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GENERAL ATOMICS

DOT COM

Deep-Space Orbital Telecommunications

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Agenda

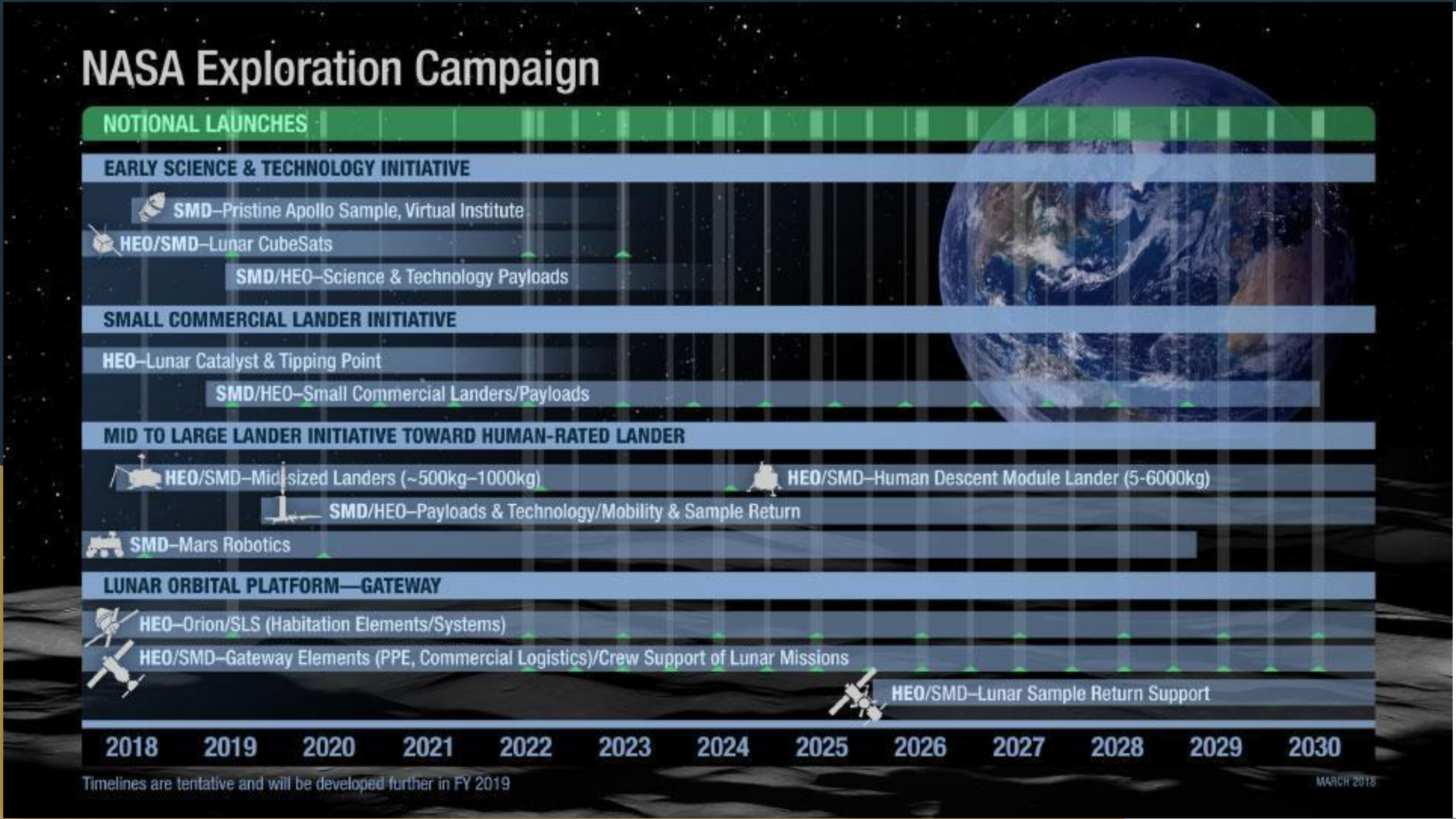
Deep-space
Orbital
Tele**COM**munications

Project Overview

Project Overview → Design Description → Test Overview → Test Results → Systems Engineering → Project Management

DOTCOM


We are going to the Moon to stay, by 2024. This is how.



NASA Exploration Campaign
NOTIONAL LAUNCHES
EARLY SCIENCE & TECHNOLOGY INITIATIVE
SMD–Pristine Apollo Sample, Virtual Institute
HEO/SMD–Lunar CubeSats
SMD/HEO–Science & Technology Payloads
SMALL COMMERCIAL LANDER INITIATIVE
HEO–Lunar Catalyst & Tipping Point
SMD/HEO–Small Commercial Landers/Payloads
MID TO LARGE LANDER INITIATIVE TOWARD HUMAN-RATED LANDER
HEO/SMD–Mid-sized Landers (~500kg–1000kg)
HEO/SMD–Human Descent Module Lander (5-6000kg)
SMD/HEO–Payloads & Technology/Mobility & Sample Return
SMD–Mars Robotics
LUNAR ORBITAL PLATFORM—GATEWAY
HEO–Orion/SLS (Habitation Elements/Systems)
HEO/SMD–Gateway Elements (PPE, Commercial Logistics)/Crew Support of Lunar Missions
HEO/SMD–Lunar Sample Return Support
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Timelines are tentative and will be developed further in FY 2019
MARCH 2018

