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GENERAL ATOMICS

DOTCOM

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 Overview

Project Overview → Testing → Project Schedule → Budget

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Network Performance Targets

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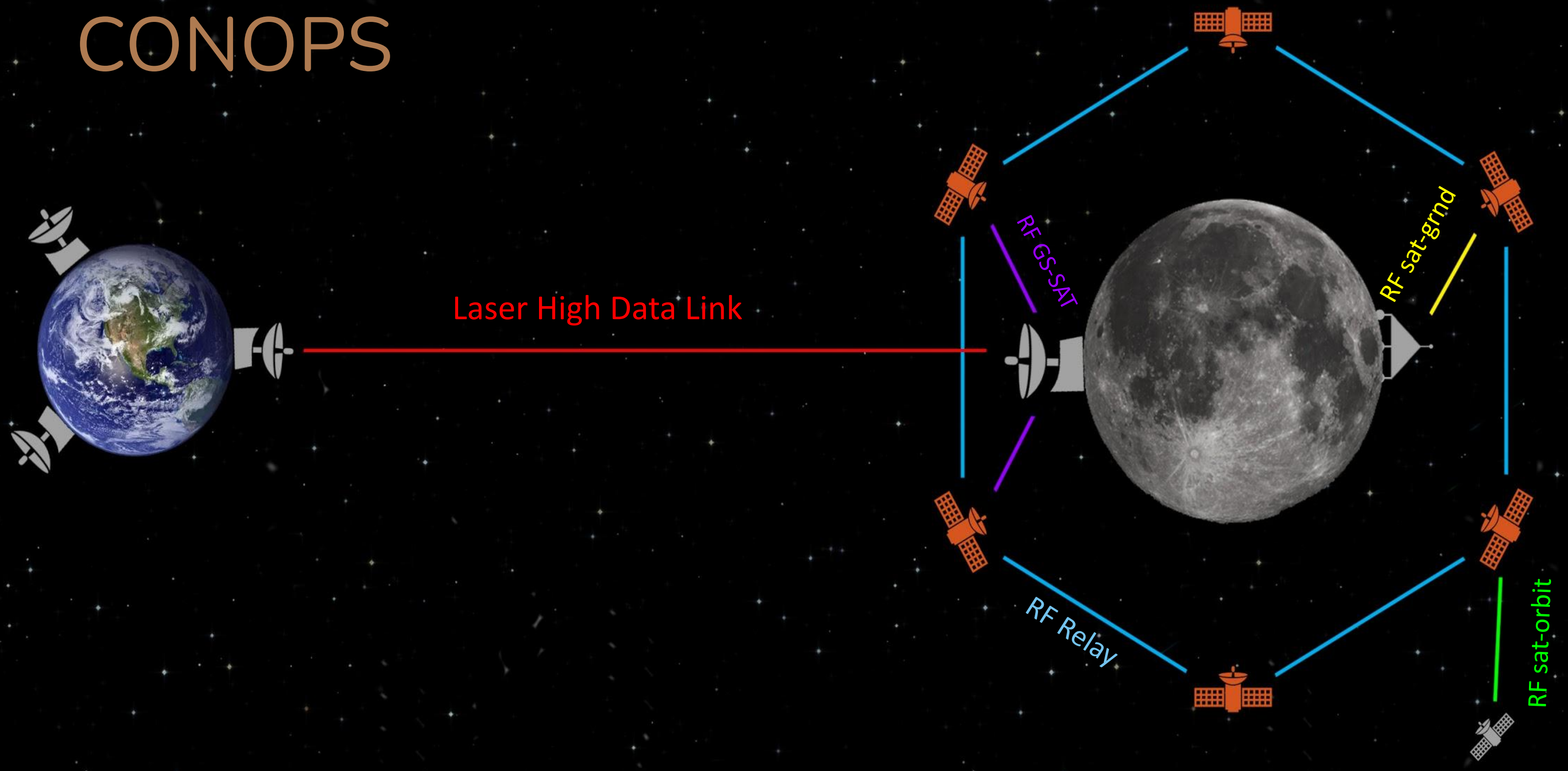
Functional Requirement	Design Requirement
FR 1 Area Coverage	99% telecommunications coverage in Lunar orbit
	99% telecommunications coverage on Lunar Surface
FR 2 Endpoint Support	5+ nodes for simultaneous 'real time' communications on Lunar surface
	10+ nodes for non simultaneous (within 6 hrs) communication 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

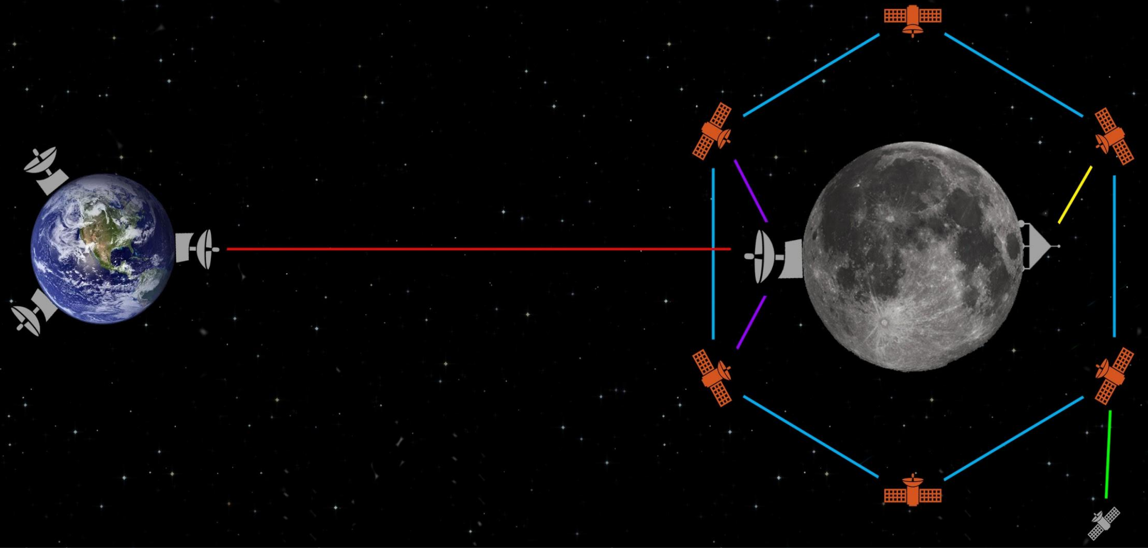
Critical Project Elements

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 Budgets	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 Constellation	Construction of ideal constellation architecture around each planetary body to satisfy coverage requirements.

CONOPS


Laser High Data Link
RF GS-SAT
RF sat-grnd
RF Relay
RF sat-orbit

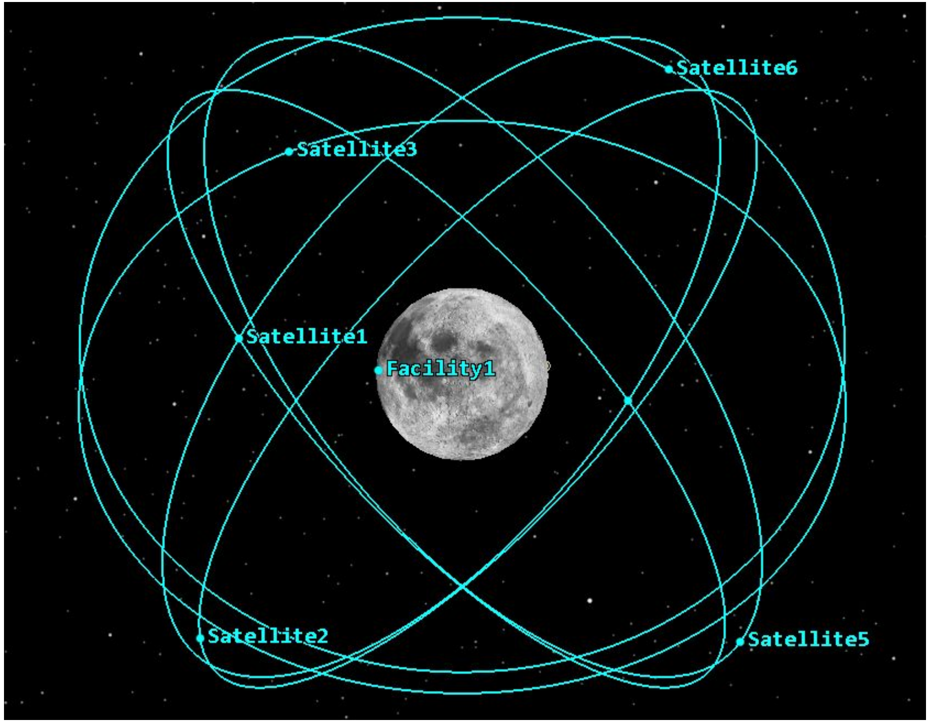
Baseline Link Budgets



Variables	Satellite to Satellite	Ground Station to Satellite	Orbital Vehicle to Satellite	Ground Vehicle to Satellite	Ground Station to Ground Station
Range	11,024 km	5,509 km	TBD	5,509 km	384,000 km
Frequency	Ka-band (26 GHz)	Ka-band(26 GHz)	Ka-band (26 GHz)	Ka-band(26 GHz)	193.4 THz (1550 nm)
Antenna Size	1 m	1 m	.5 m	.1 m	1.5 m
Receive System Noise Temperature	700 K (Source: ITU)	300 K (Source: Sat. Antenna Trade Study)	700 K	300 K	N/A

Baseline Constellation

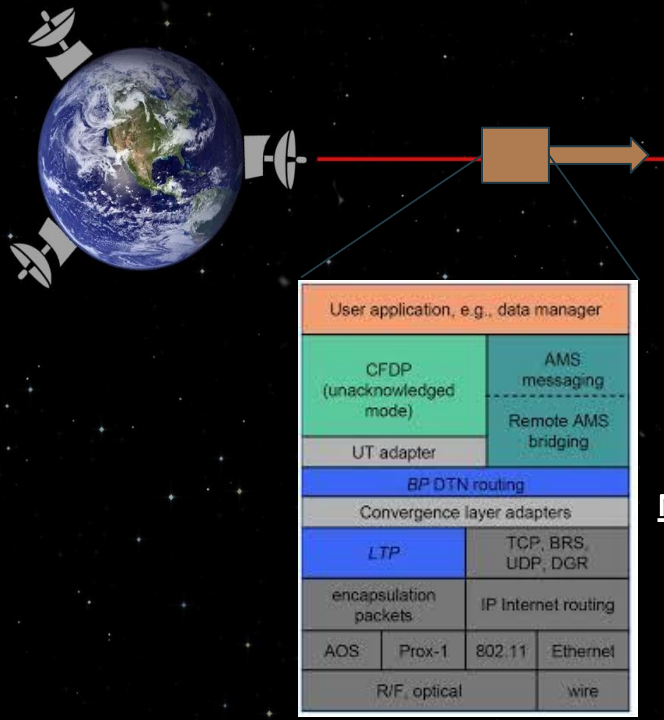
Constellation Design Parameters	Values
Range to Ground	5509 km
Range to Adjacent Satellites	9173-11024 km
Configuration	Walker-Delta 6/6/4
Orbital Period	15.38 hrs
Coverage	Single

