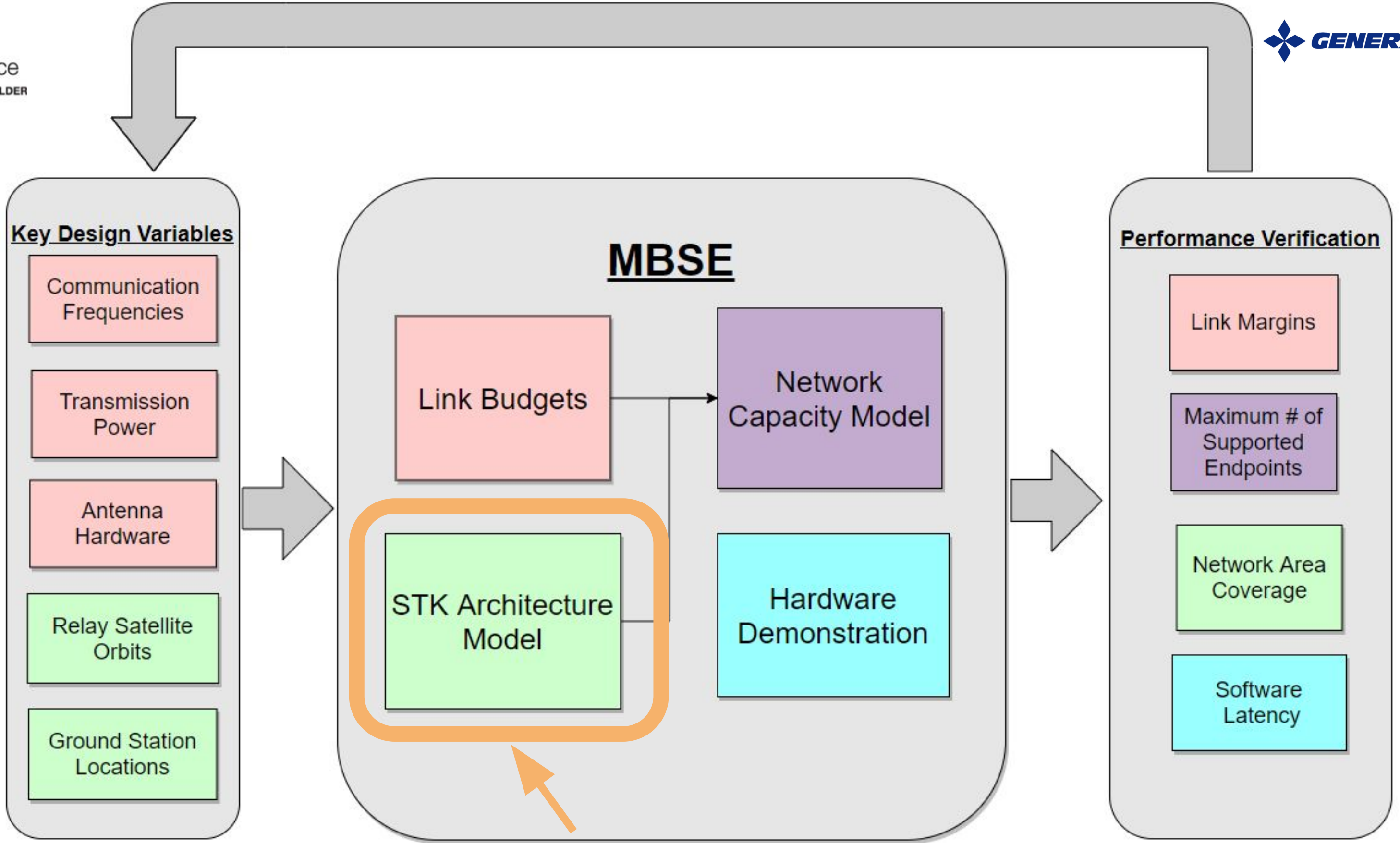

STK Architecture Model

Purpose: Determine the ground station configuration and satellite constellation architecture necessary to enable 99% Lunar coverage and “real time” communication between the Earth and the moon.

Model Logistics:

- Connection window simulation using Orbital STK
- ***Inputs***: ground station locations (based on findings from atmospheric attenuation), satellite orbit geometry, satellite downlink beamwidth
- ***Outputs***: Connection window illustration, 99% lunar coverage verification

Model Validation: Existing architecture verification (Deep Space Network), sensitivity analysis, and available literature/research.

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STK Constellation Orbital Model

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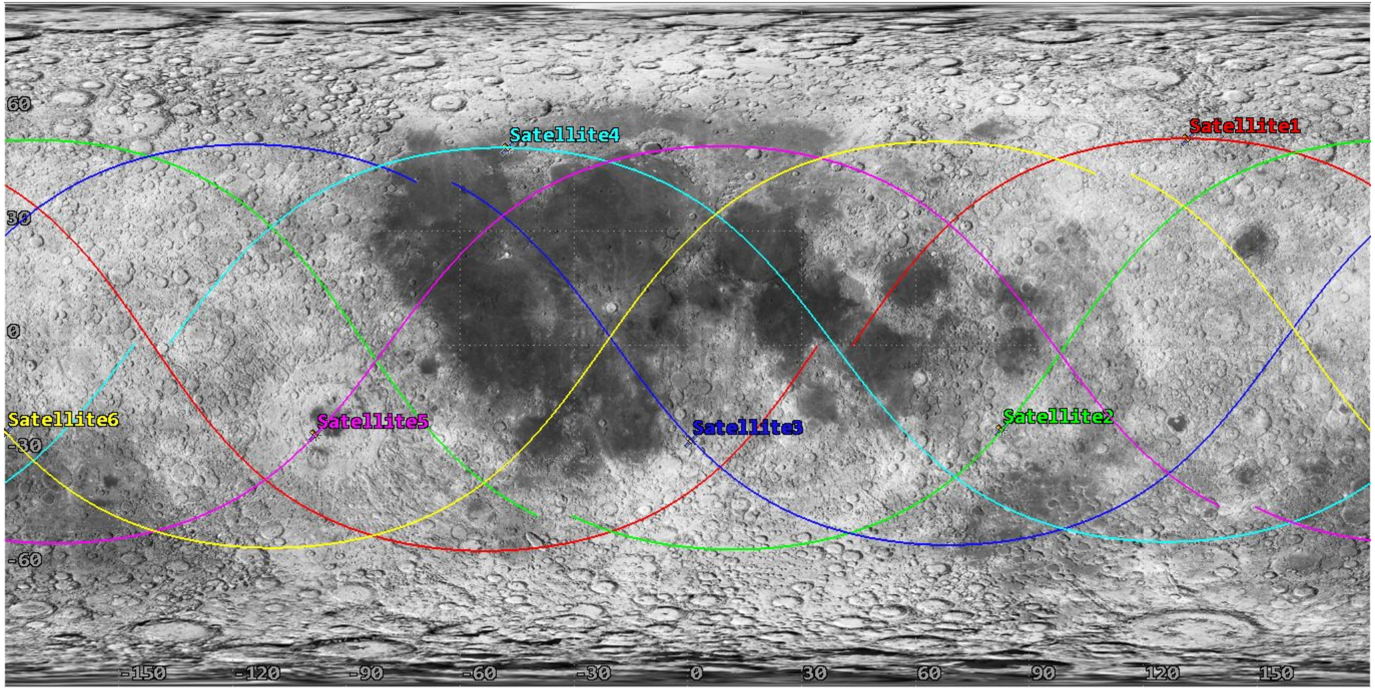

*Pictured above (baseline design) - Walker J.G., Continuous Whole−Earth Coverage by Circular−Orbit Satellite Patterns, Royal Aircraft Establishment, September 23, 1977

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STK Architecture Build Progress

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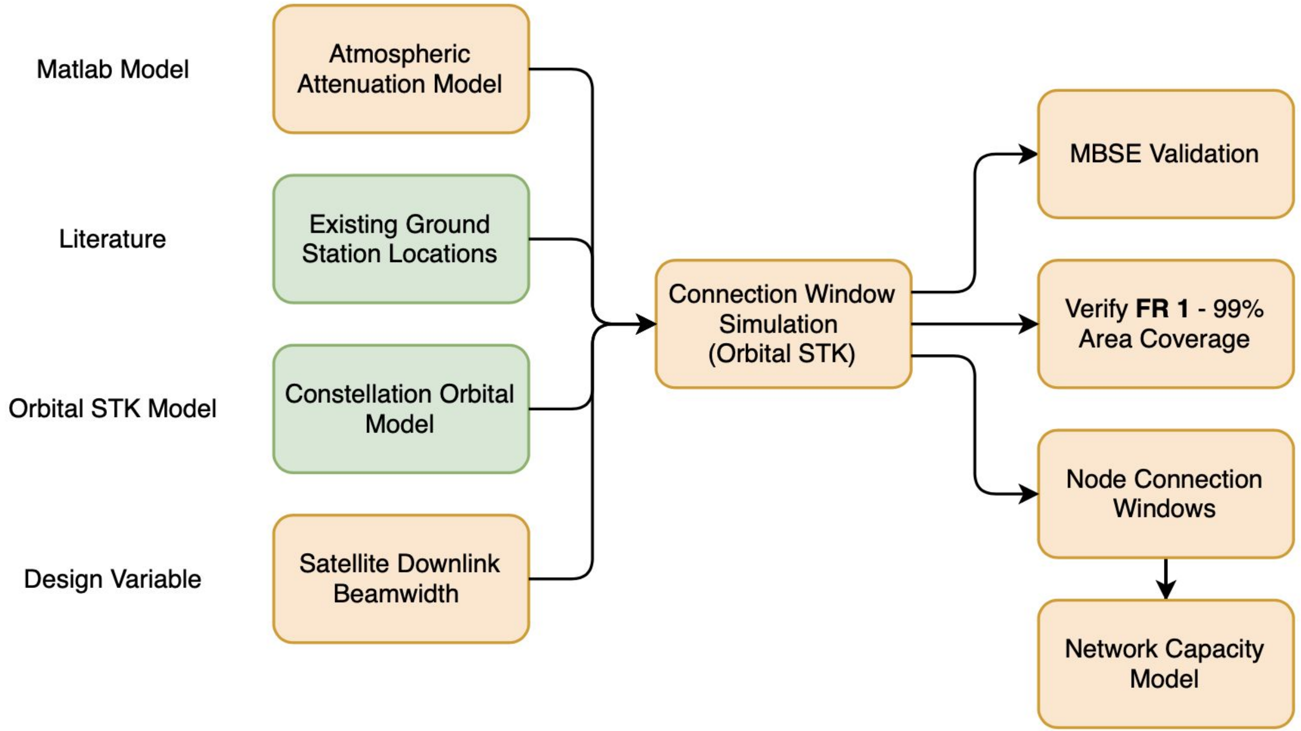