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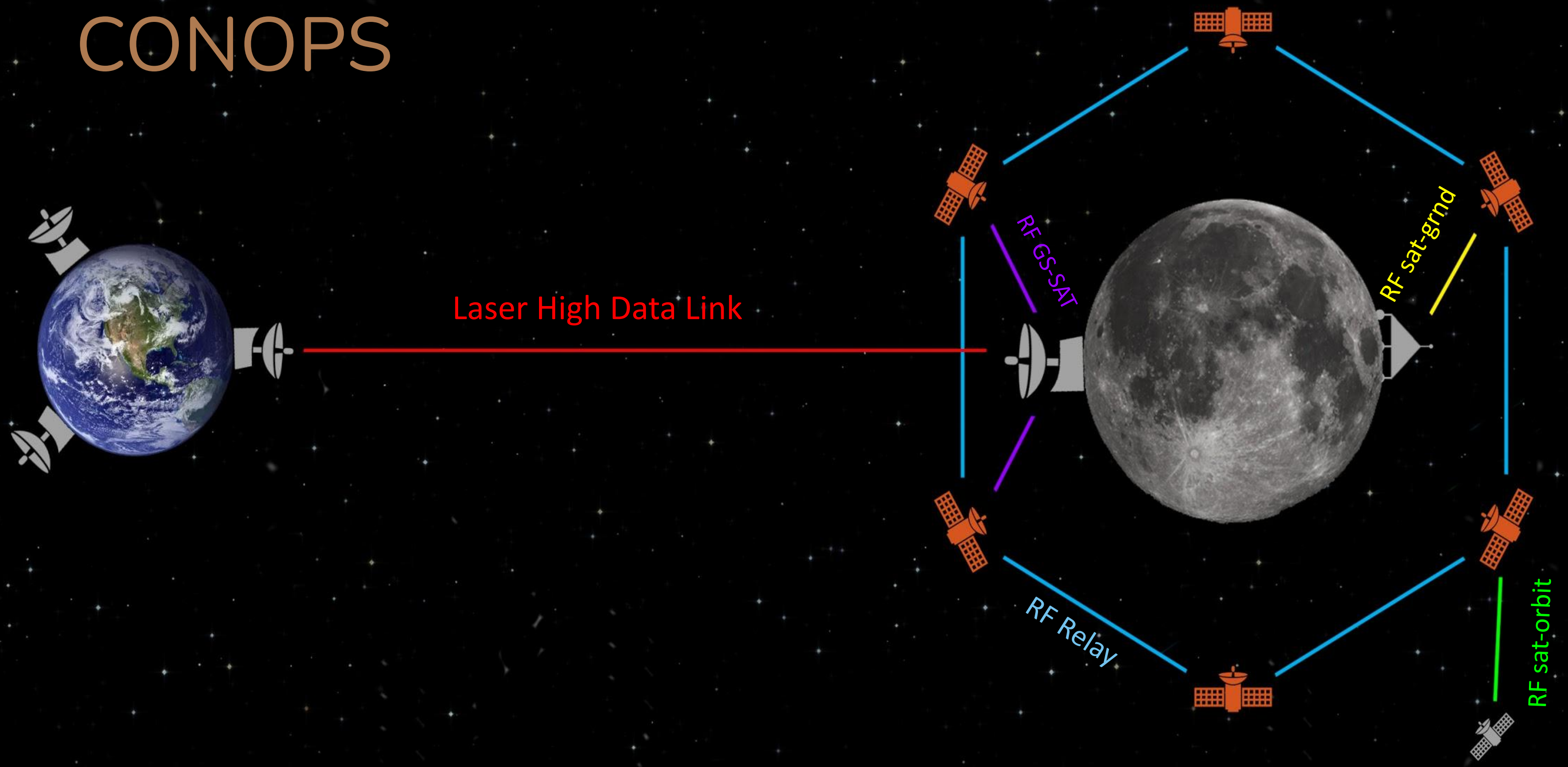
Mission Statement

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 systems engineering.**

CONOPS


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

Network 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

Level 1	Design Meets Performance Requirements	
	99% coverage of Lunar Surface	O
	99% coverage in Lunar Orbit	O
	Ability to command lunar surface vehicles	O
	Ability to command lunar orbiting vehicles	O
	Simultaneus coms support for 5 surface locations	O
	Simultaneous coms for 10 orbital vehicles	O
	Store and forward support for 10 surface locations	O
	Store and forward support for 20 orbital vehicles	O
	Earth to Moon data rate exceeds 500 Mbps	O
Level 2	**Hardware Proof of Concept**	
	Aquire ION software	O
	Load ION software on Raspberry Pi units	O
	Send Messages between nodes using ION	O
	Software/Hardware latency test	X
	Network capacity validation test	X
Level 3	**Required Satellite and Ground Station Specs**	
	Transmission power requirements	O
	Link budgets	O
	Thermal requirements	X
	Pointing accuracy	X
	Propulsion budgets	X
Level 4	**Exploration of Cost and Mission timeline**	
	Cost of each unit	X
	Cost of deployment	X
	Expected lifespan	X
	Study of mission timeline	X
	Resiliency study	X

Full level 1 success

Majority level 2 success

Partial level 3 success

No level 4 success

Design Description

- Project Overview
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- Test Overview
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- Project Management