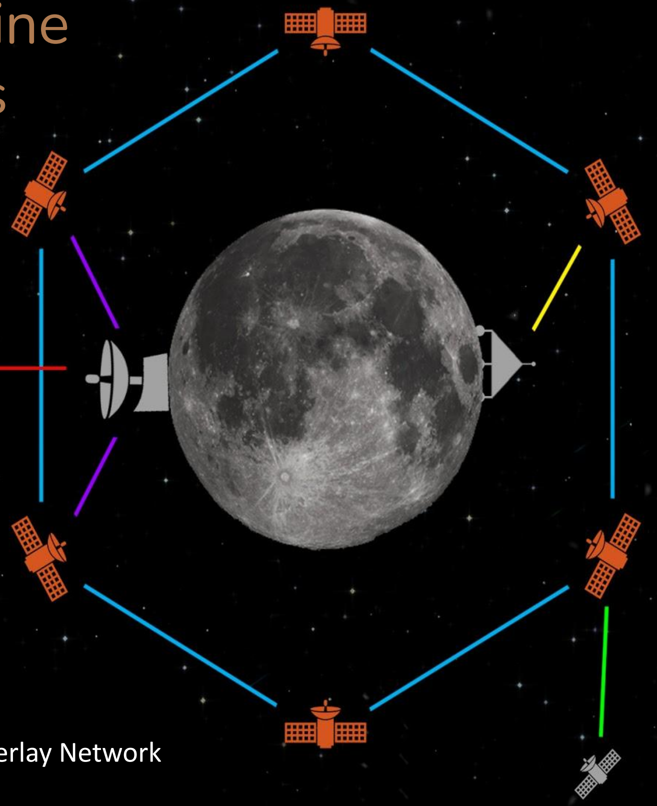


Additional Baseline Considerations

Deep Space Relay Stations

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

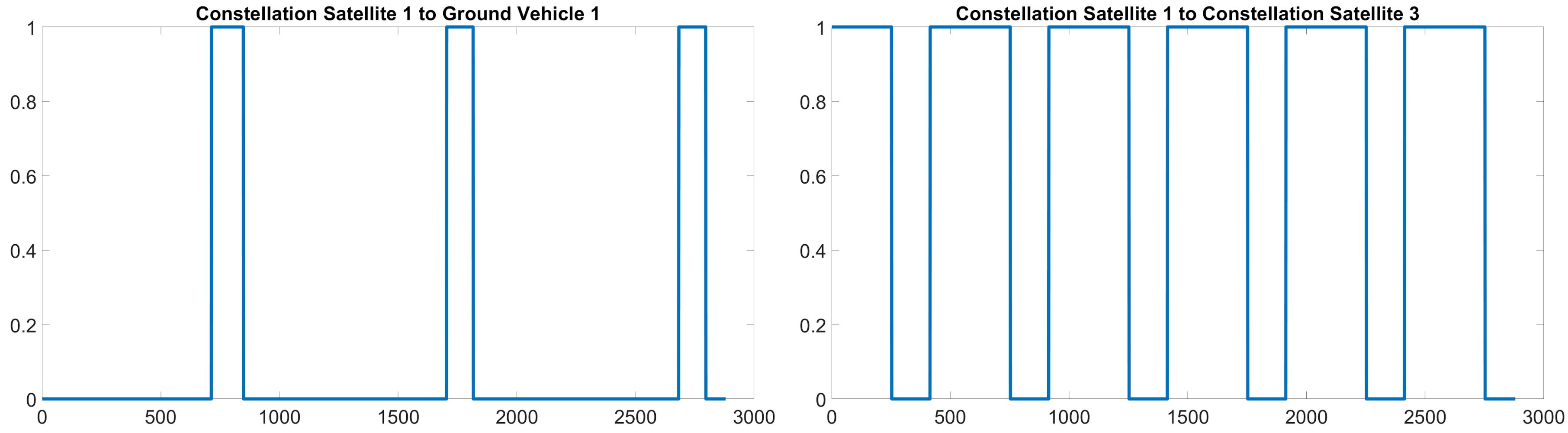




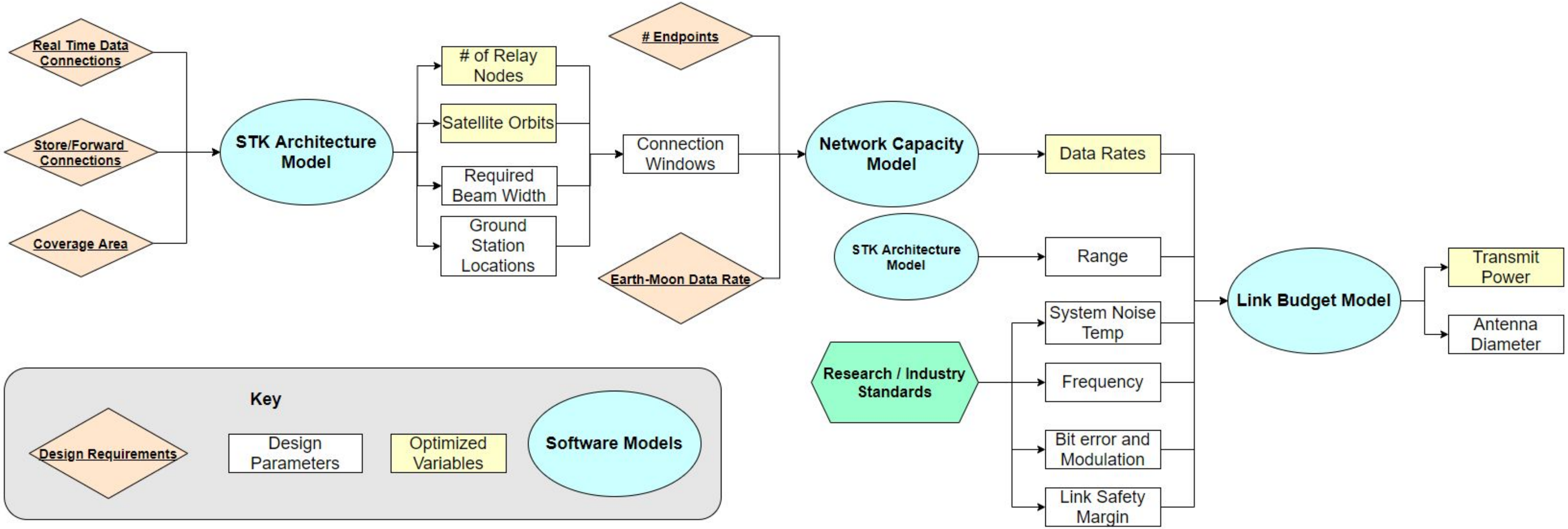
Network Protocol

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

Connection Window Examples



Optimization FBD



Testing

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

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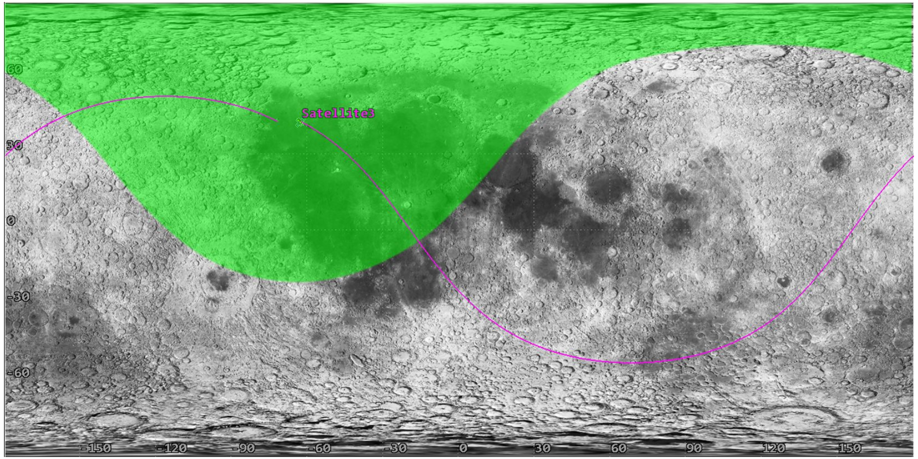
Network Coverage Test

Desired Outcomes:

- Verify that a particular orbit geometry is able to provide >99% coverage of lunar surface and orbit
- Ensure FR1 is met



Test Design:

- Import satellite ephemeris from STK
- Numerically assess the ability of points in the lunar system to connect into the network at each time

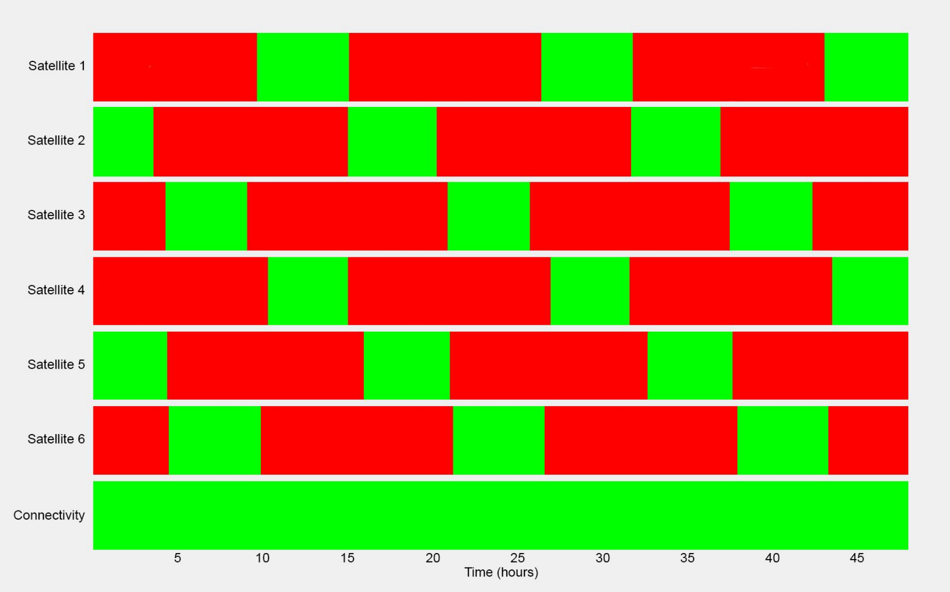
Continuous Connection Test

Desired Outcomes:

- Verify that a particular network configuration allows for **uninterrupted data flow at all times** for required number of nodes
- Ensure **FR 2** is met

Test Design:

- Import **STK network configuration**
- Calculate connection windows for each node
- Verify that connections between endpoints needing continuous connection are **always available**



Data Rate Optimization Test

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Desired Outcomes:

1. Optimize data rates
2. Ensure **FR 2** - endpoint communication support is met

Test Design:

1. Vary input/output data rates and **observe changes** to network capacity outputs
2. Performed using the **Network Capacity Model** written in MATLAB

Data Rate Optimization Test - Variables and Controls

<u>Independent Variables:</u>

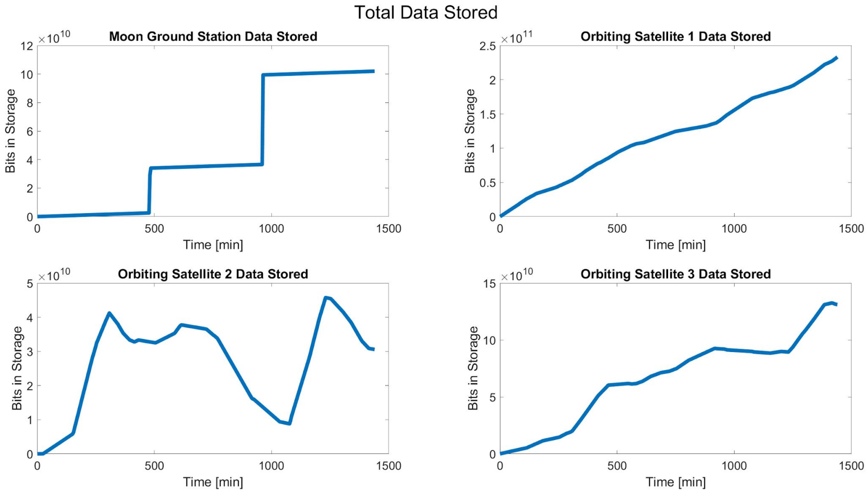
- Earth Ground Station data rate
- Moon Ground Station data rate
- Constellation Satellite data rate

<u>Controls:</u>

- Connection Windows
- Number of surface vehicles/constellation satellites/ground stations.
- Data generation in network

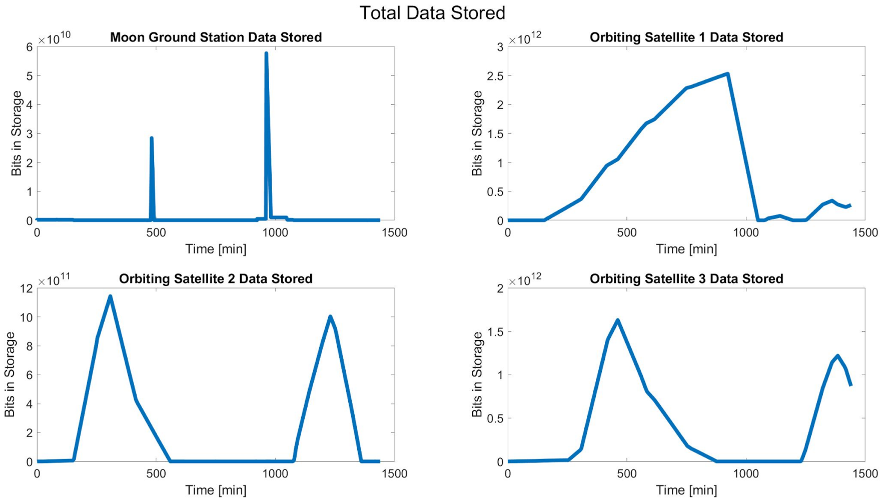
Data Rate Test - Design and Expectations

Over Capacity Network



*An over capacity network **cannot distribute data fast enough** to overcome the incoming data, this gradually fills each node's internal storage

Under Capacity Network



*An under capacity network manages to distribute data to the respective nodes **quicker than the internal storage can fill.**

Capacity Model Hardware Validation Test

Desired Outcomes:

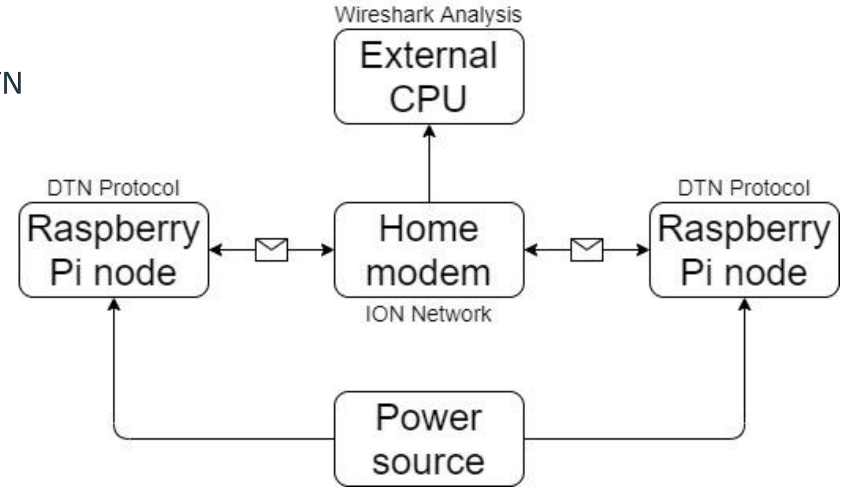
Validate capacity model calculation method through **hardware comparison.**

Test Design:

Build a r-pi network of nodes and observe its **data storage behavior**. Match behavior to **hypothesized behavior** generated from capacity model.