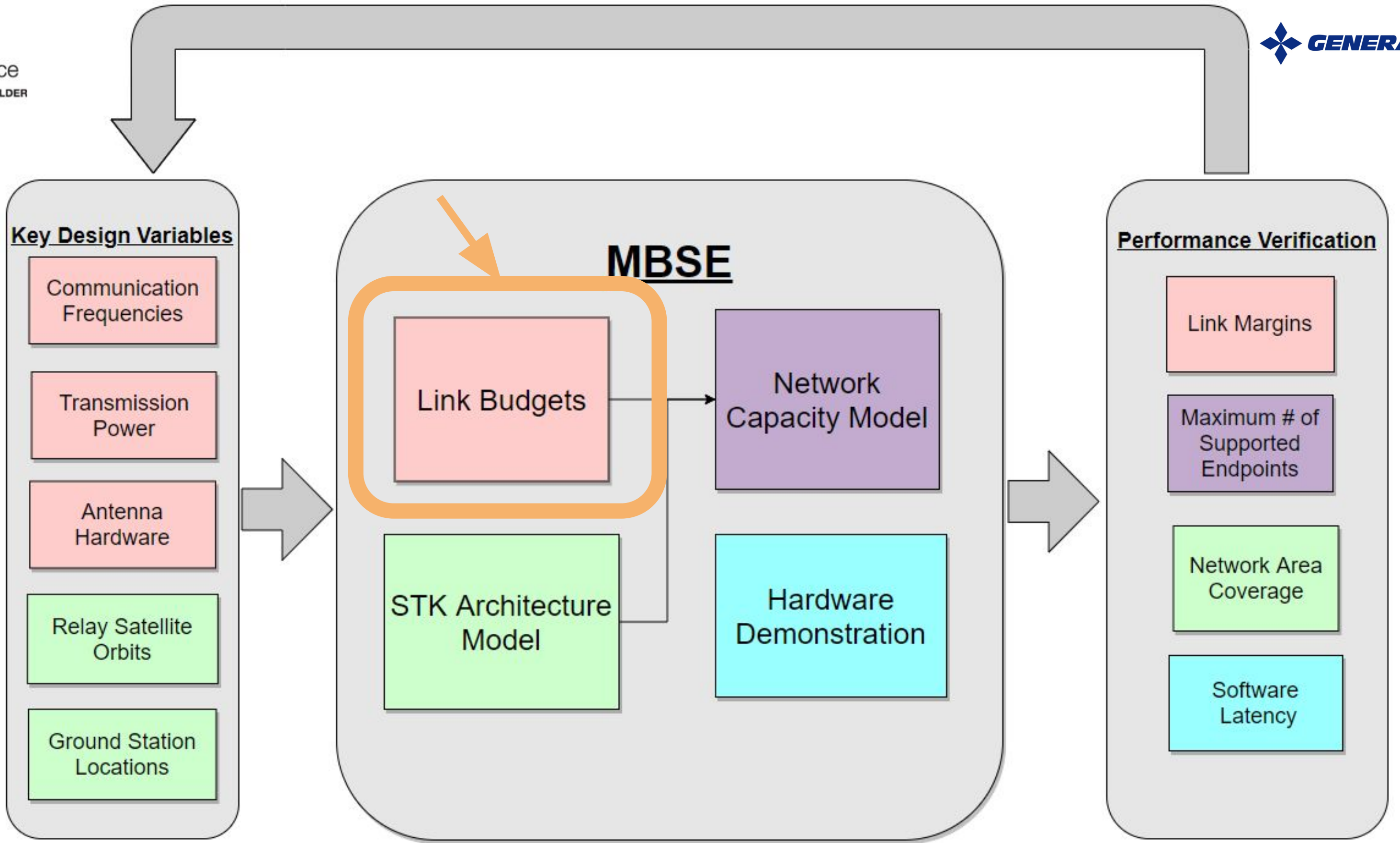

Key Design Variables
Communication Frequencies
Transmission Power
Antenna Hardware
Relay Satellite Orbits
Ground Station Locations
MBSE
Link Budgets
Network Capacity Model
STK Architecture Model
Hardware Demonstration
Performance Verification
Link Margins
Maximum # of Supported Endpoints
Network Area Coverage
Software Latency

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RF Link Model

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Purpose: Process necessary inputs to create a successful link (positive link margin)

Model Logistics:

- Programed using MatLab
- ***Inputs:*** Range, Frequency, Antenna Size, Transmit Power, Data Rate, System Noise temperature, Required Energy per bit to noise ratio (Eb/No) for desired BER, Required Design Margin
- ***Outputs:*** Link Margin