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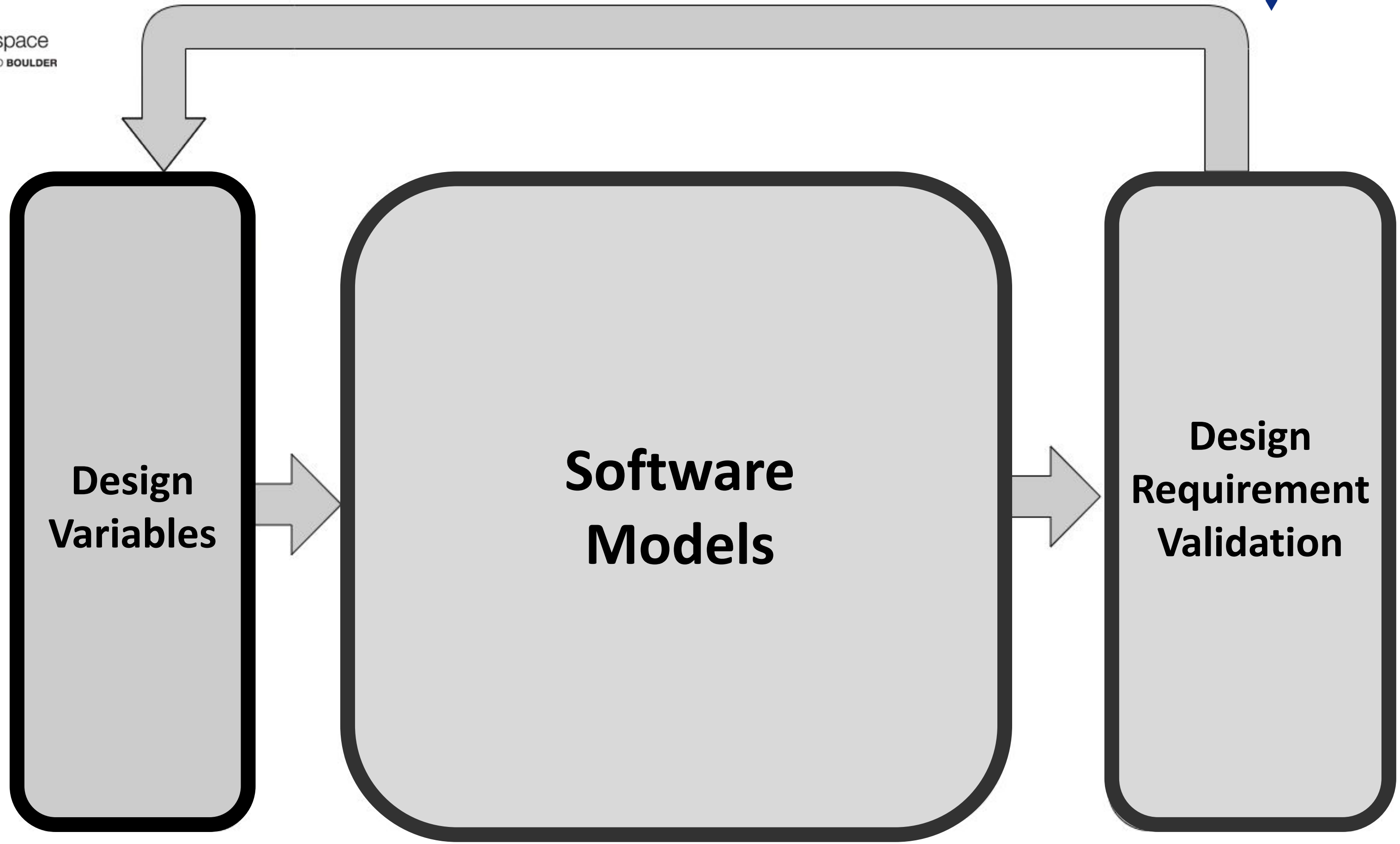


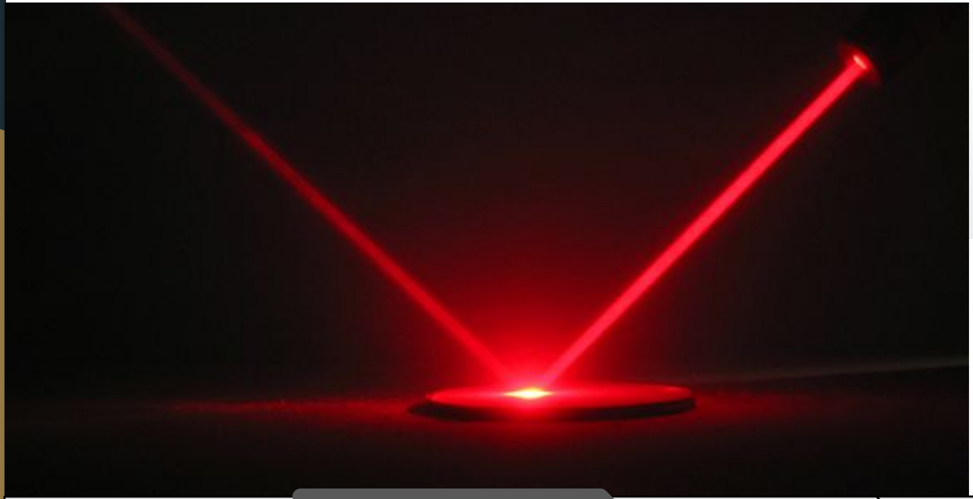
Critical Project Elements

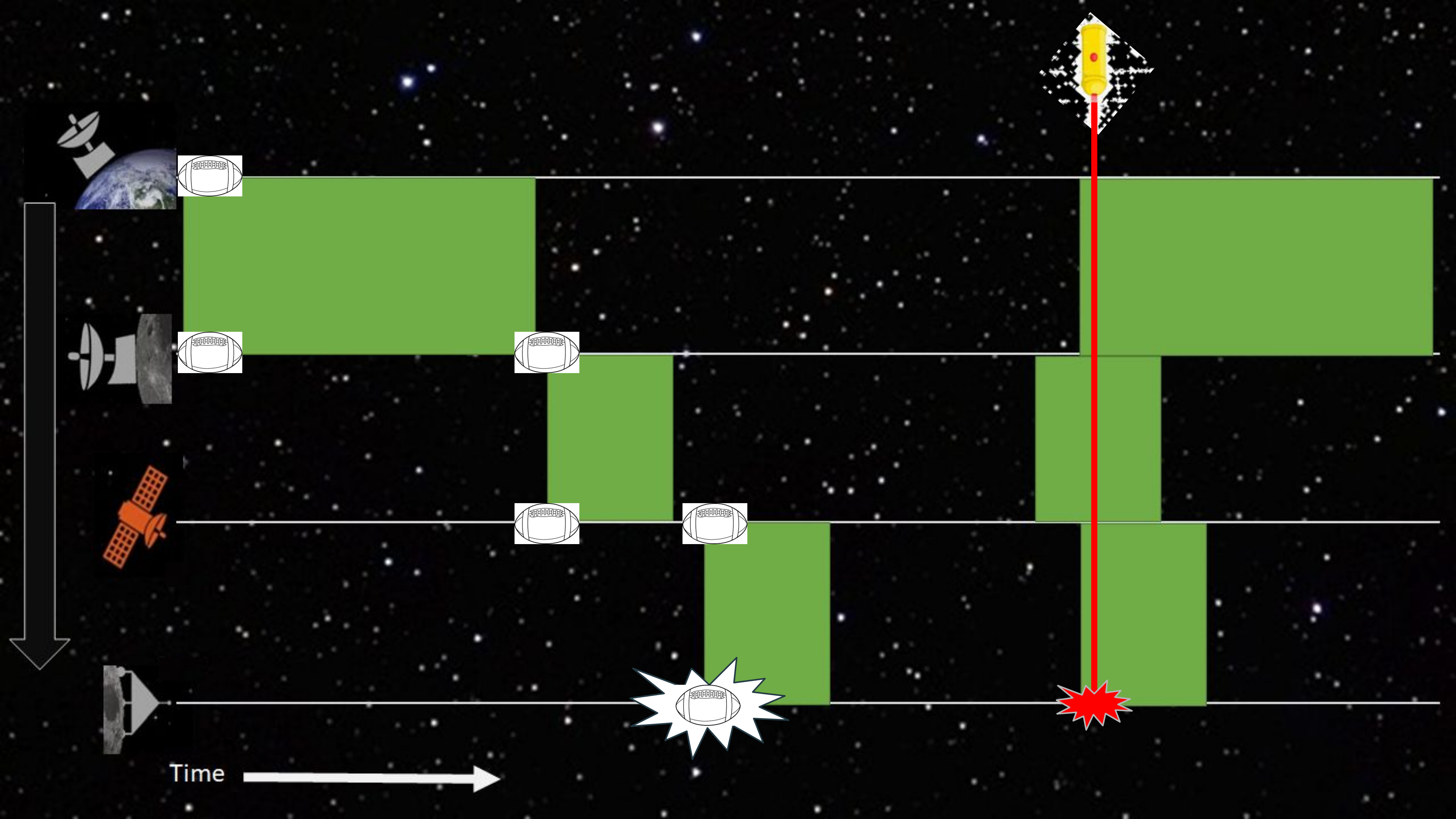
Designation	CPE	Critical Characteristics
CPE-1	Network Protocol	Structured data transmission methodology that allows for high speed reliable communications from node to node.
CPE-2	System Link Budgets	The project will meet certain data-relay rates for communication between all communication nodes.
CPE-3	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.