Capacity Model Hardware Test Setup

- **Setup**
  - Raspberry Pi nodes configured and running ION-DTN
- **Procedures**
  - Send data throughout the system
- **Collected Data (Wireshark)**
  - Timestamps of data sent and received
  - Data stored in each node
- **Data Analyzation (MATLAB)**
  - Data stored in each node over time
  - Hardware and Software Latency Values



Power Optimization Test

Desired Outcomes:

1. **Optimize power required** in each link budget
2. Ensure data links fall within **acceptable safety factors**

Test Design:

1. Vary key design parameters and observe the **impact to** transmission power required
2. Performed using the **Link Budget** MatLab software model

Power Optimization Test - Variables and Controls

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Optimized Parameter:

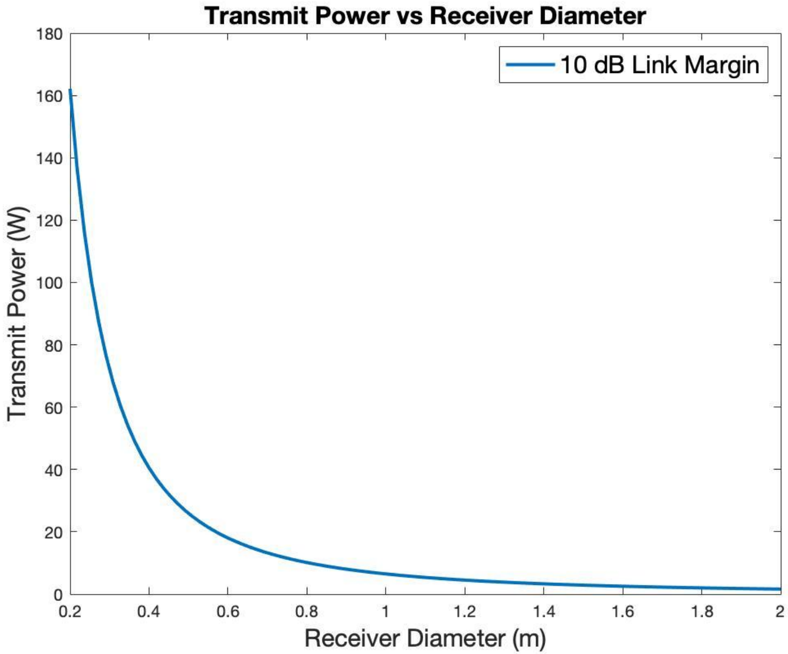
- Power

Independent Variable:

- Antenna Size

Main Control Variables:

- Frequency
- Range
- Data Rate



Link Budget Validation Tests

- AMSAT IARU Link Budget Calculator
  - Check against our link budget model
- Study on Intersatellite Link Antenna
  - Trade off of satellite antennas with associated link budgets

MBSE Validation Test

Desired Outcome:

- The output data from system architecture, network capacity and link budget satisfy the project requirement

Test Design:

- **SysML** simulates the output data by tracing requirement to the subsystems to check if they are satisfy the project requirements
- The output data is the text file data that formats in TLE's (Two-line element set)

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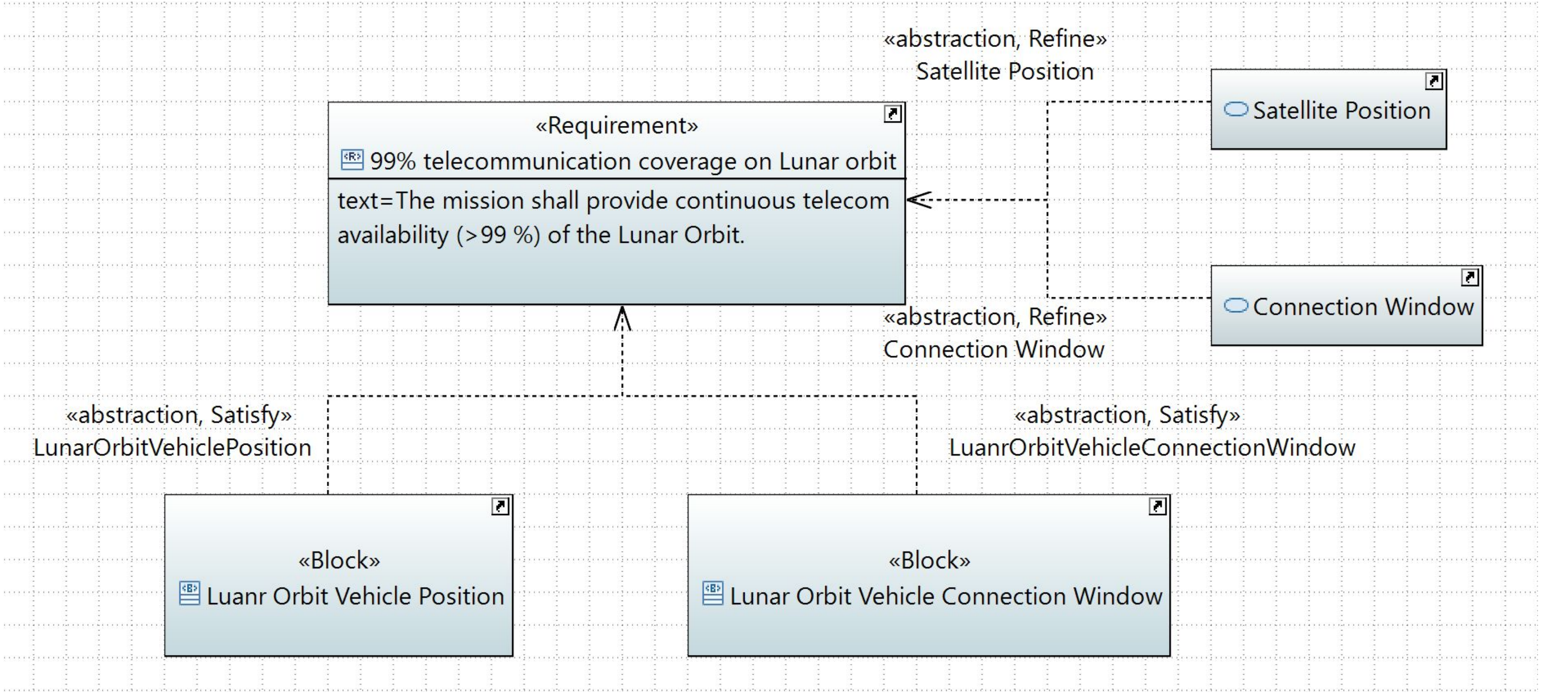
		A	B
		name : String [0..1]	/satisfiedBy : NamedElement [*]
0	/ownedElement		
1	FR-1: Comms must have transmit/receive capability simultaneously & non-simultaneously between Earth, Moon, Mars.	FR-1: Comms must have transmit/receive capability simultaneously & non-simultaneously between Earth, Moon, Mars.	x
2	/ownedElement		
3	R-001: Real time data relay between environments	R-001: Real time data relay between environments	AntennaIO, AntennaIO, AntennaIO
4	R-005: Data relay between mission segments.	R-005: Data relay between mission segments.	LunarSat, EarthSat, EarthGroundStation, LunarGroundStation
5	R-008: Simultaneous comms to 5 locations on Lunar surface.	R-008: Simultaneous comms to 5 locations on Lunar surface.	inboundSignalProcessing, outboundSignalProcessing
6	R-009: Non-simultaneous comms to 10+ locations on Lunar surface.	R-009: Non-simultaneous comms to 10+ locations on Lunar surface.	inboundSignalProcessing, outboundSignalProcessing, centralStorage


«abstraction, Refine»
Satellite Position
Satellite Position
«Requirement»
99% telecommunication coverage on Lunar orbit
text=The mission shall provide continuous telecom availability (>99 %) of the Lunar Orbit.
Connection Window
«abstraction, Refine»
Connection Window
«abstraction, Satisfy»
LunarOrbitVehiclePosition
«abstraction, Satisfy»
LuanrOrbitVehicleConnectionWindow
«Block»
Luanr Orbit Vehicle Position
«Block»
Lunar Orbit Vehicle Connection Window

Test Status

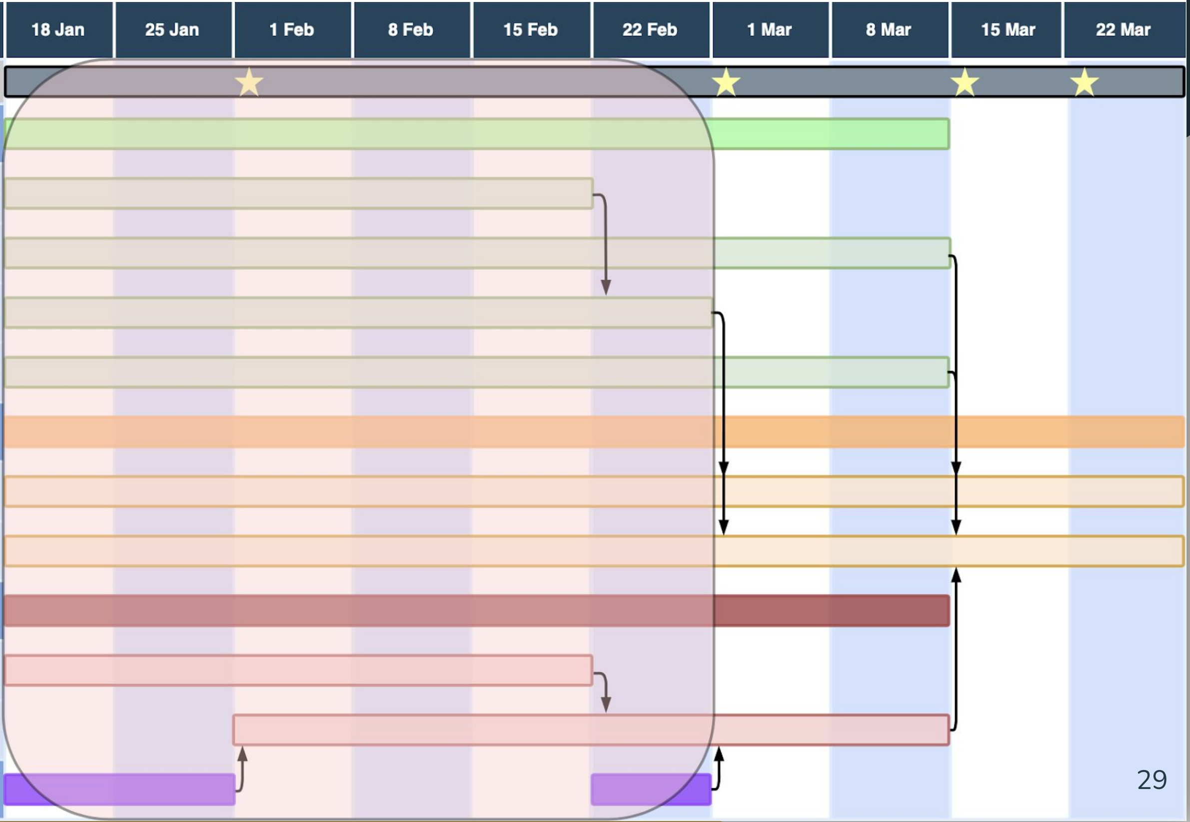
1) **Architecture Tests**
   a) **Done:** Established >99% coverage geometry for all time steps
   b) **In progress:** Verify continuous connection windows for all required nodes
2) **Network Capacity**
   a) **Done:** Created data rate design for an under and over capacity system
   b) **In progress:** Optimize design to find critical data rates while staying under capacity
3) **Link Budget**
   a) **Done:** Optimized for baseline case
   b) **In progress:** Optimization for different links
4) **Hardware**
   a) **Done:** Concept proven ⟶ 2 Raspberry Pis running ION-DTN
   b) **In progress:** Establish connection between two nodes, analyze network traffic via Wireshark, determine test node scalability
5) **MBSE**
   a) **Done:** Created the block definition diagram, internal block diagram, and use case diagram
   b) **In progress:** other structural diagrams and behavioral diagrams that apply to the requirement tracing, implement output data from each subteam to the SysML to do requirement tracking