Model Validation: Available literature and research, sensitivity analysis

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RF Link Model Progress

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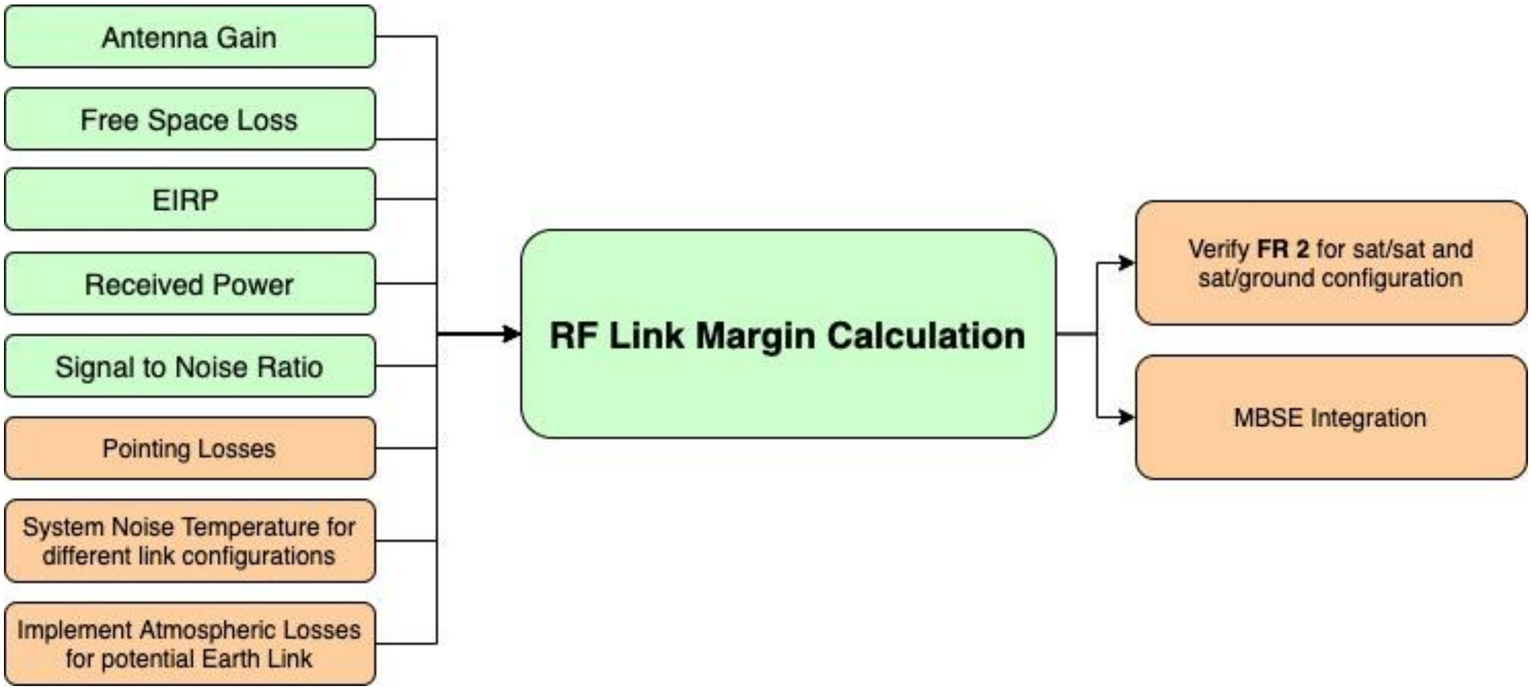
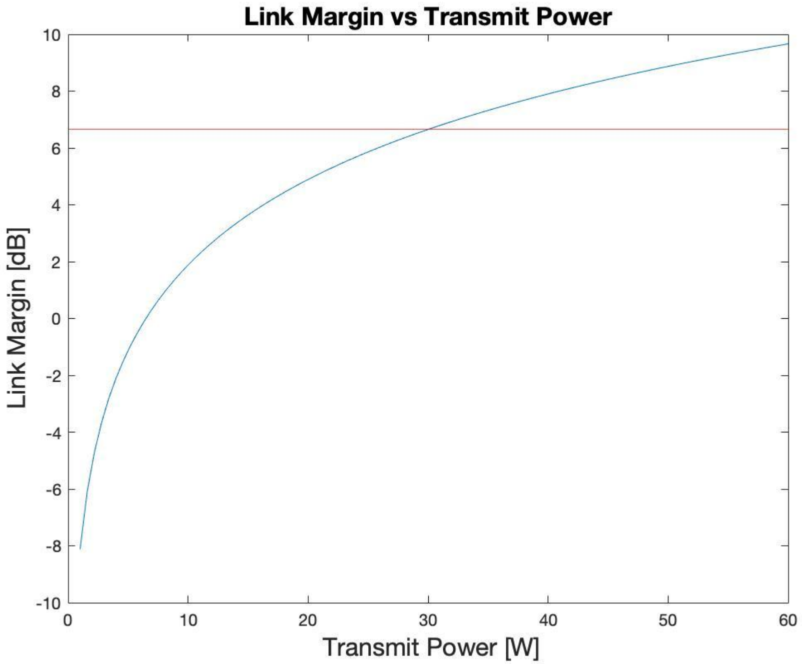
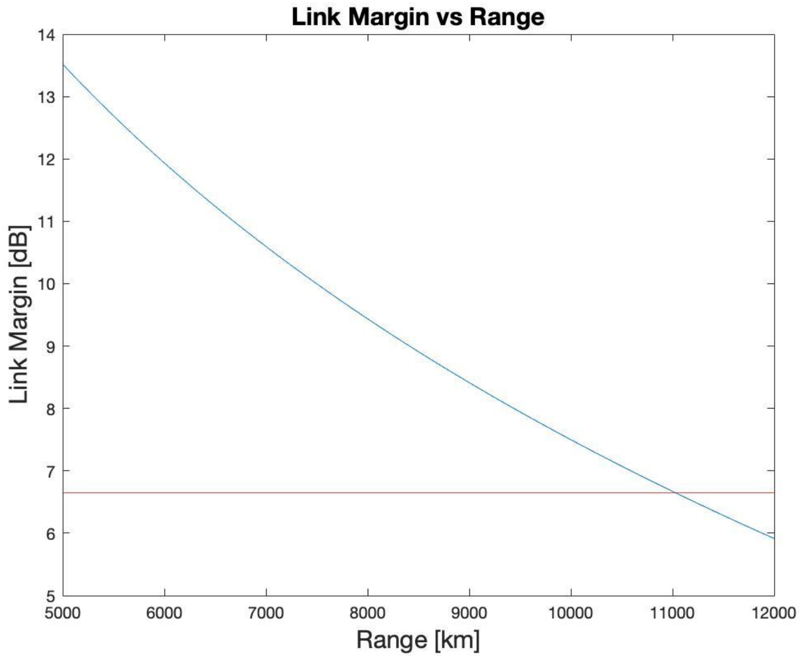


Baseline Sensitivity Analysis
Intersatellite Link





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Laser Link Model

GENERAL ATOMICS

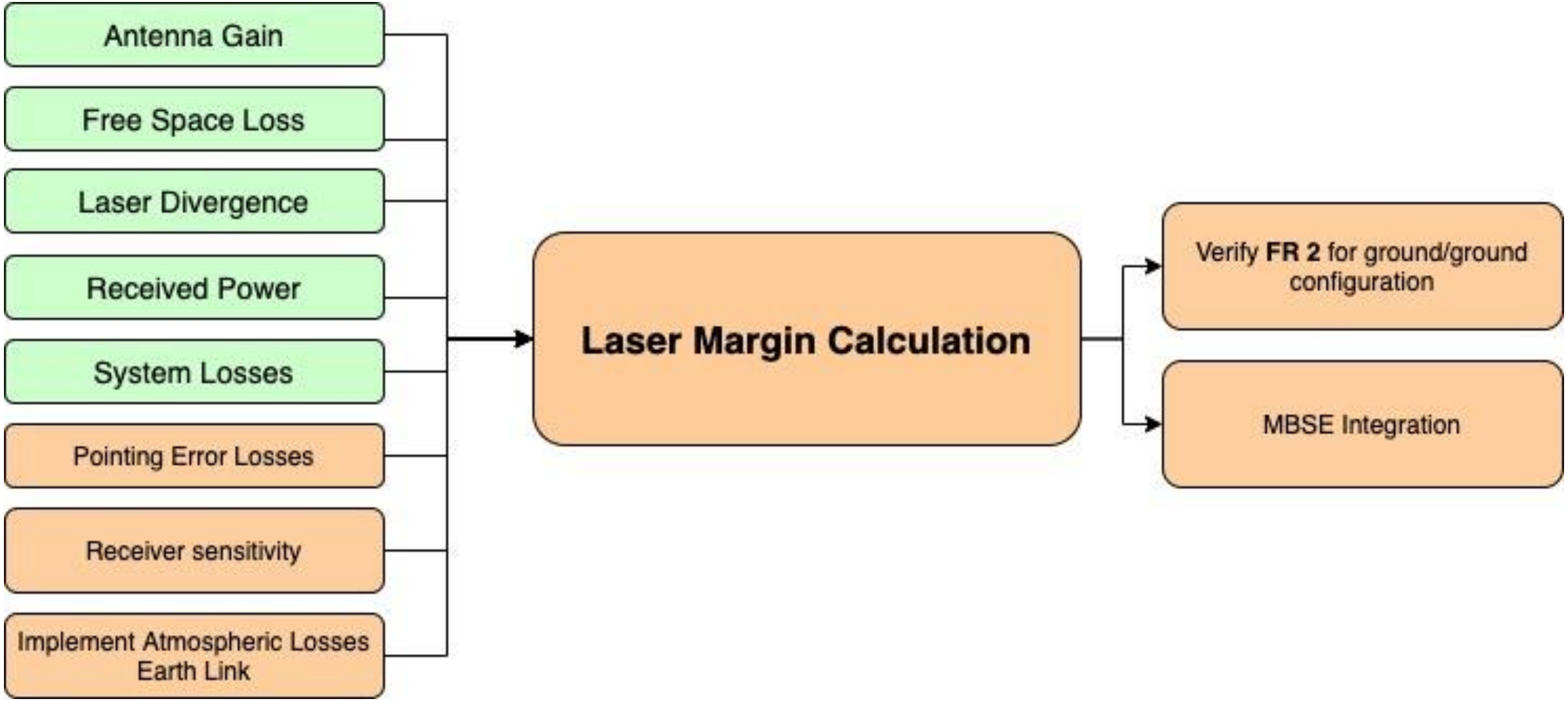
Purpose: Process necessary inputs to create a successful link (positive link margin)