Network Protocol

DTN

TCP/IP

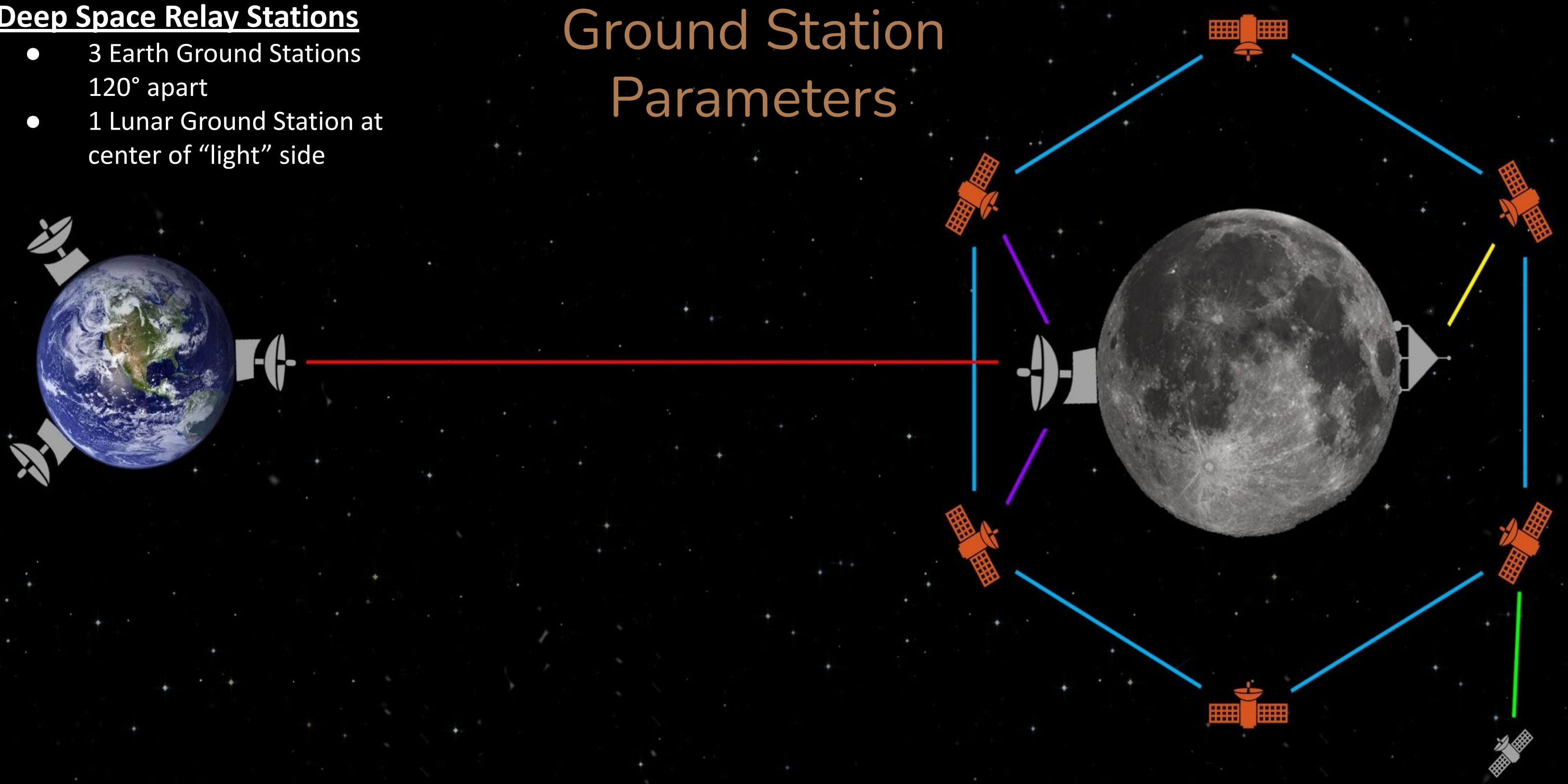



Time

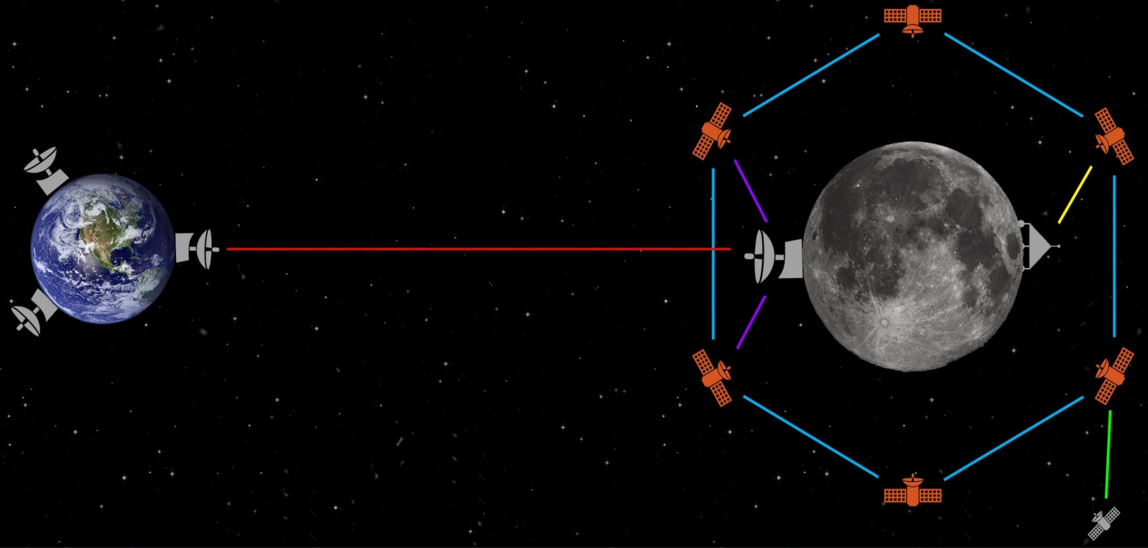
Ground Station Parameters

Deep Space Relay Stations

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



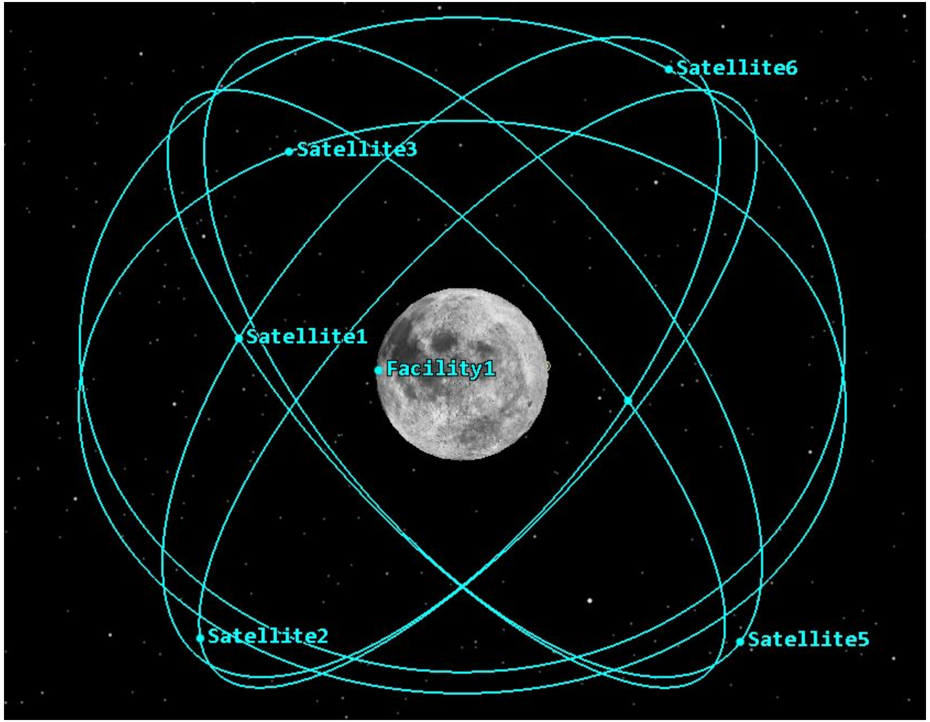
System Link Budgets



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	11,000 km	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

Constellation Parameters

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



Test Overview

Project Overview | Design Description | **Test Overview** | Test Results | Systems Engineering | Project Management