Project Schedule

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

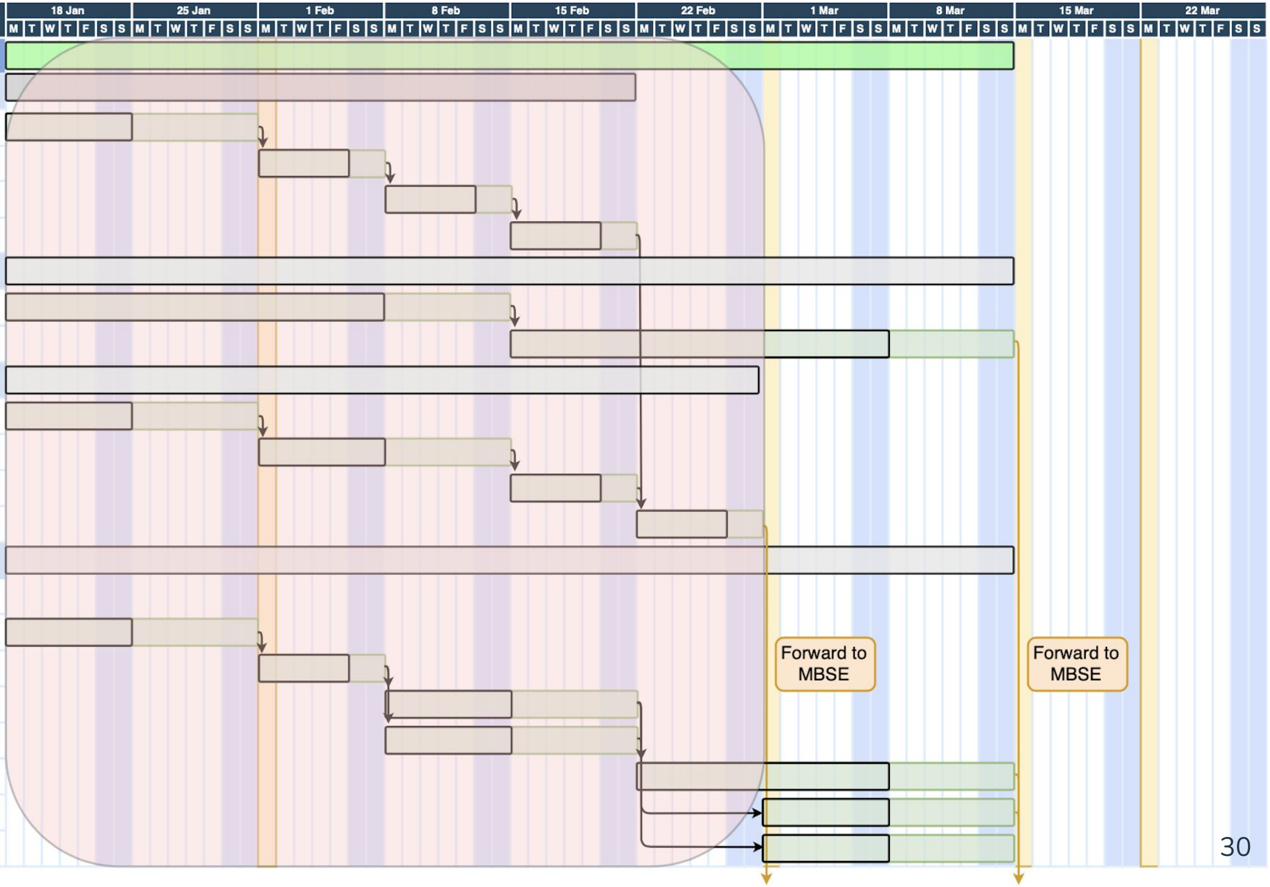
Schedule Overview

Task Name	Duration	Start	End
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	56 days	01.18.21	03.14.21
Manufacturing	35 days	01.18.21	02.21.21
Network Demonstration	56 days	02.01.21	03.14.21
Purchases	21 days	01.18.21	02.28.21



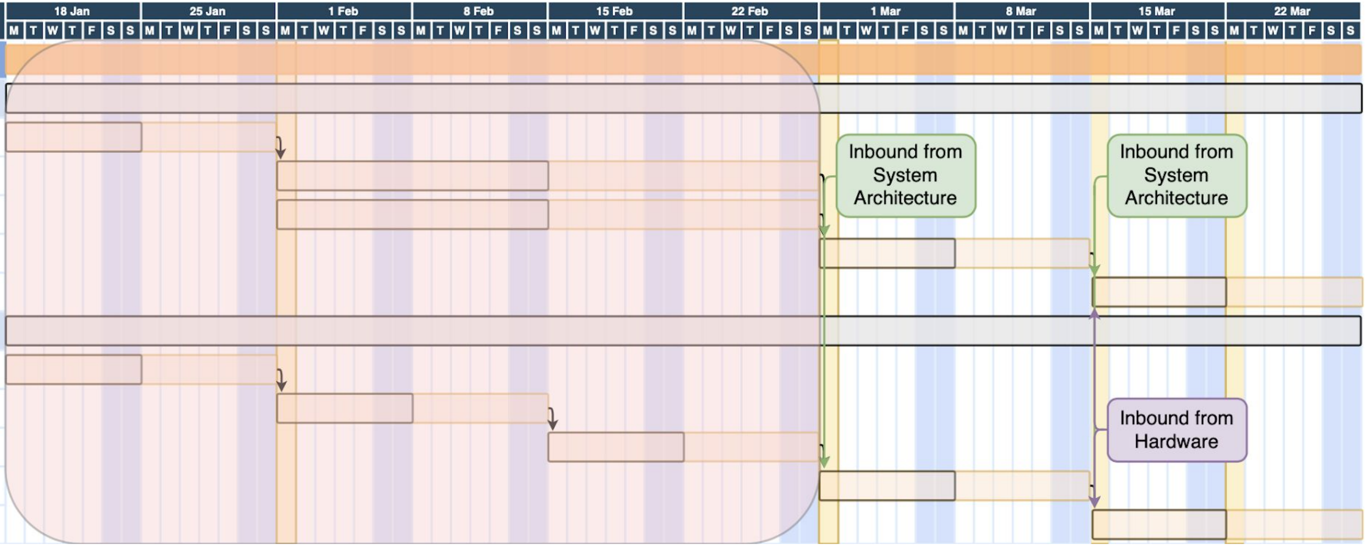
System Architecture Schedule

Task Name	Duration	Start	End
System Architecture	56 days	01.18.21	03.14.21
Relay Stations	42 days	01.18.21	02.28.21
Earth's Atmospheric Conditions	14 days	01.18.21	01.31.21
Relay Station Determination	7 days	01.31.21	02.07.21
Existing Relay Station Locations	7 days	02.07.21	02.14.21
Relay Station Placement	7 days	02.14.21	02.21.21
Link Budget	42 days	01.18.21	03.14.21
RF Link Budget	21 days	01.18.21	02.14.21
Laser Link Budget	21 days	02.14.21	03.14.21
Constellation Architecture	42 days	01.18.21	02.28.21
Constellation Geometry Output	14 days	01.18.21	01.31.21
Network Connection Windows	14 days	01.31.21	02.14.21
Surface/Orbital Coverage Verification	7 days	02.14.21	02.21.21
Full System Coverage Verification	7 days	02.21.21	02.28.21
Network Protocol	56 days	01.18.21	03.14.21
Single Flow Model	0 days	---	---
Multiple Path Model	7 days	01.18.21	01.31.21
Variable Connections Model	7 days	01.31.21	02.07.21
Latency Assumptions Update	14 days	02.07.21	02.21.21
Discreet Data Packages Experimentation	14 days	02.07.21	02.21.21
Model Hardware Verification	7 days	02.21.21	02.28.21
Architecture Optimization	14 days	02.28.21	03.14.21
DTN DevKit Emulation	14 days	02.28.21	03.14.21



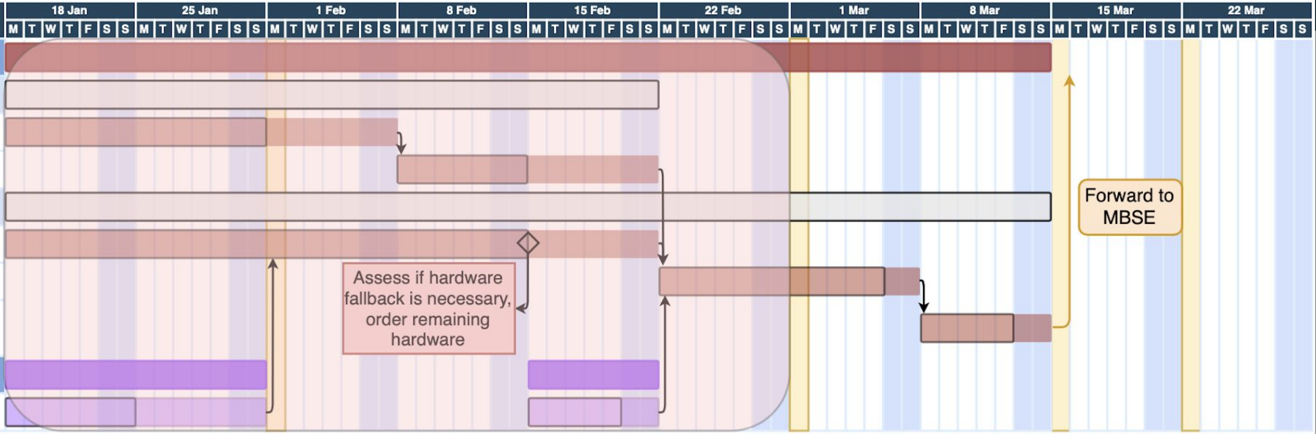
MBSE Schedule

Task Name	Duration	Start	End
MBSE Modeling	70 days	01.18.21	03.28.21
Structural Modeling	70 days	01.18.21	03.28.21
Data Type Enumeration	14 days	01.18.21	01.31.21
Block Definition Modeling	14 days	01.31.21	02.14.21
Internal Block Modeling	14 days	02.14.21	02.28.21
Dependency Modeling	14 days	02.28.21	03.14.21
Parametric Modeling	14 days	03.14.21	03.28.21
Behavioral Modeling	70 days	01.18.21	03.28.21
Use Case Modeling	14 days	01.18.21	01.31.21
State Machine Modeling	14 days	01.31.21	02.14.21
Requirements Tracing	14 days	02.14.21	02.28.21
Sequence Modeling	14 days	02.28.21	03.14.21
Activity Modeling	14 days	03.14.21	03.28.21



Hardware Schedule

Task Name	Duration	Start	End
Hardware	56 days	01.18.21	03.14.21
Manufacturing	35 days	01.18.21	02.21.21
CAD Model	21 days	01.18.21	02.07.21
3D Print Casting	14 days	02.08.21	02.21.21
Network Demonstration	56 days	01.18.21	03.14.21
Dual/Multi-Node Network	35 days	01.18.21	02.21.21
Single Node ION Implementation	14 days	02.22.21	03.07.21
Prescribed Latencies and Bundle File Sizes Implemented	7 days	03.08.21	03.14.21
Purchase	21 days	01.18.21	02.21.21
Hardware	21 days	01.18.21	02.21.21