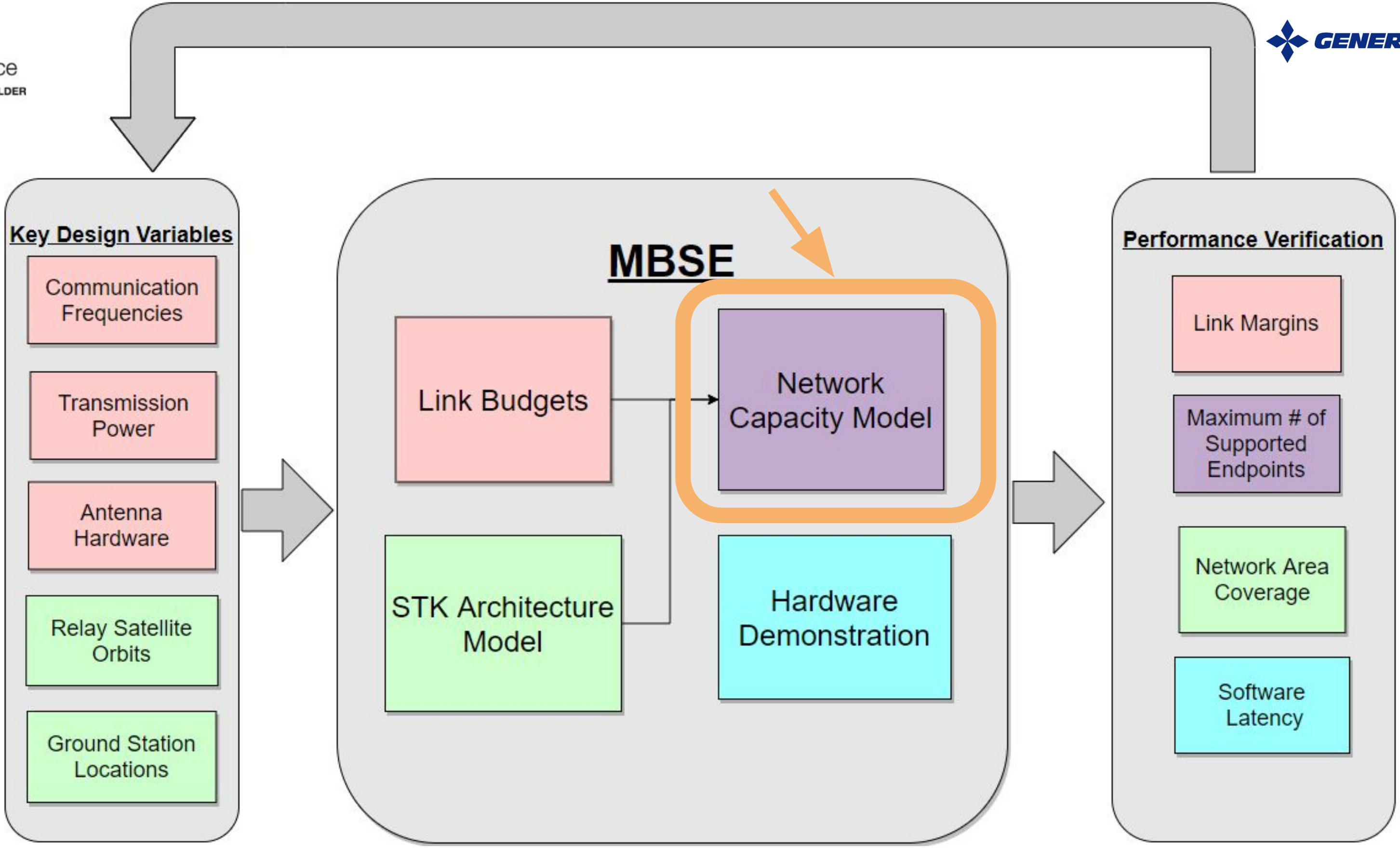
Model Logistics:

- Programed using MatLab
- ***Inputs:*** Range, Frequency, Antenna Size, Transmit Power, Data Rate, System Losses (Atmospheric, transmit, receiver)
- ***Outputs:*** Link Margin

Model Validation: Available literature and research, sensitivity analysis

Laser Link Model Progress





Key Design Variables
Communication Frequencies
Transmission Power
Antenna Hardware
Relay Satellite Orbits
Ground Station Locations
MBSE
Link Budgets
Network Capacity Model
STK Architecture Model
Hardware Demonstration
Performance Verification
Link Margins
Maximum # of Supported Endpoints
Network Area Coverage
Software Latency

Network Capacity Model

Purpose: Verify that the network can support the required number of endpoints

Model Logistics:

- Iterative data rates computation method performed using MatLab
- ***Inputs***: node connections, link data rates, endpoint data requirements, bit error rates, data propagation delay
- ***Outputs***: Data stored in each node over time

Model Validation: Benchmarking and hardware verification test

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Capacity Model: Build Progress

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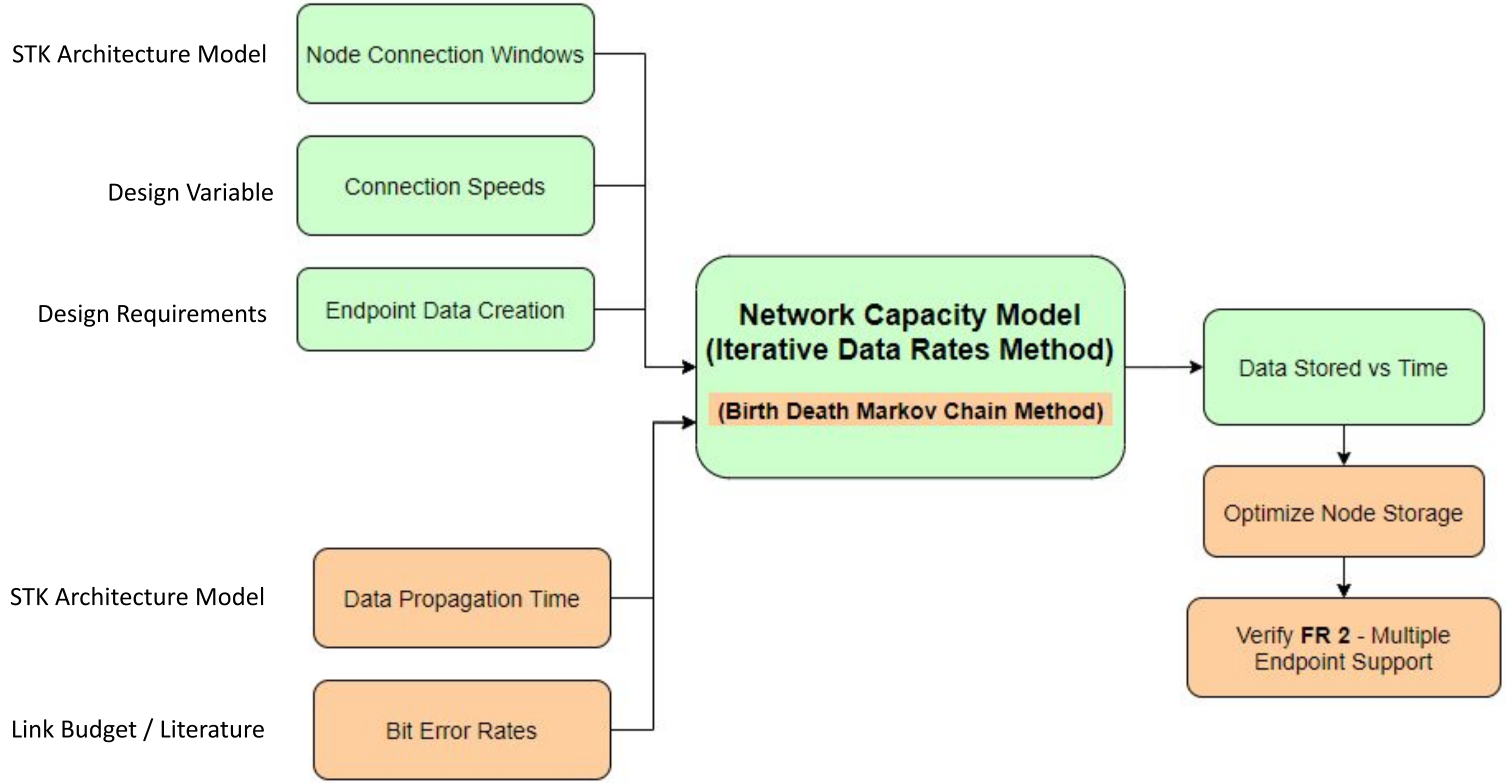

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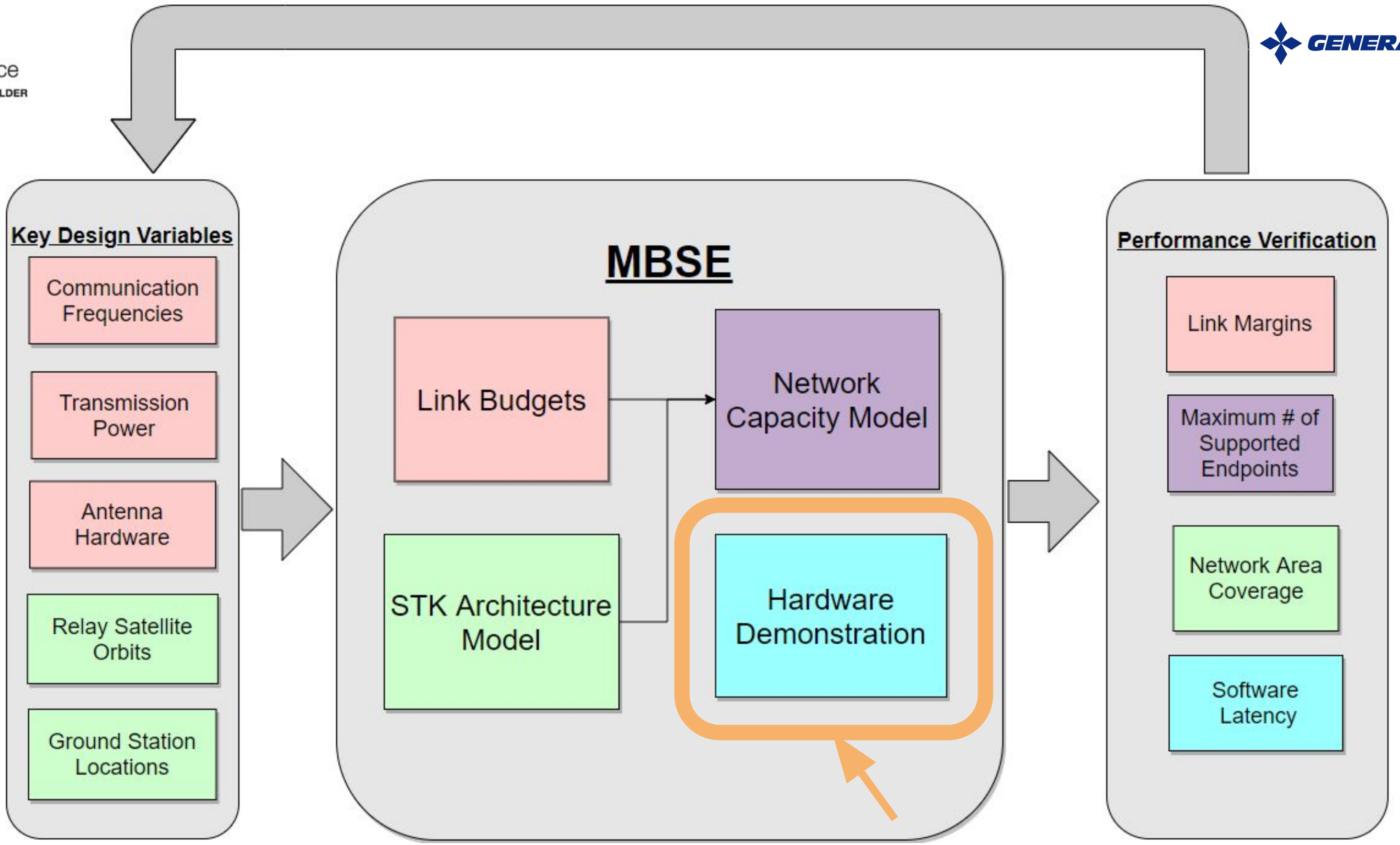