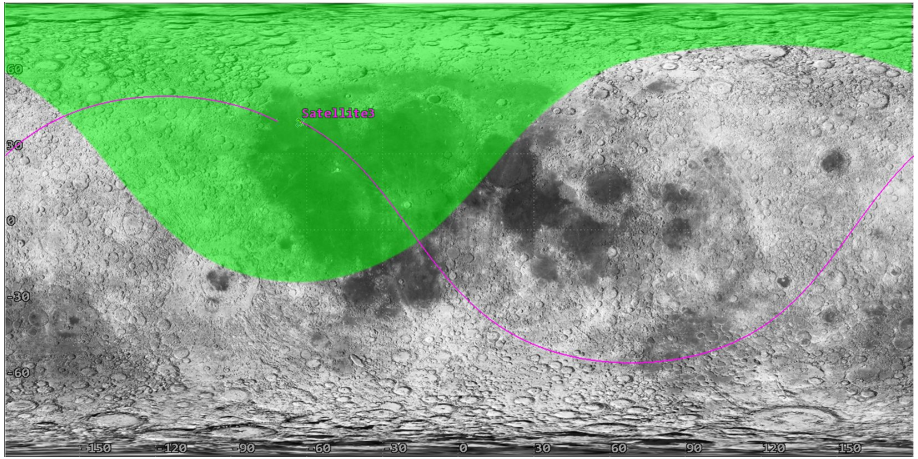
Network Coverage

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



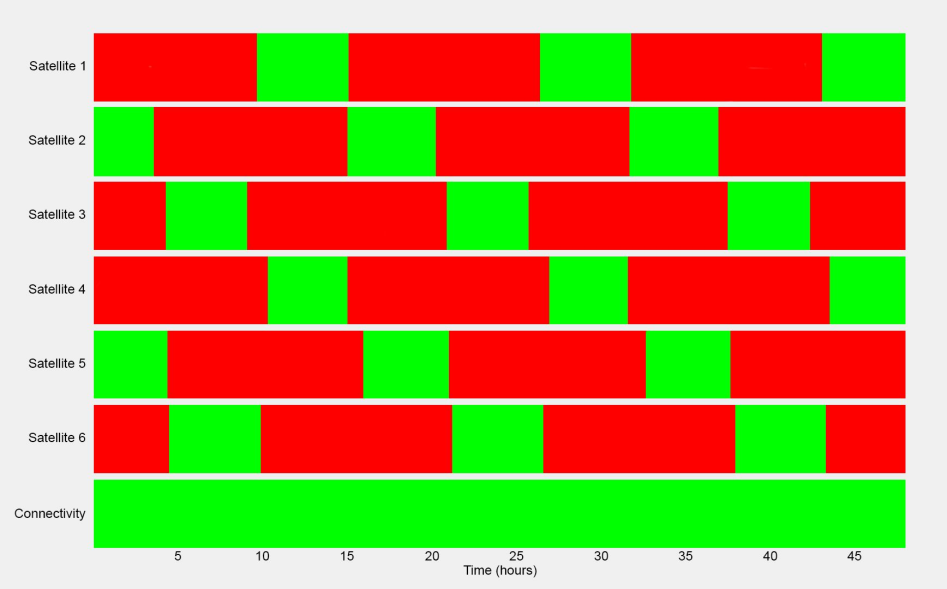
Continuous Connection

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**



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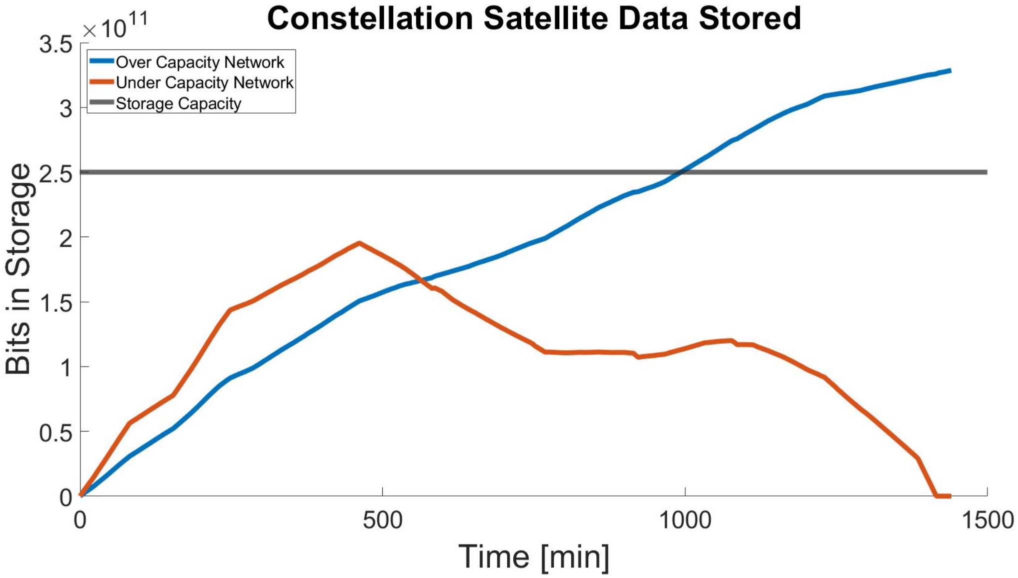
Data Rate Optimization

<u>Desired Outcomes</u>

- Satisfy **functional requirement 2** - endpoint support.

<u>Test Design:</u>

- Model of network configuration in MATLAB.
- Designed to determine the minimum required data rate on the constellation satellites for minimizing power required.



Power Optimization Test

Desired Outcomes:

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

Test Design:

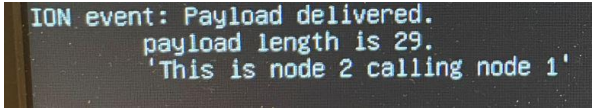
1. Vary key design parameters and observe the **impact to** transmission power required
2. Performed using the **Link Budget** MatLab software model

Network Protocol: Hardware Validation

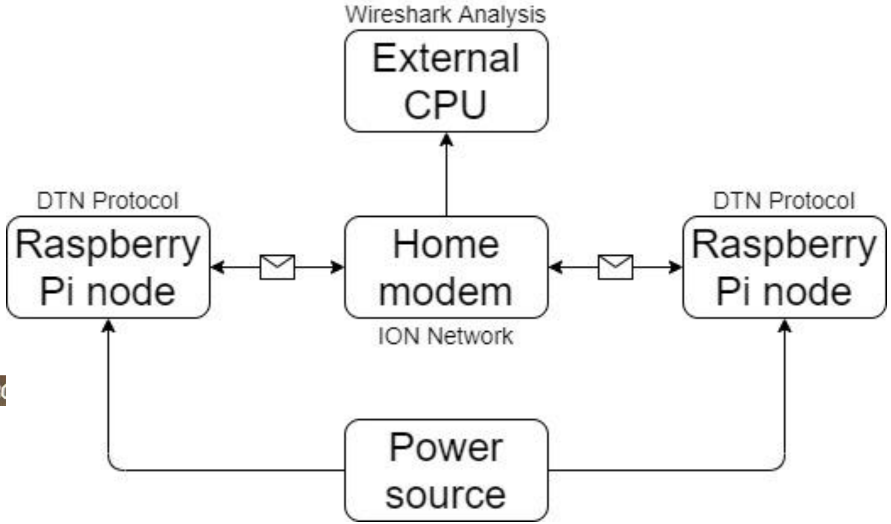
Test Purpose and Design:

1. Validate capacity model calculation method through **hardware comparison** and provide proof of concept**.**

Input (node 2):



Output (node 1):