Budget

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

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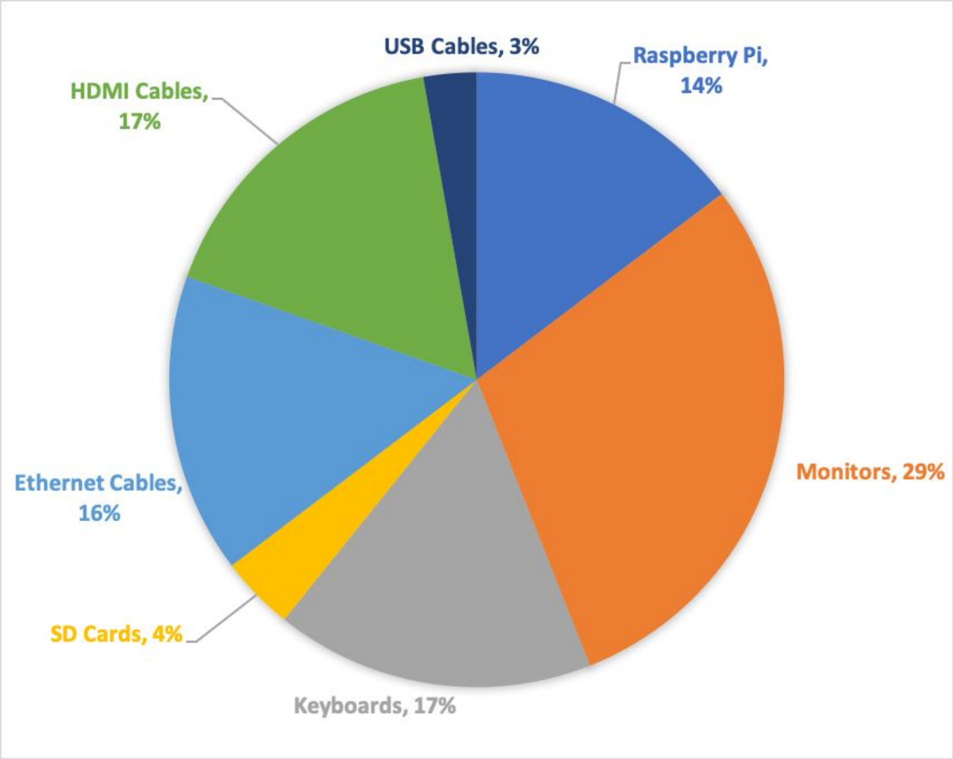
Hardware Procurement Update

Hardware Parts	Status
2 Raspberry Pis	Received
2 Monitors	Received
2 HDMI Cables	Received
2 Keyboards	Received
2 Ethernet Cables	Received
Total:	**$538.92**

Hardware Parts	Status
1 Raspberry Pi	Ordered
2 SD Cards	Yet to be purchased
2 HDMI Cables	Yet to be purchased
2 Ethernet Cables	Yet to be purchased
Total:	**$184.88**

Updated Budget

Raspberry Pi (3)
Monitors (2)
SD Cards (2)
Keyboards (2)
HDMI Cables (4)
Ethernet Cables (4)
Total: $723.80
Margin: $4,276.20



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Questions?

APPENDIX

Power Optimization Variables

Link Parameters	**Value**
Max Range	11,024 km
Frequency	26 GHz
Antenna Size (Diameter)	Varied
Transmit Power	Output
Data Rate	50 Mbps
Receive System Noise Temperature	700 K *
Required Eb/No [BPSK Modulation, BER = 10^-7]	11 dB
Required Safety Design Margin	3 dB
Link Margin	10 dB

*Source: Robert C. Morre, "Satellite RF Communications and Onboard Processing", Encyclopedia of physical Science and Technology (Third Edition), 2003

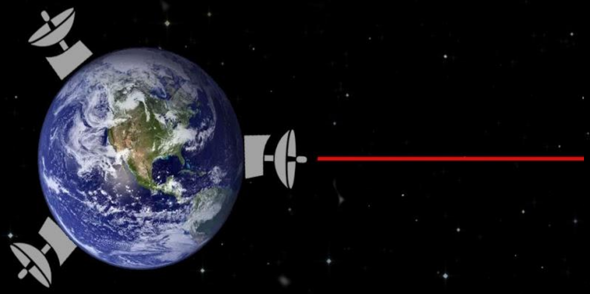
Baseline Parameters for Intersatellite Link

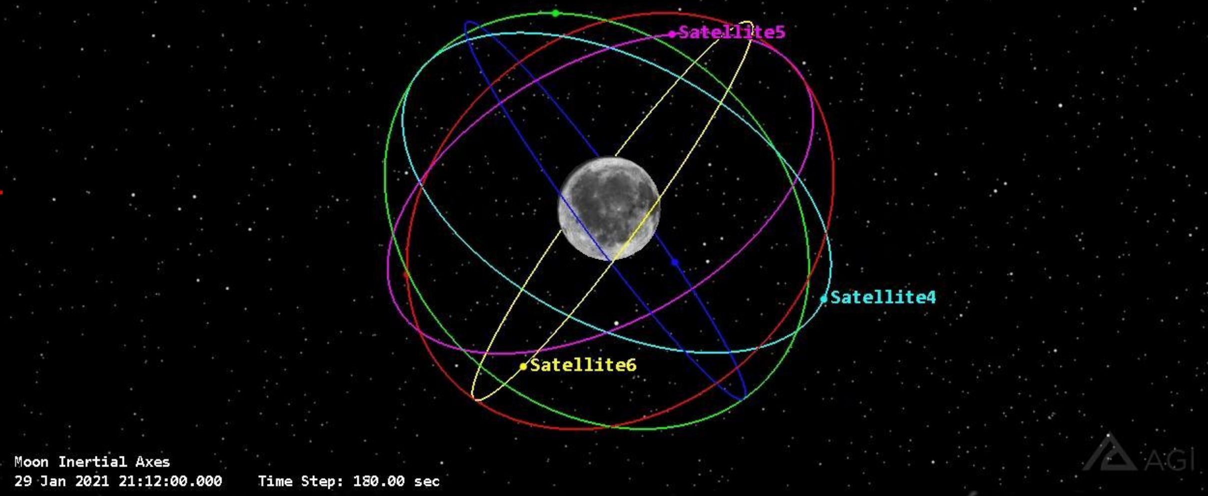
Key Input Variables	Value
Range (km)*	11,024 km
Frequency (GHz)	26
Antenna Size (D)	1 m
Transmit Power (W)	30 W
Data Rate (Mbps)*	50 Mbps
Receive System Noise Temperature (K)	700 K
Required Eb/No (dB) [BPSK Modulation, BER = 10^-7]*	11 dB
Required Design Margin*	3 dB

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

Satellite Constellation Architecture

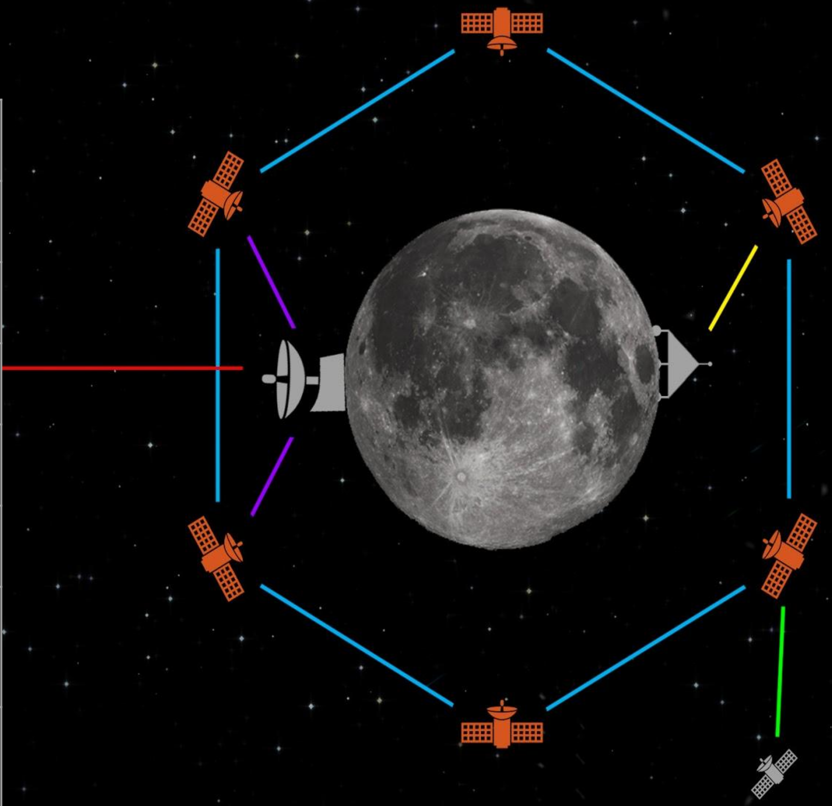
- Walker-Delta configuration
  - ~53 deg inclination
  - 6/6/4 configuration
  - MEO equivalent altitude