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Hardware Demonstration

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Purpose: Demonstrate functionality of DTN protocol for Earth-based applications using ION-DTN software

Model Logistics:

- **ION-DTN** software downloaded from SourceForge.net and loaded onto two Ubuntu 18.04 server machines

Model Validation: ION-DTN was developed by Dr. Scott Burleigh of NASA's Jet Propulsion Laboratory

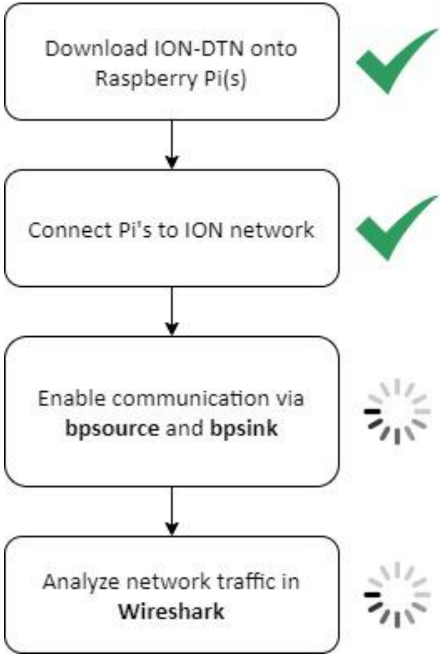
Hardware Demonstration Timeline

Current development:

- Ubuntu server & ION-DTN installed
- Proof-of-concept validated

Future Development:

- Enabling communications between two Pi machines
    - Must debug given **Assembly** test file
- Use **Wireshark** to calculate internal hardware latencies
    - **RISK:** time intensive, steep learning curve



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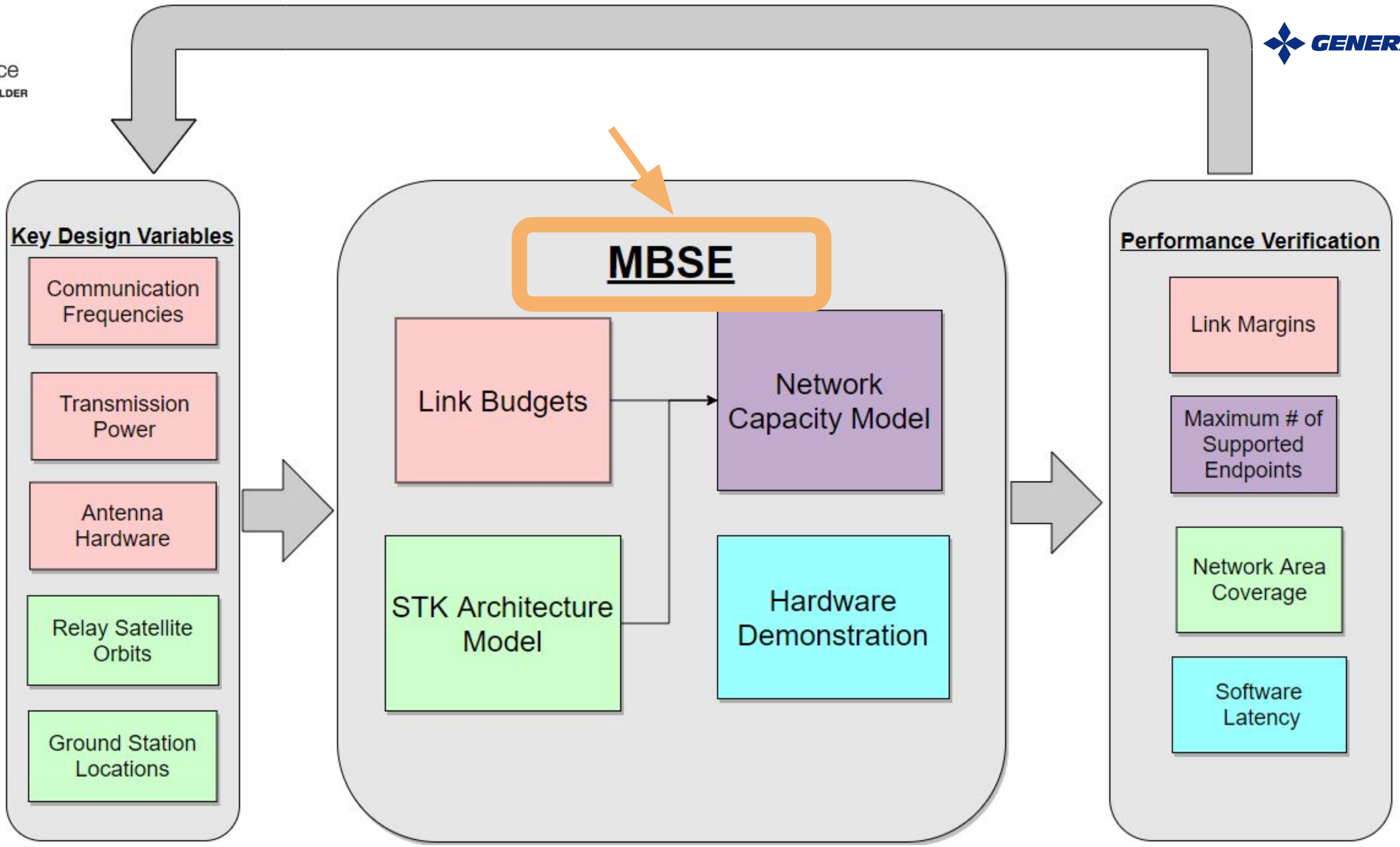


SysML Modeling/MBSE

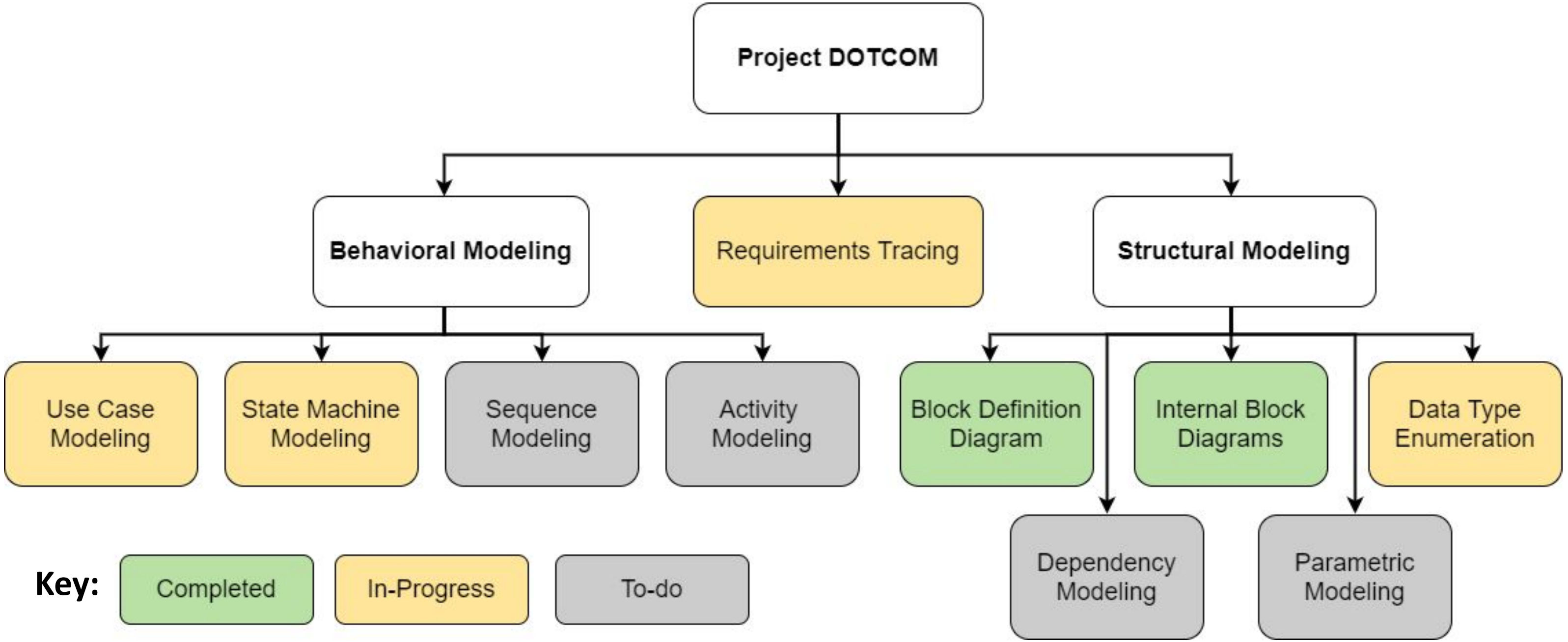
Purpose: Integration of separate project elements and model outputs (network capacity, link budget, etc.) into one project space, and trace requirements to the subsystems that satisfy them.