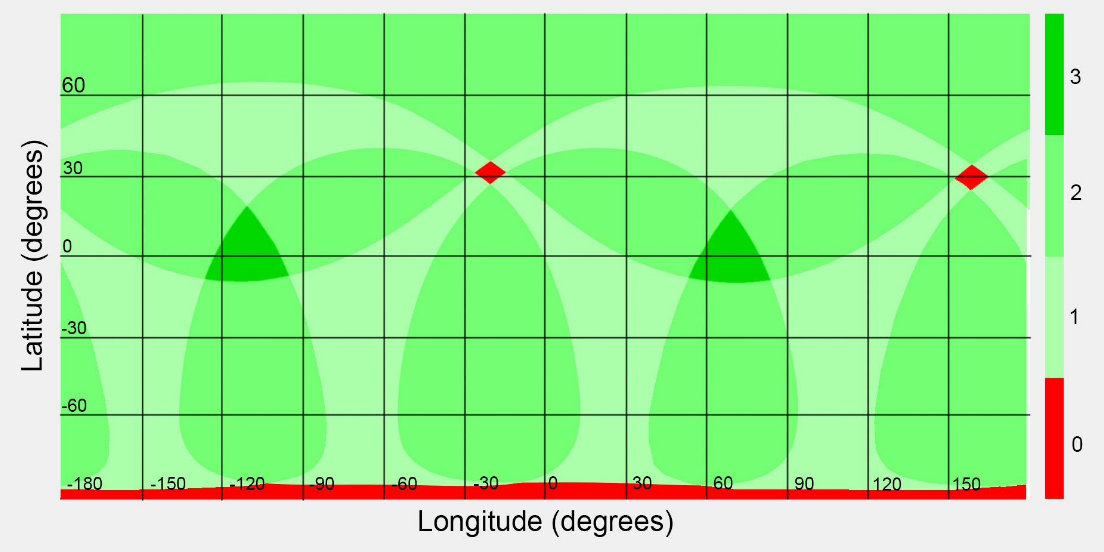


Test Results

Project Overview | Design Description | Test Overview | **Test Results** | Systems Engineering | Project Management

Network Coverage - Baseline

- Met and exceeded coverage requirements. Area coverage varied between 100% and 99.4%.
- Areas without coverage made up 0.0376% of all points considered



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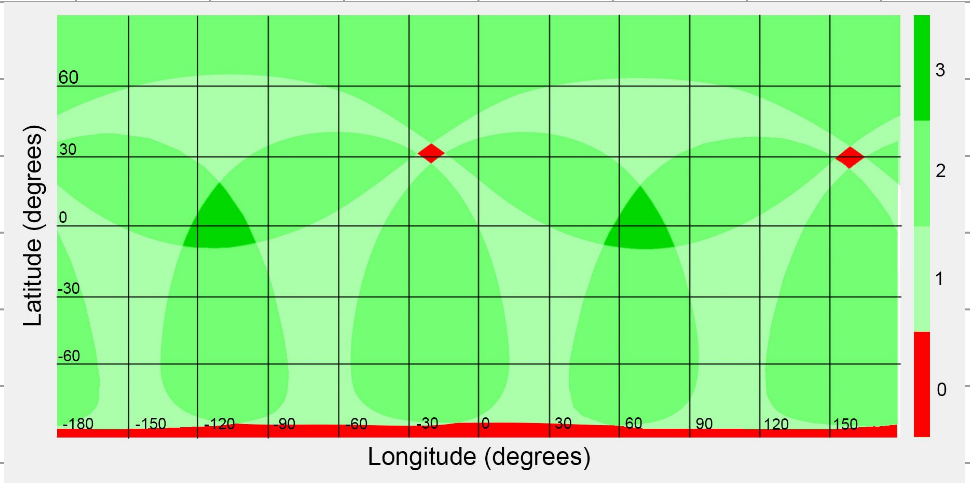
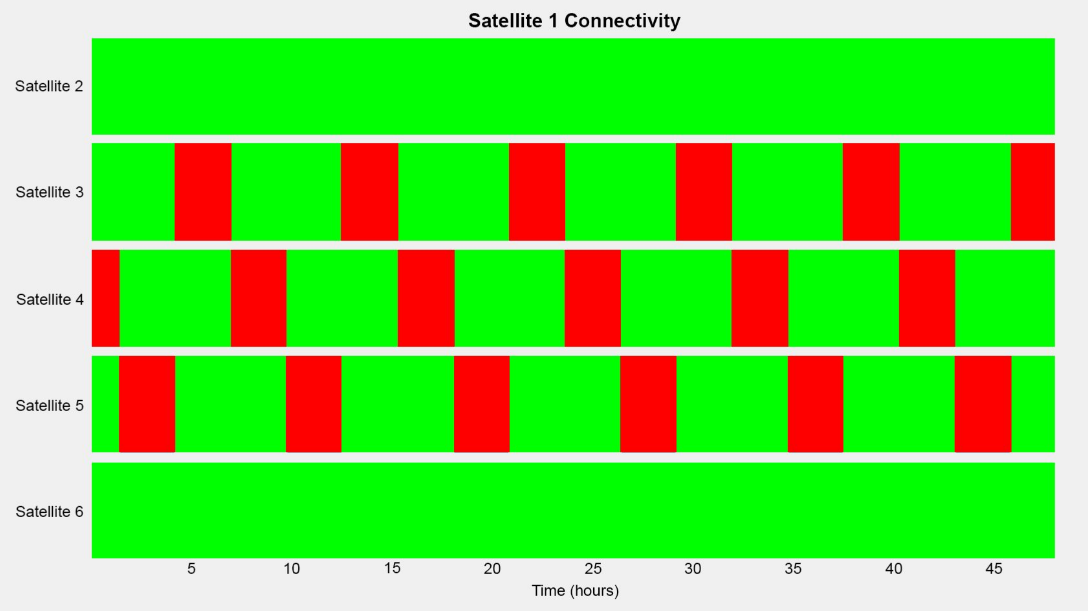
Network Coverage - Multiple Coverage

	Coverage (%)										
Configuration	0x	1x	2x	3x	4x	5x	6x	7x	8x	9x	10x
6/6/4	0.038	38.7	57.9	3.41	0	0	0	0	0	0	0
12/12/10	0	0								0	0
12/6/4	0	0								0	0
15/15/2	0	0								0	0
18/6/4	0	0								0	0
15/15/6	0	0								2.16	0.137
24/6/4	0	0								9.39	2.37