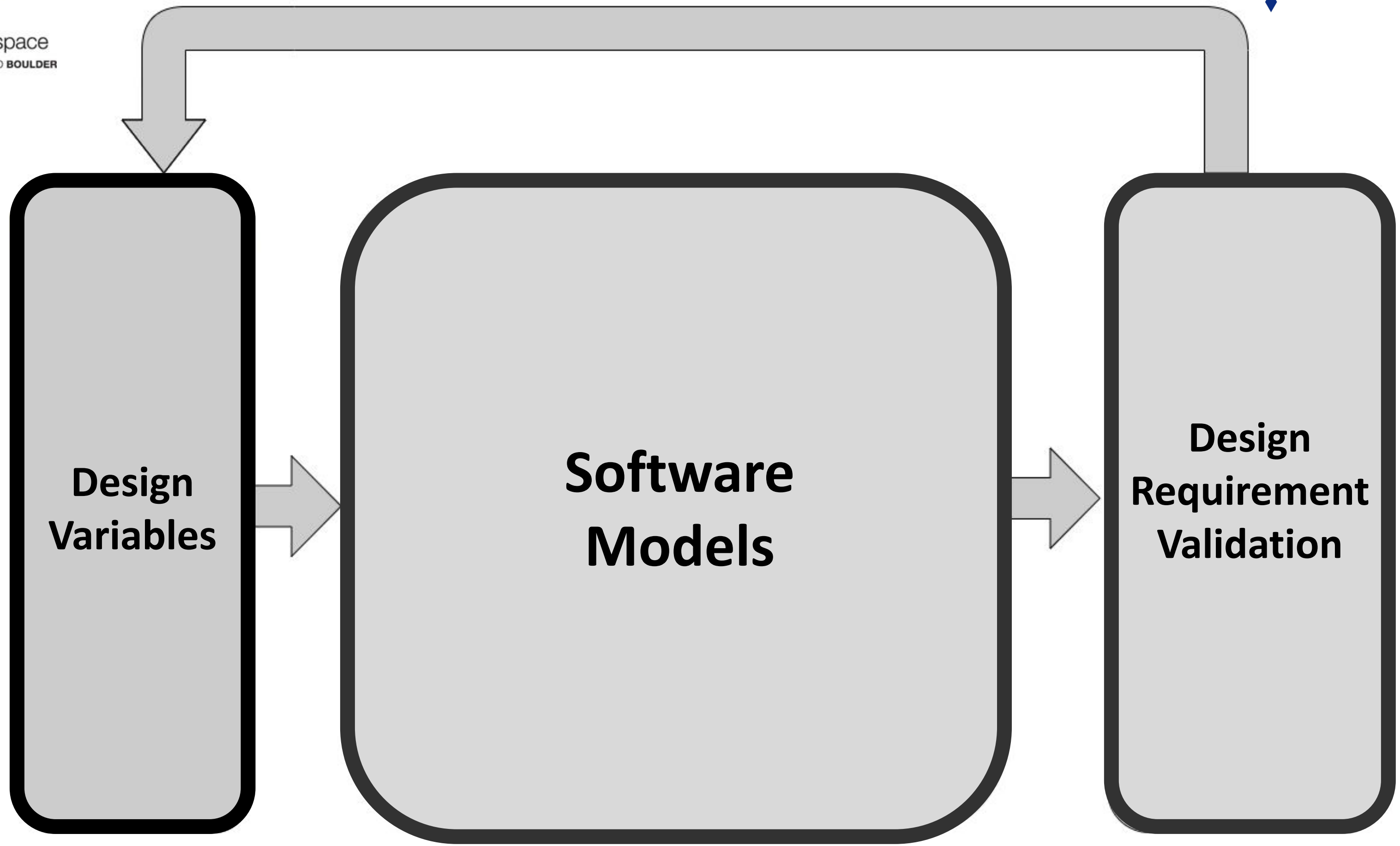




Inter-Constellation Satellite Link Budget

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




Design
Variables
Software
Models
Design
Requirement
Validation

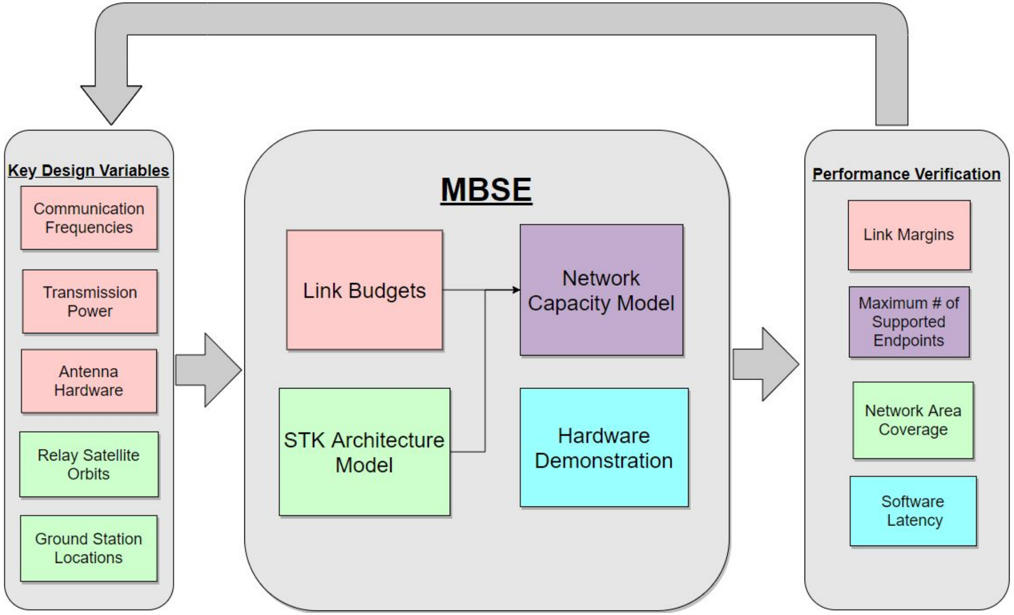
Manufacturing Tasks

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



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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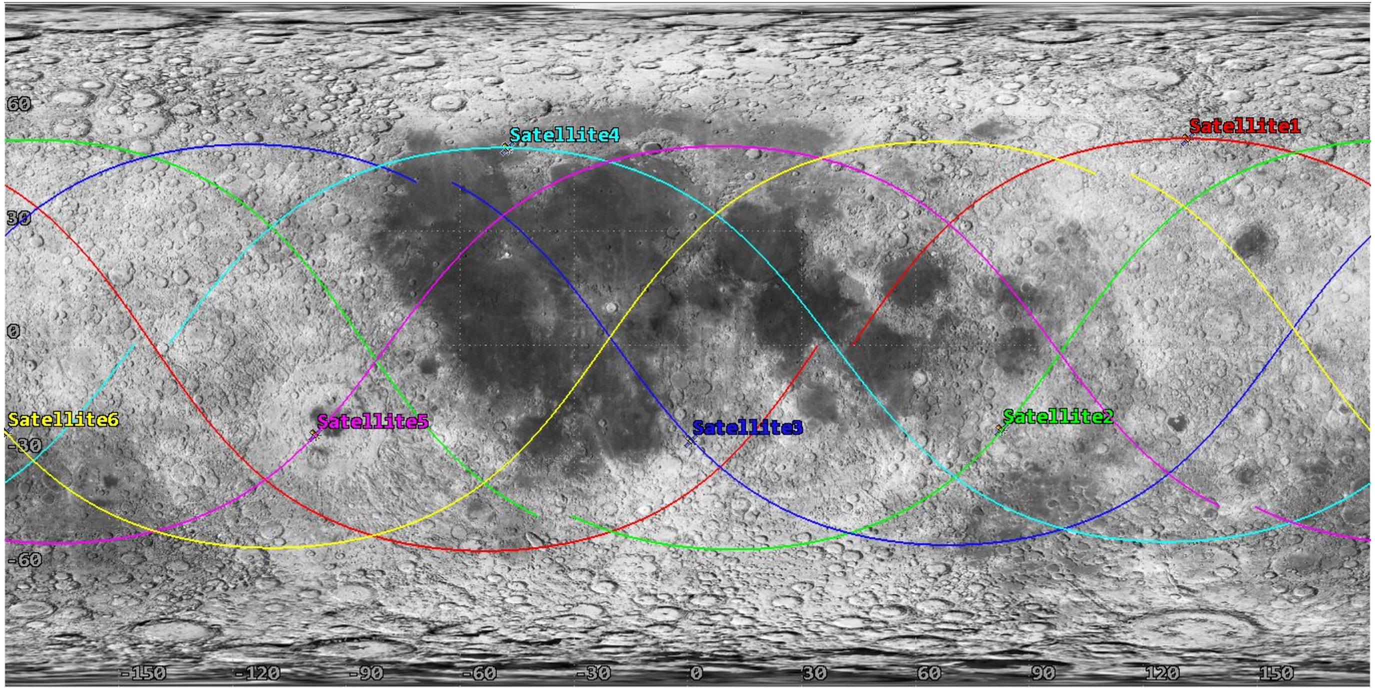
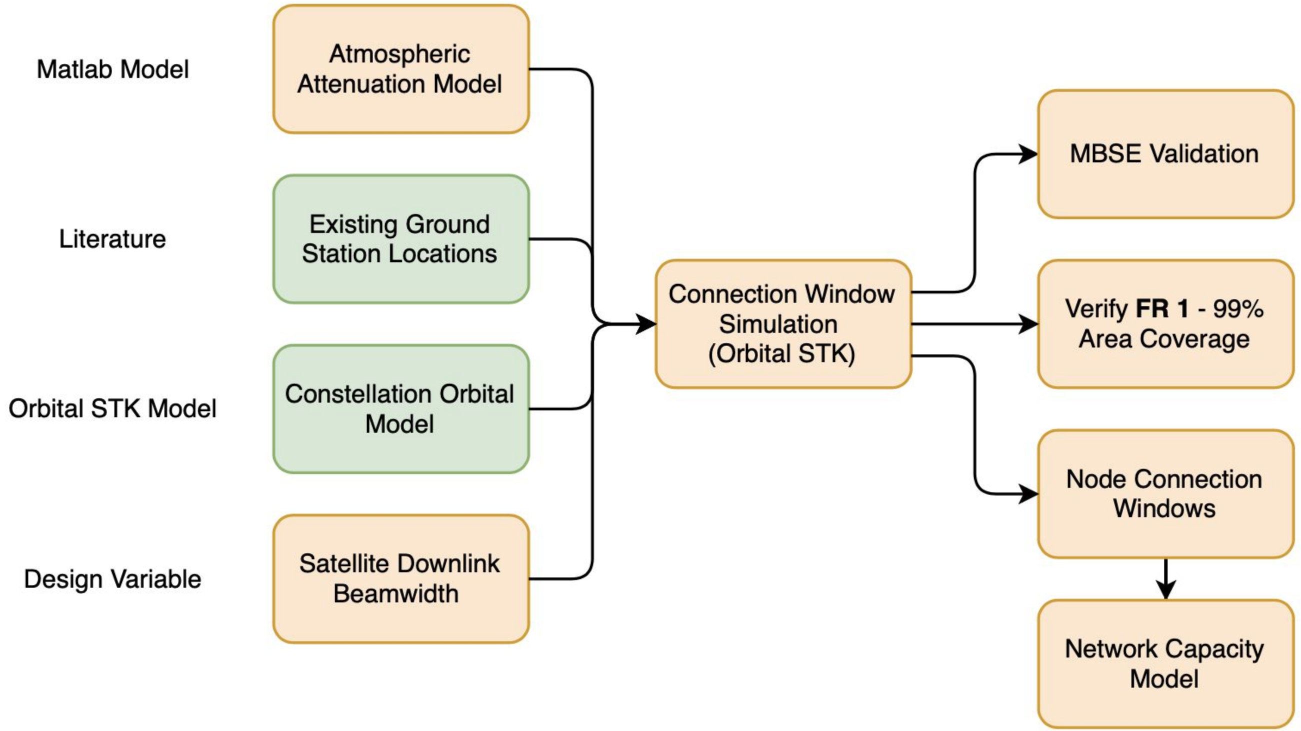
STK Constellation Orbital Model



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

STK Architecture Build Progress



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RF Link Model

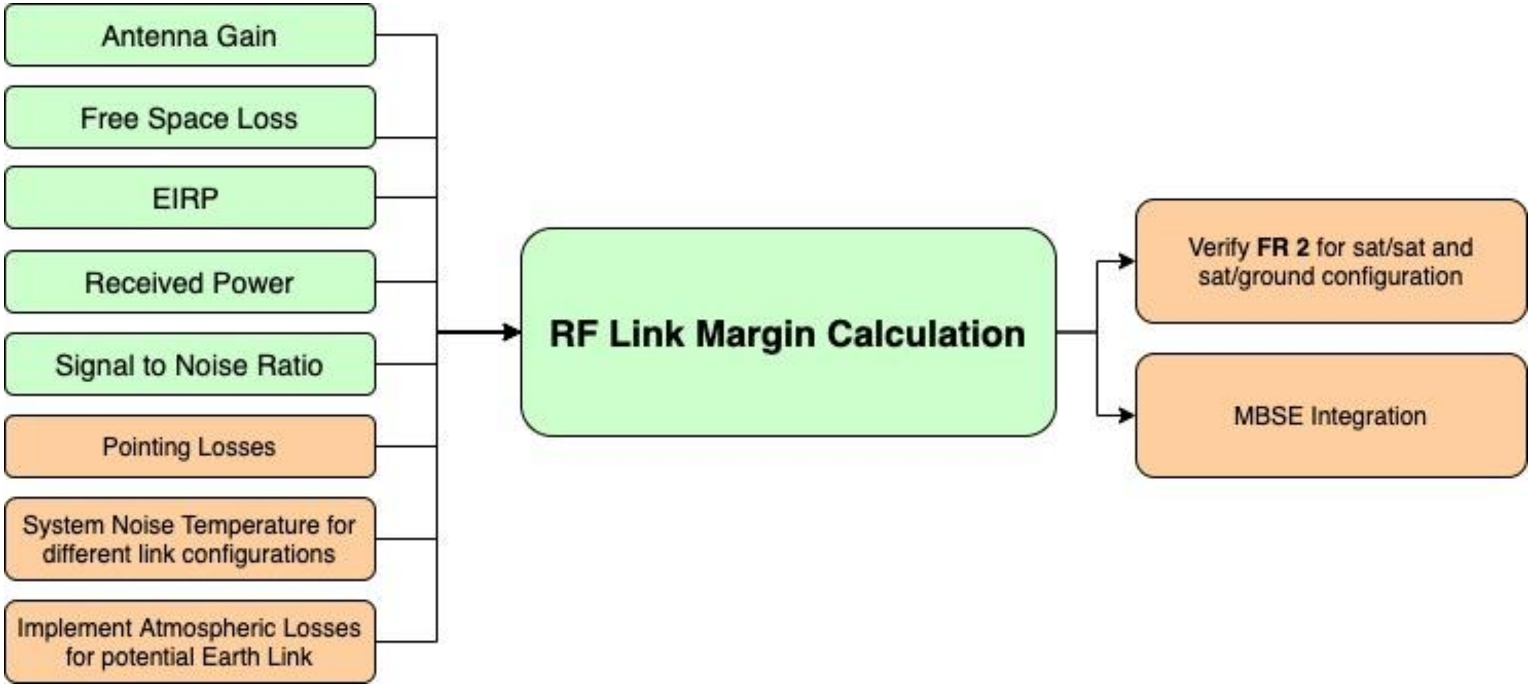
Purpose: Process necessary inputs to create a successful link (positive link margin)

Model Logistics:

- Programmed 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

RF Link Model Progress



Laser Link Model

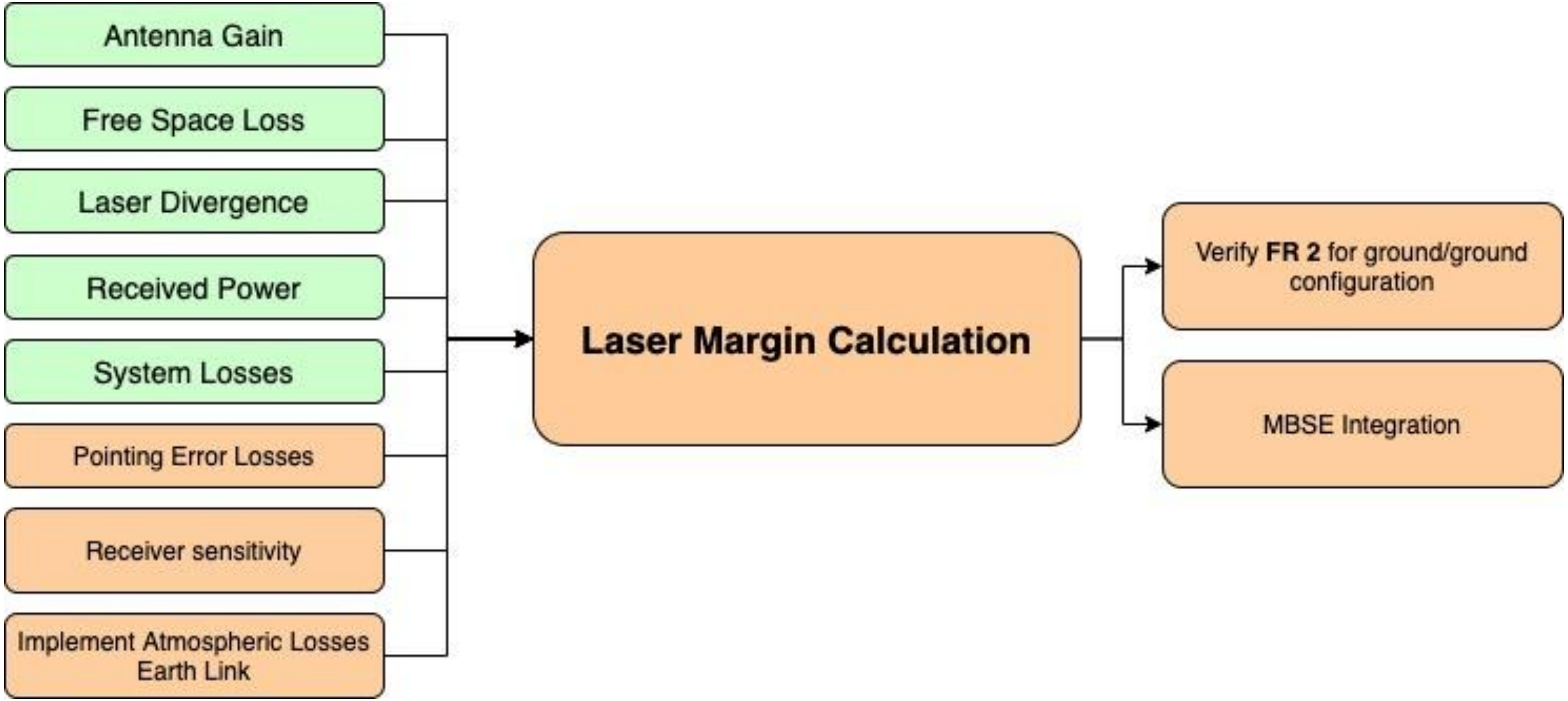
Purpose: Process necessary inputs to create a successful link (positive link margin)