Model Logistics:

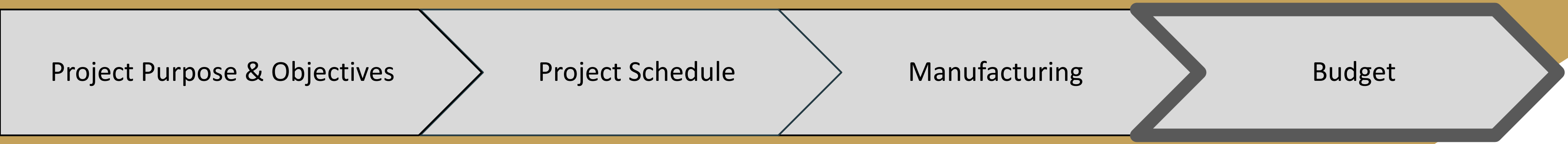
- Created in the SysML modeling language
- ***Inputs***: Completed modeling of project subsystems
- ***Outputs***: Cohesive DOTCOM project deliverable, including mapping of subsystem connections and modeling behavior of network nodes.

Model Validation: Validation of project inputs will come from their own verification and testing steps, as outputs from these models are loaded into the SysML simulation.

SysML Modeling Progress Update



Budget


Project Purpose & Objectives
Project Schedule
Manufacturing
Budget

Hardware Procurement Update

Hardware Parts	Status
2 Raspberry Pis	Received
2 Power Cords	Received
2 Monitors	Received
2 HDMI Cables	Received
2 Keyboards	Received
Total:	**$474.94**

Hardware Parts	Status
5 Raspberry Pi	Yet to be ordered
5 Power Cords	Yet to be ordered
5 SD Cards	Yet to be ordered
5 HDMI Cables	Yet to be ordered
5 USB Cables	Yet to be ordered
Total:	**$984.40**

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Updated Budget

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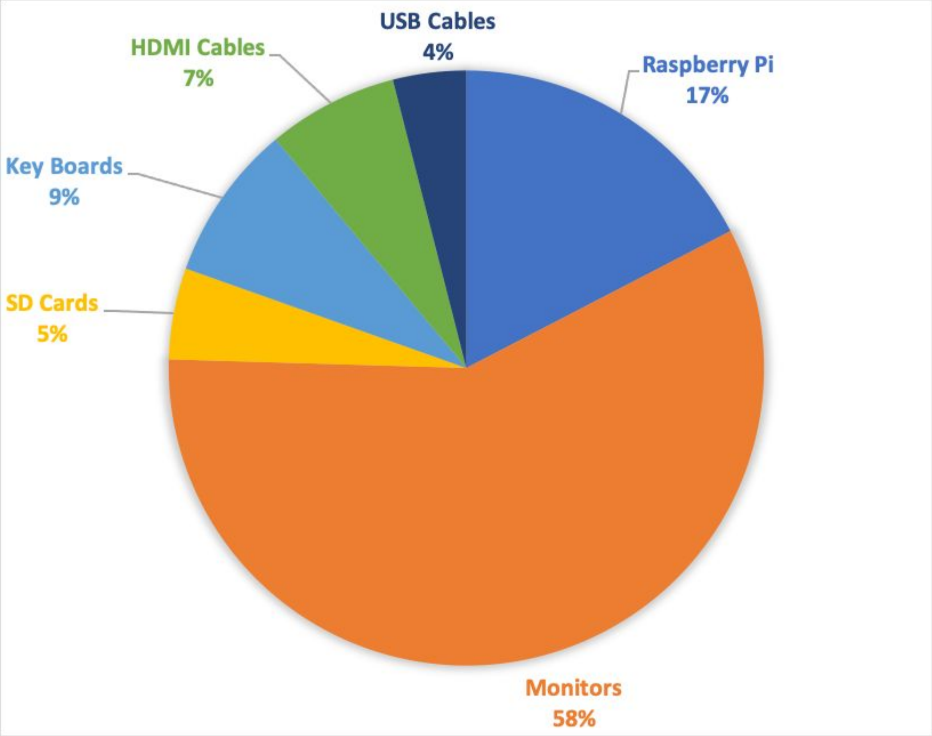
Key Hardware Components:
Raspberry Pi (7)
Monitors (7)
SD Cards (5)
Keyboards (2)
HDMI Cables (7)
Power Cables (7)
Total: $1,459.34
Margin: $3,540.66

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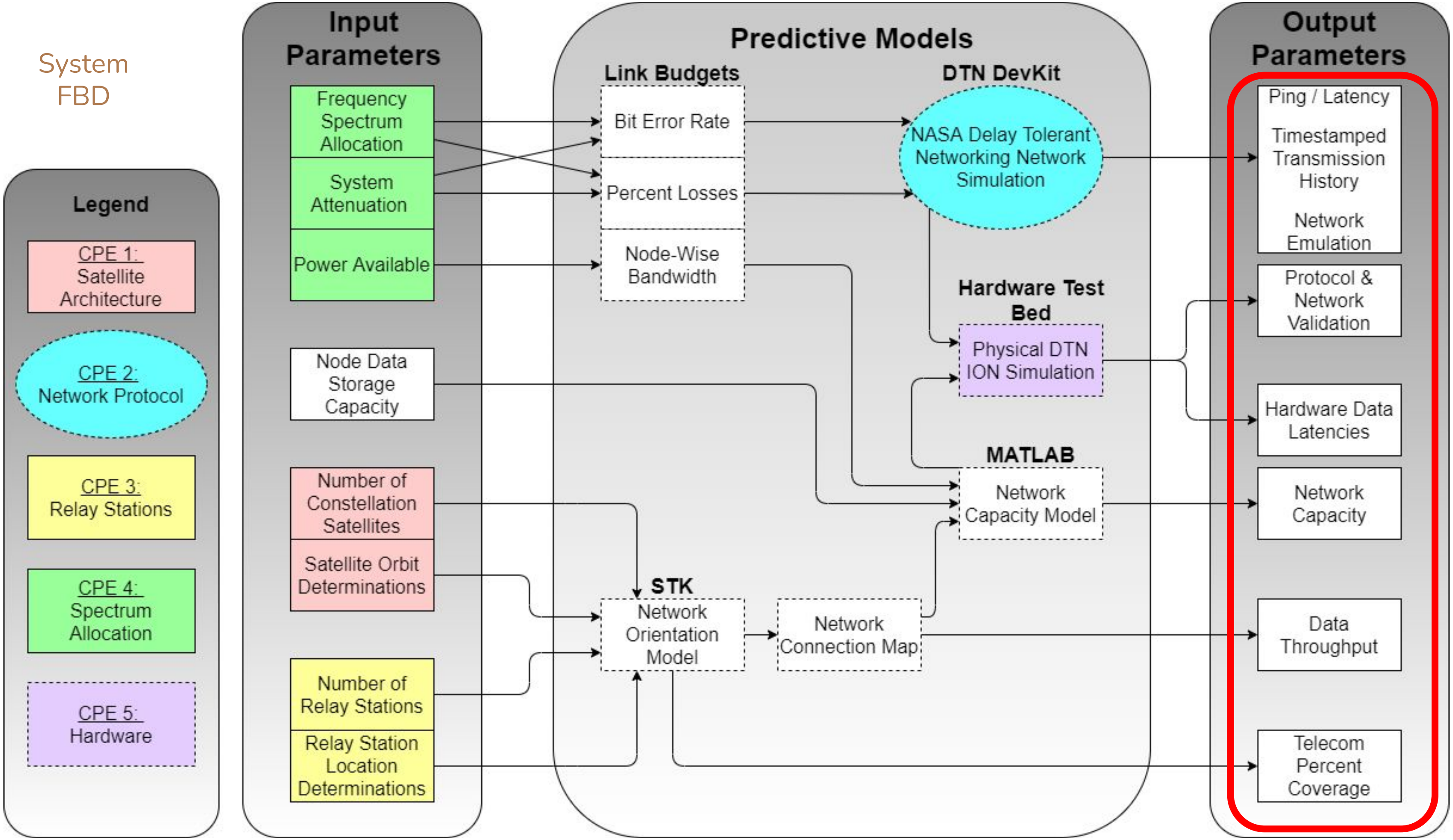
APPENDIX

System FBD


Legend
CPE 1: Satellite Architecture
CPE 2: Network Protocol
CPE 3: Relay Stations
CPE 4: Spectrum Allocation
CPE 5: Hardware
Input Parameters
Frequency Spectrum Allocation
System Attenuation
Power Available
Node Data Storage Capacity
Number of Constellation Satellites
Satellite Orbit Determinations
Number of Relay Stations
Relay Station Location Determinations
Predictive Models
Link Budgets
Bit Error Rate
Percent Losses
Node-Wise Bandwidth
DTN DevKit
NASA Delay Tolerant Networking Network Simulation
Hardware Test Bed
Physical DTN ION Simulation
MATLAB
Network Capacity Model
STK
Network Orientation Model
Network Connection Map
Output Parameters
Ping / Latency
Timestamped Transmission History
Network Emulation
Protocol & Network Validation
Hardware Data Latencies
Network Capacity
Data Throughput
Telecom Percent Coverage

Relay Station Models

- Atmospheric Attenuation Evaluation (Matlab)
  - Input: Atmospheric humidity %, thickness of atmosphere, (elevation?)
  - Output: Signal Absorption (atmospheric loss variable)
  - Status: In progress
- Connection Window Evaluation (Orbital STK)
  - Input: Relay Station Positions
  - Output: Mapping of Earth relay stations' connectivity windows to the Moon relay station
  - Status: Not Started
- Model Verification (Orbital STK)
  - Repeat modeling techniques for well-documented system (Deep Space Network)
  - Compare modeled results to real-life behavior
  - Status: Not started

Constellation Architecture Testing and Verification

- Connection Window Evaluation (Matlab)
  - Input: Satellite position vs. time data
  - Output: Viability of each link at all times
  - Status: In progress
- Coverage Map (Matlab)
  - Input: Satellite position vs. time data
  - Output: Map of which points in the system have coverage at all times (target: >99%)
  - Status: In progress
- Model Verification
  - Repeat modeling techniques for well-documented system (GPS)
  - Compare modeled results to real-life behavior
  - Status: Not started

Constellation Configuration 6/6/4

Variables
Number of Satellites (T)
Number of Orbital Planes (P)
Satellite Spacing (F)
Inclination (i)
Right Ascention of Ascending Node (RAAN)
True Anomaly (v)

Configuration has format T/P/F

RAAN separation = 360°/P = 60°

v separation = F * RAAN separation = 240°

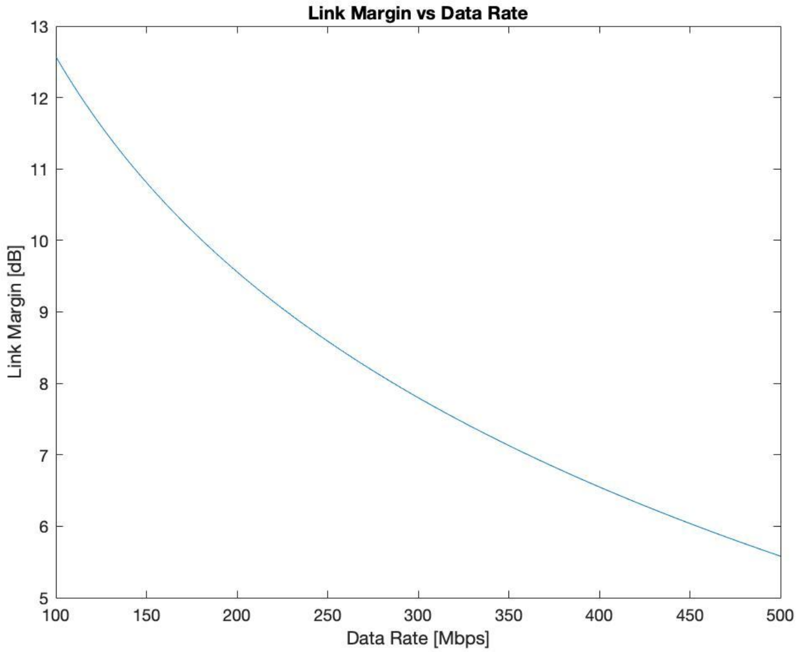
i = 53.1° = constant

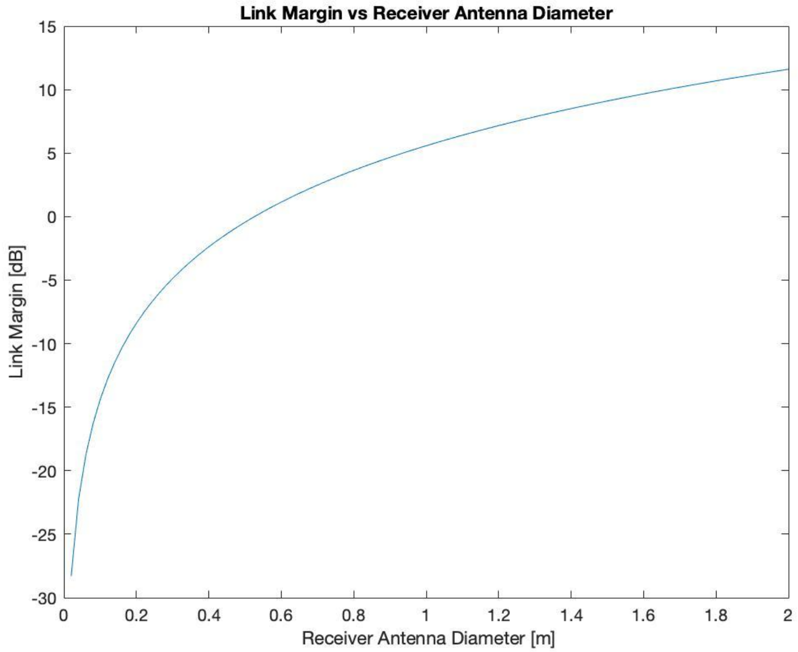
Baseline Parameters for Intersatellite Link

Key Input Variables	Value
Range (km)*	11,024 km
Frequency (GHz)	26
Antenna Size (D)	1 m
Transmit Power (W)	30 W
Data Rate (Mbps)*	500
Receive System Noise Temperature (K)	700 K
Required Eb/No (dB) [BPSK Modulation, BER = 10^-7]*	11 dB
Required Design Margin*	3 dB

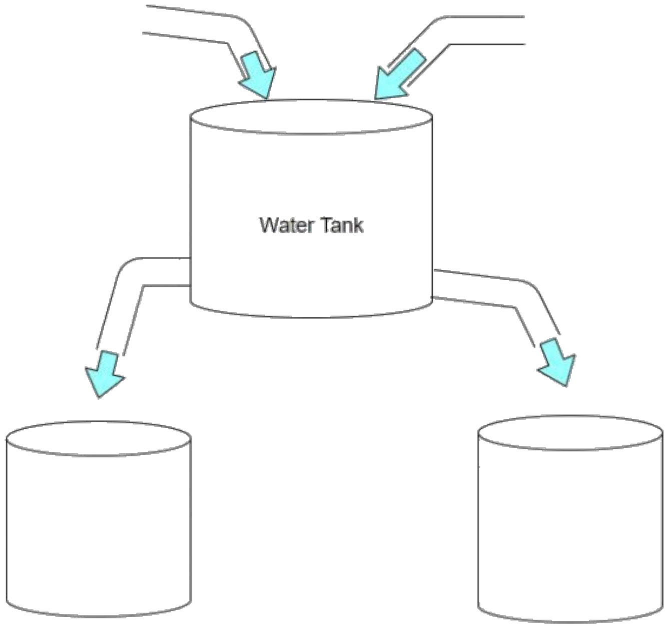
Outputs	Value
EIRP	61.9 dB
Antenna Gain	46.1 dB
Free Space Loss	200 dB
Received Power	-139.6 dB
Signal to Noise	19.5 dB
Link Margin	5.5 dB

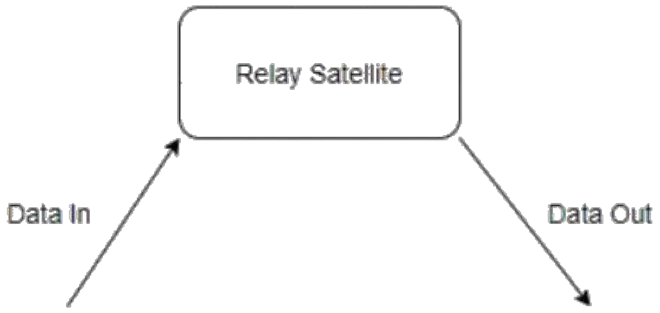
Baseline Sensitivity Analysis Intersatellite Link





Network Capacity Model





Overflowing water tank is analogous to a saturated / max capacity network

Data Rate in - Data Rate out = Used Memory Change Rate

Network endpoints analogous to faucets adding water to the system

Data Rates

Forward Link Requirements

Data Type (Reliable Channel)	**Data Rates**	**Element**
Speech	10 kbps	Astronaut
Digital Channel	200 bps	Astronaut
Digital Channel	2 kbps	Transport / Rover / Base