Model Logistics:

- Programmed 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



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

Capacity Model: Build Progress

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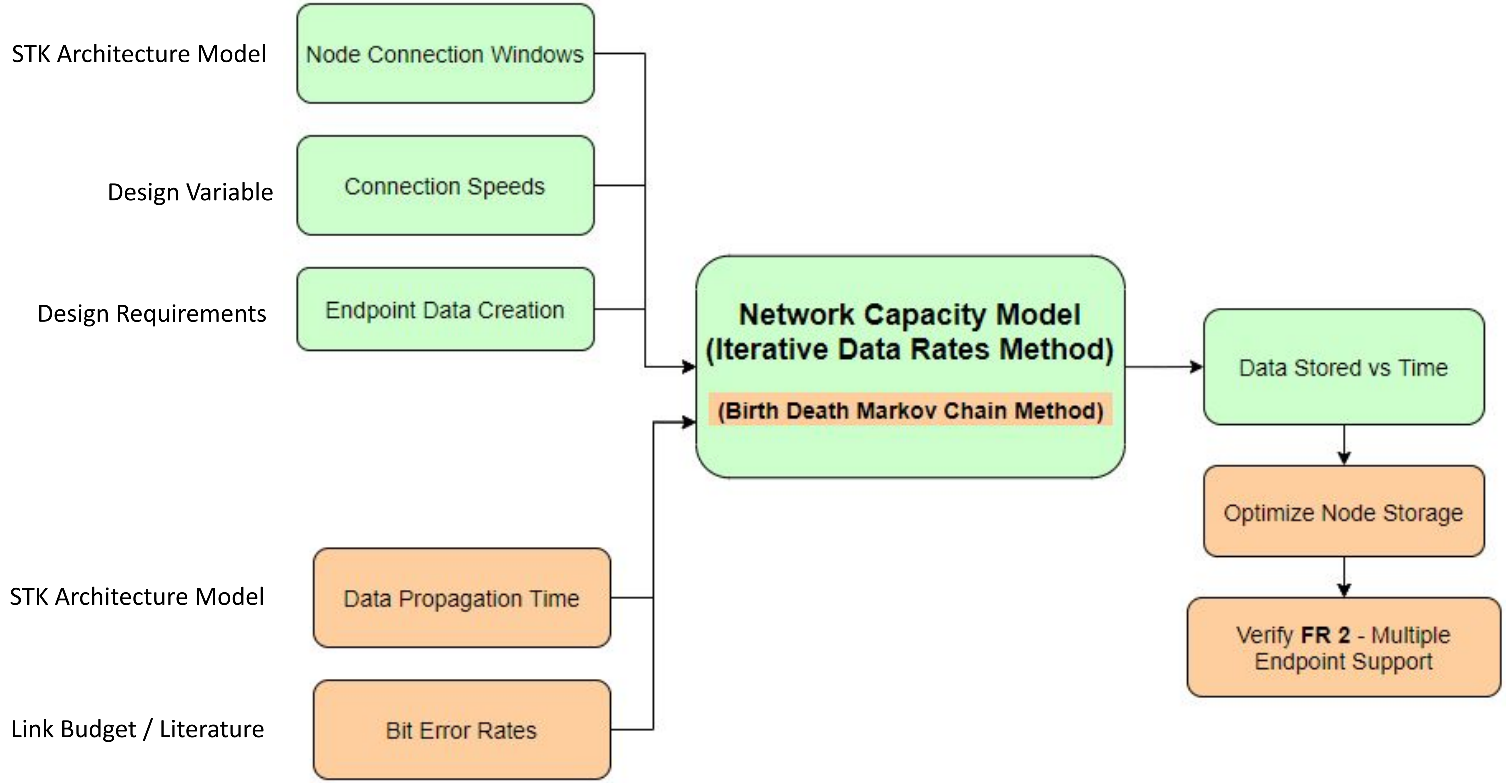
UNIVERSITY OF COLORADO BOULDER

GENERAL ATOMICS



Hardware Demonstration

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

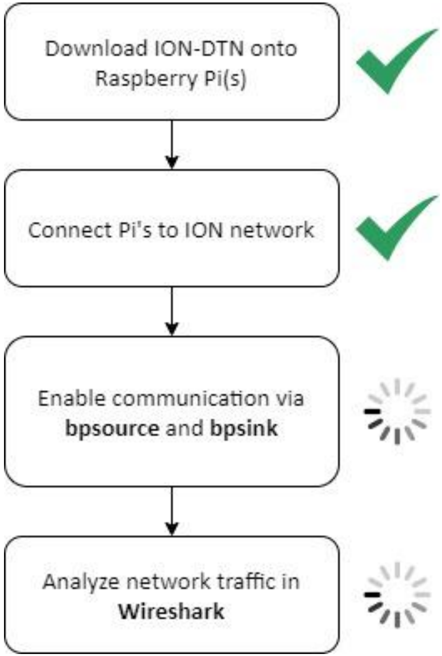
Hardware Demonstration Timeline

Current development:

- Ubuntu server & ION-DTN installed
- Validating proof-of-concept

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

GENERAL ATOMICS

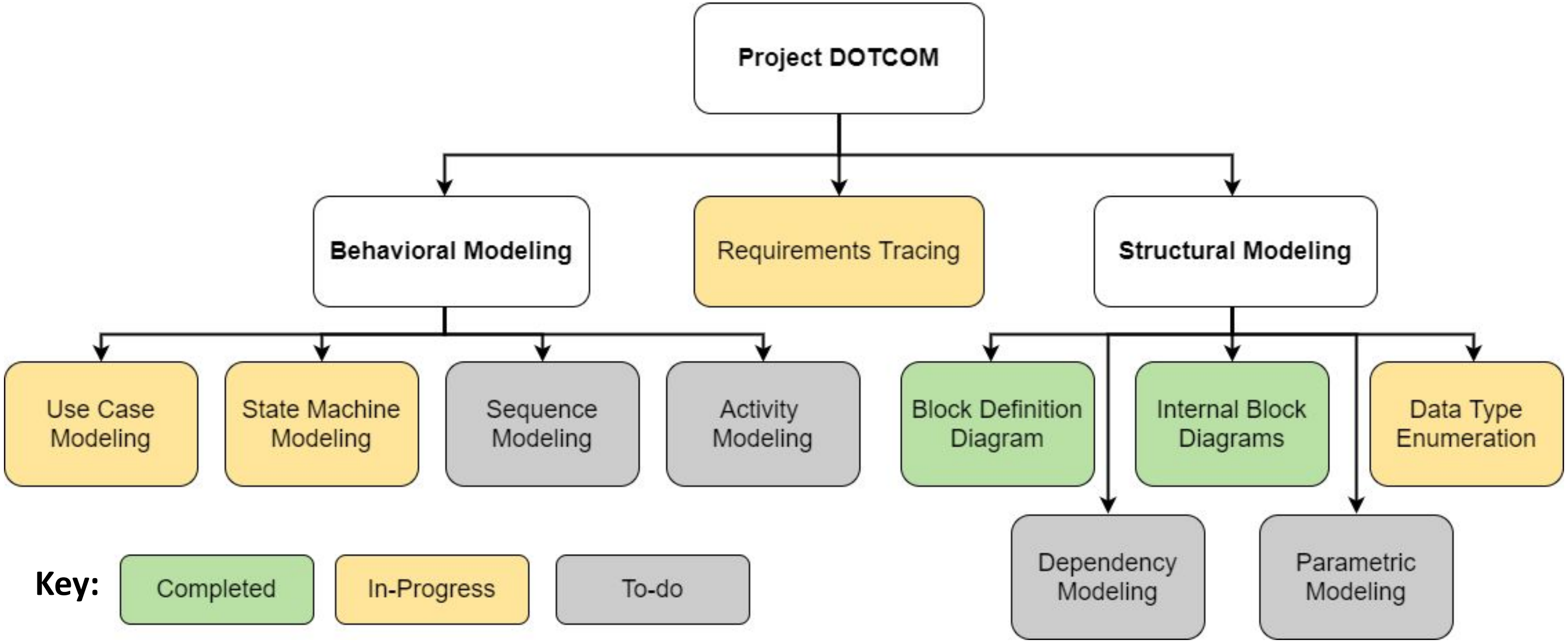
Purpose: Integration of separate project elements and model outputs (network capacity, link budget, etc.) into one project space, and trace requirements to the subsystems that satisfy them.

Model Logistics:

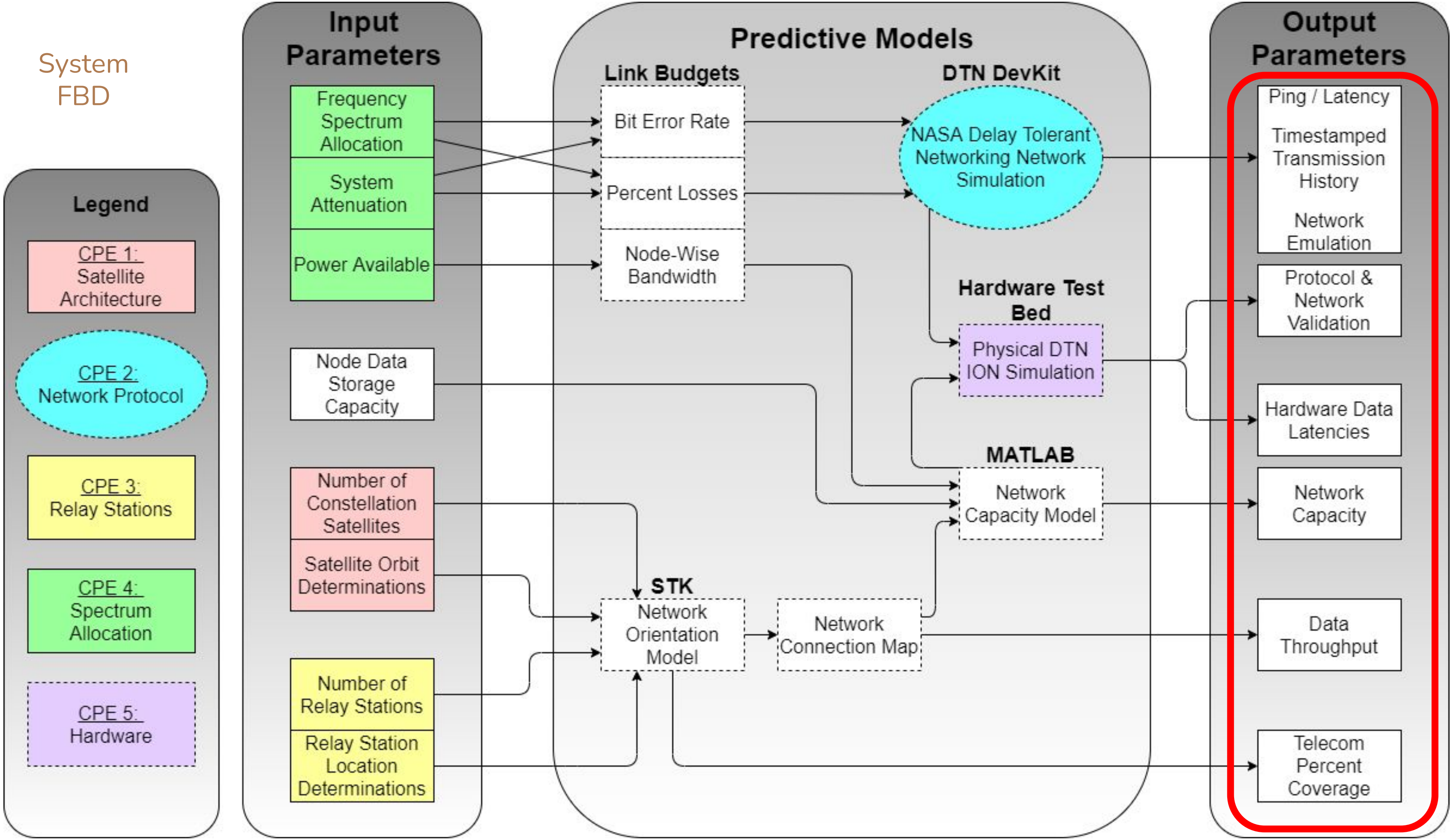
- Created in the SysML modeling language
- ***Inputs***: Completed modeling of project subsystems
- ***Outputs***: Cohesive DOTCOM project deliverable, including mapping of subsystem connections and modeling behavior of network nodes.