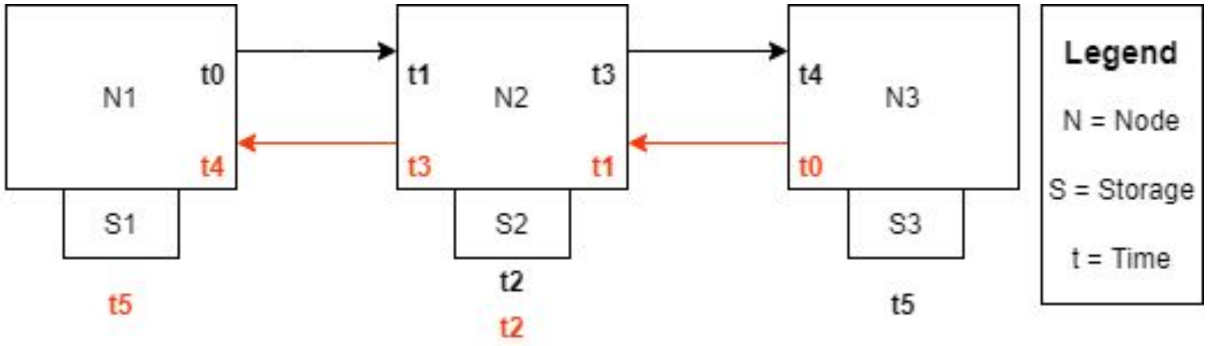
Data Type (High Rate Channel)	**Data Rates**	**Element**
Command Loads	100 kbps	Transport / Rover / Base
CD-quality Audio	128 kbps	Astronaut
Video (TV, Videoconference)	1.5 Mbps	Astronaut

Return Link Requirements

Data Type (Reliable Channel)	**Data Rates**	**Element**
Speech	10 kbps	Astronaut
Engineering Data	2 kbps	Astronaut
Engineering Data	20 kbps	Transport / Rover / Base
Video	100 kbps	Helmet Camera
Video	1.5 Mbps	Rover

Data Type (High Rate Channel)	**Data Rates**	**Element**
High Definition TV	20 Mbps	Astronaut
Biomedics	35 Mbps	Astronaut
Hyperspectral Imaging	150 Mbps	Science Payload
Synthetic Aperture Radar	100 Mbps	Science Payload

Key Measurement Methodology

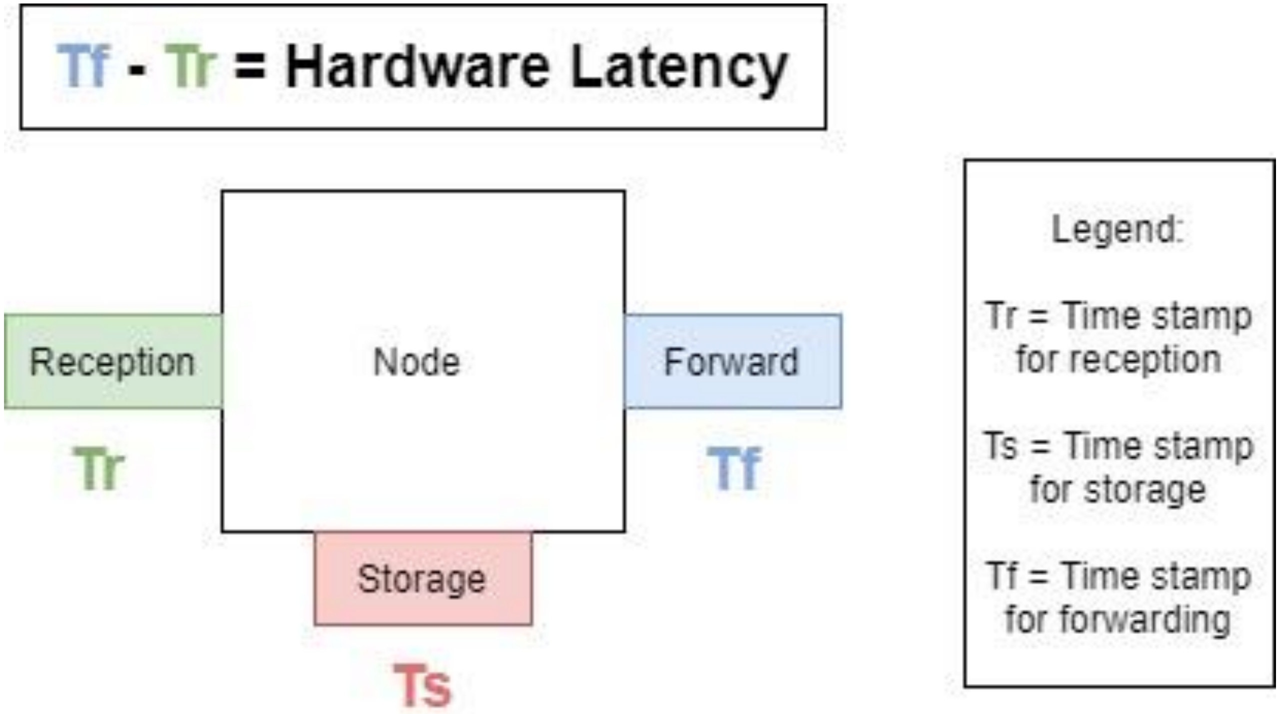


Synchronous

t1 - t0 = Light Time Latency
t2 - t1 = N2 Storage Latency
t3 - t2 = N2 Forward Latency
t3 - t1 = N2 Hardware Latency
t5 - t0 = Total Signal Latency
(t5-t0)-t4-t1 = Total Hardware Latency

Asynchronous

t1 - t0 = Light Time Latency
t2 - t1 = N2 Storage Latency
t3 - t2 = N2 Forward Latency
t3 - t1 = N2 Hardware Latency
t5 - t0 = Total Signal Latency
(t5-t0)-t4-t1 = Total Hardware Latency


Tf - Tr = Hardware Latency
Reception
Node
Forward
Tr
Tf
Storage
Ts
Legend:
Tr = Time stamp for reception
Ts = Time stamp for storage
Tf = Time stamp for forwarding

Completed testing

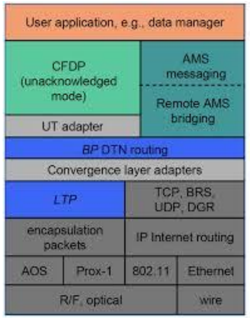
SOURCEFORGE

Completed:

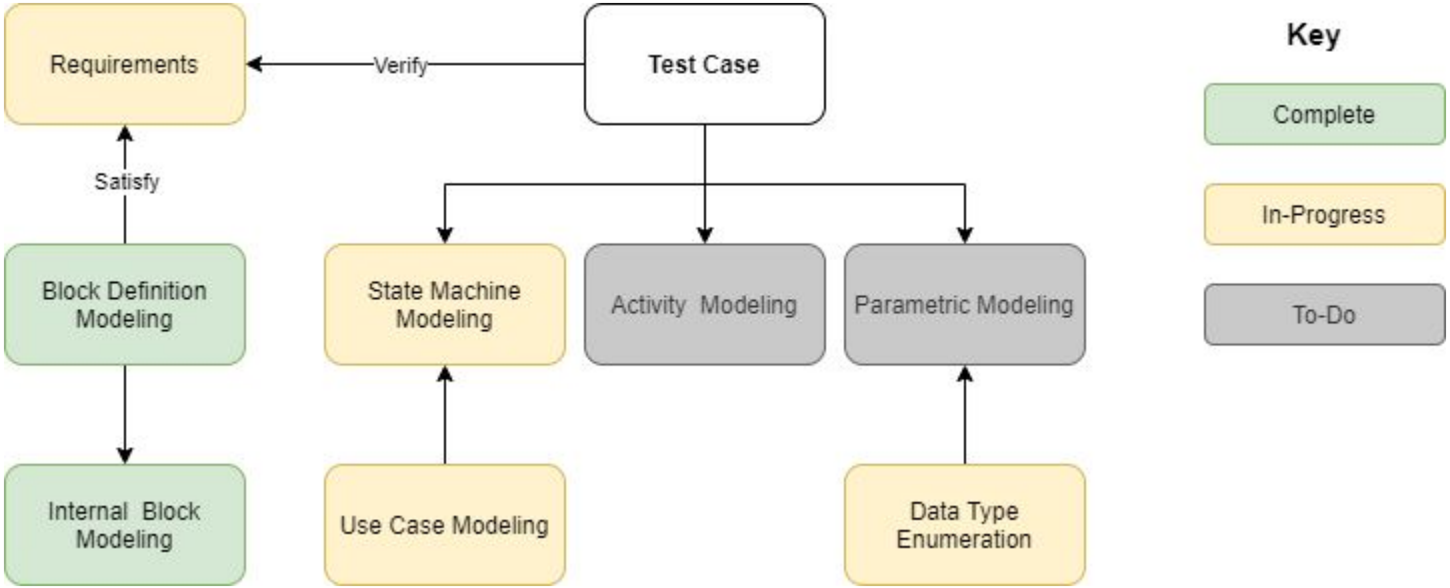
1) Ubuntu installed
2) Software installed
3) Software configured

In progress:

1) Debug given test file



SysML Modeling Validation



SysML workspace validation will be completed in part via test-case verification of other network modeling, as outputs from these models are simply loaded into the SysML simulation. SysML-specific verification is thus mainly redundant checking of requirements satisfaction/diagram completeness.

Current Budget

Key Hardware Components:
Raspberry Pi (2)
Monitors (2)
Keyboards (2)
HDMI Cables (2)
Power Cables (2)
Total: $474.94
Margin: $4,524.06