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



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, angle of signal through atmosphere, height of relay station
  - Output: Attenuation (atmospheric loss variable)
  - Status: In progress
- 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)

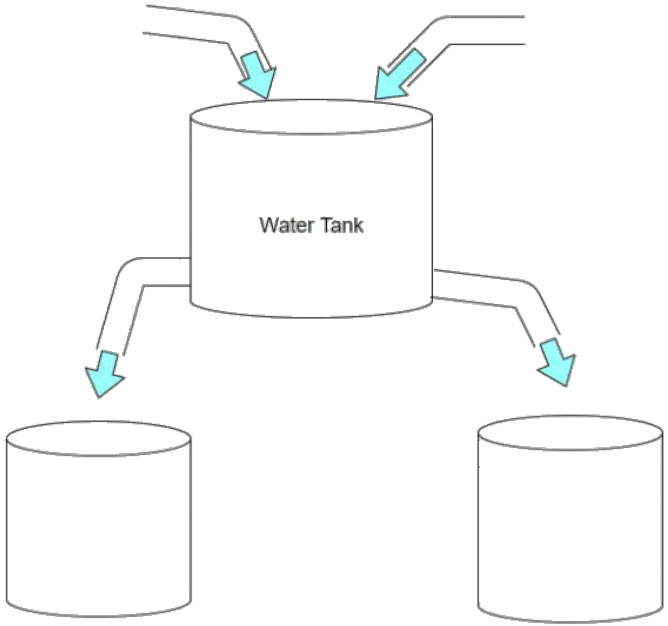
Configuration has format T/P/F

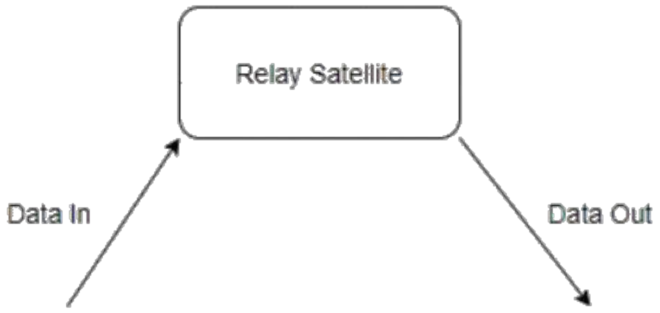
RAAN separation = 360°/P = 60°

v separation = F * RAAN separation = 240°

i = 53.1° = constant

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

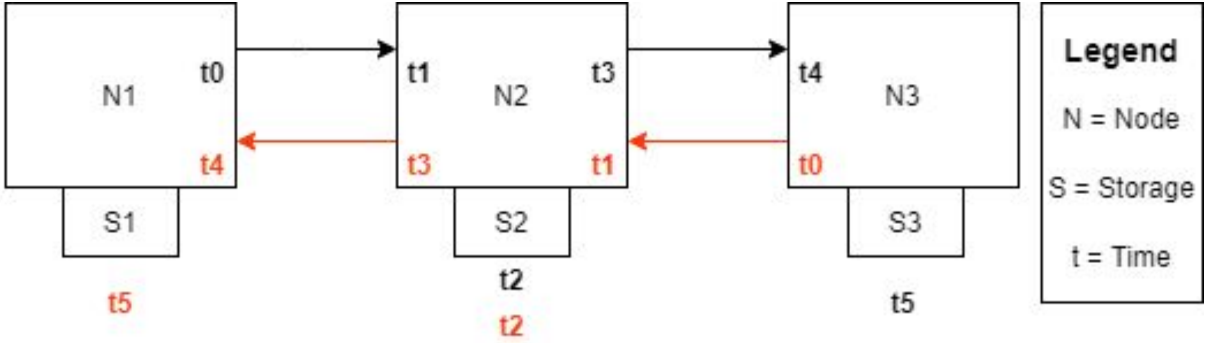
Data Type (High Rate Channel)	**Data Rates**	**Element**
Command Loads	100 kbps	Transport / Rover / Base
CD-quality Audio	128 kbps	Astronaut
Video (TV, Videoconference)	1.5 Mbps	Astronaut

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

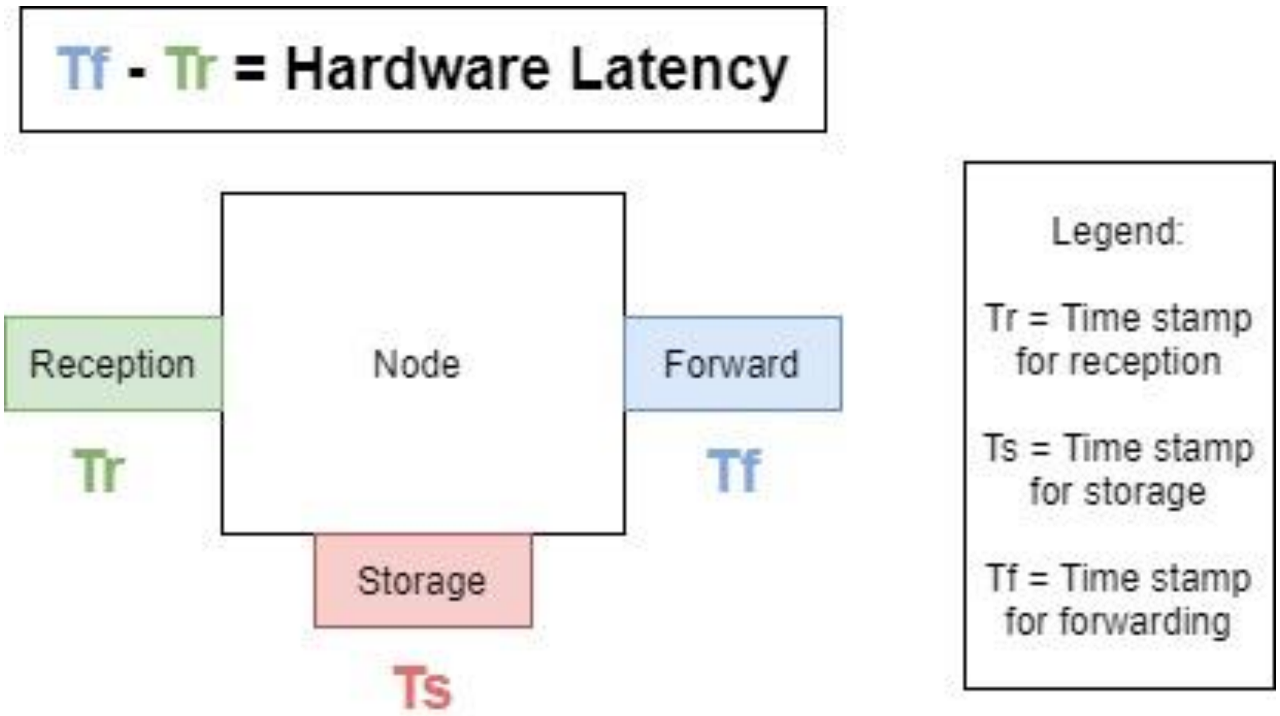


Synchronous

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

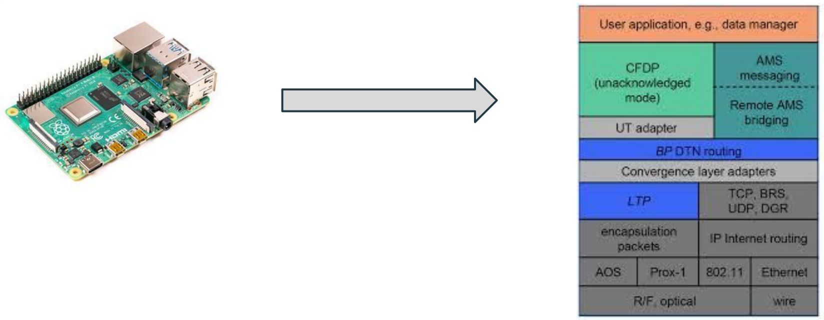
Completed:

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

In progress:

1) Debug given test file

SOURCEFORGE



Hardware CONOPS

GENERAL ATOMICS

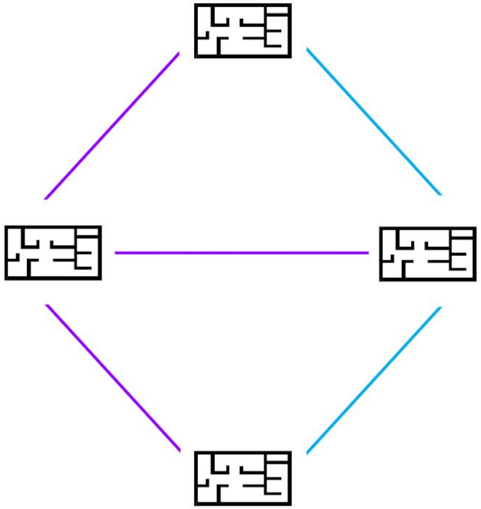
Level 1 Success

Legend

Rasperry Pi node

Ground station to ground station link

Level 2 Success



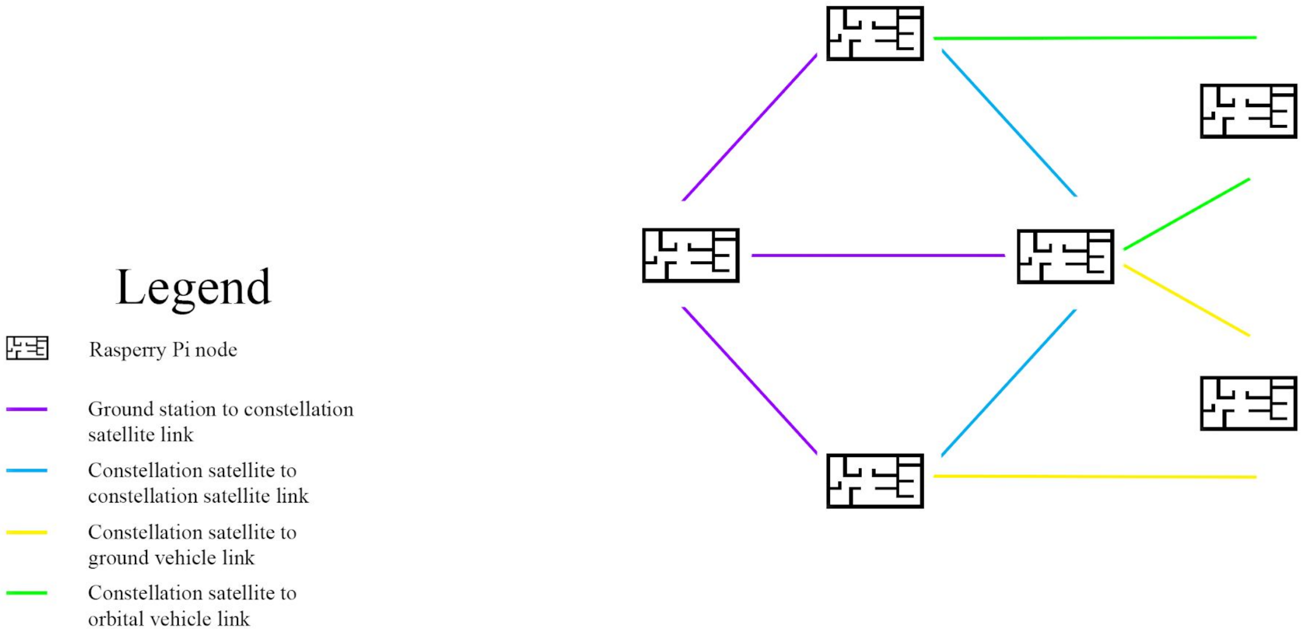
Legend

Rasperry Pi node

Ground station to constellation satellite link

Constellation satellite to constellation satellite link

Level 3 Success



Level 4 Success