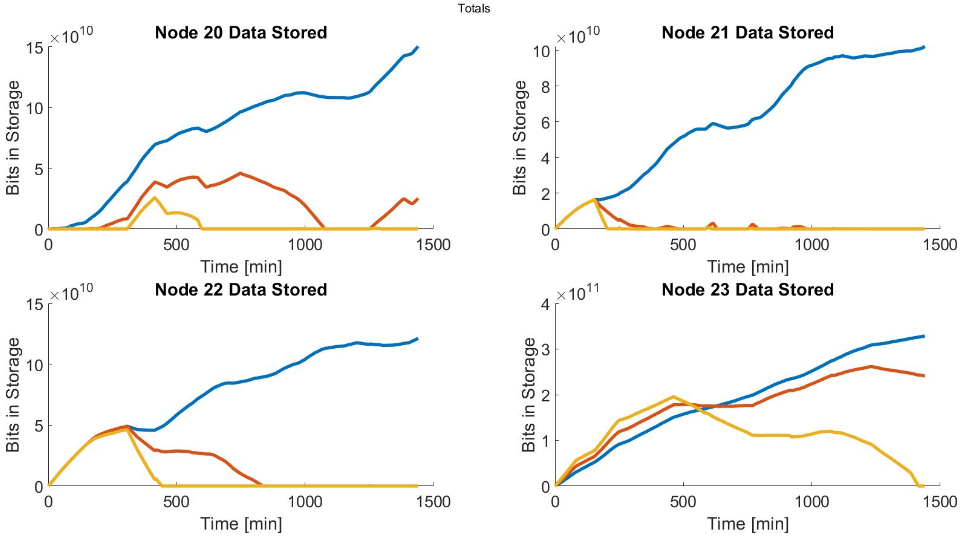
Continuous Connection

- Adjacent satellites are always able to connect
- Configurations with persistent, 100% coverage (all except baseline) have universal continuous connection eligibility



Data Rate Optimization

- Number of nodes modeled: 45 - met FR2 node support requirements.
- Minimum data rate in constellation satellites: 35.4 Mbps.
- Minimum data rate then utilized in link budgets.
- Can easily utilize different network configurations for future needs.



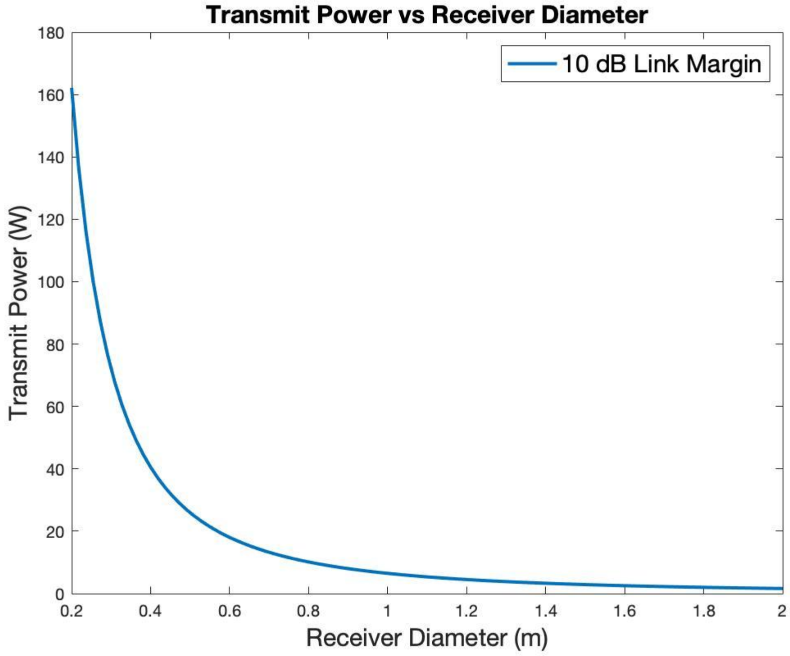
Power Optimization Test

Test Purpose and Design:

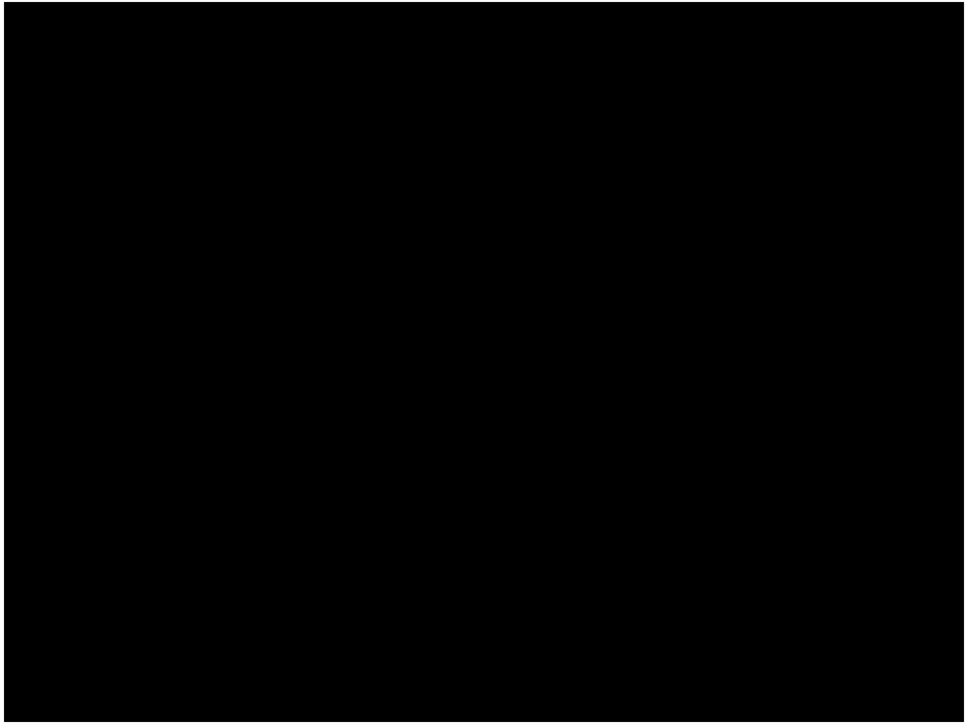
1. **Minimize power required** in the system
2. Vary key design parameters and observe the **impact to** transmission power required

Test Results:

1. Minimized the power (42 W Transmission Power) throughout the system while also meeting data rate requirements needed to meet **FR 2**



Hardware



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Network Structure Modeling

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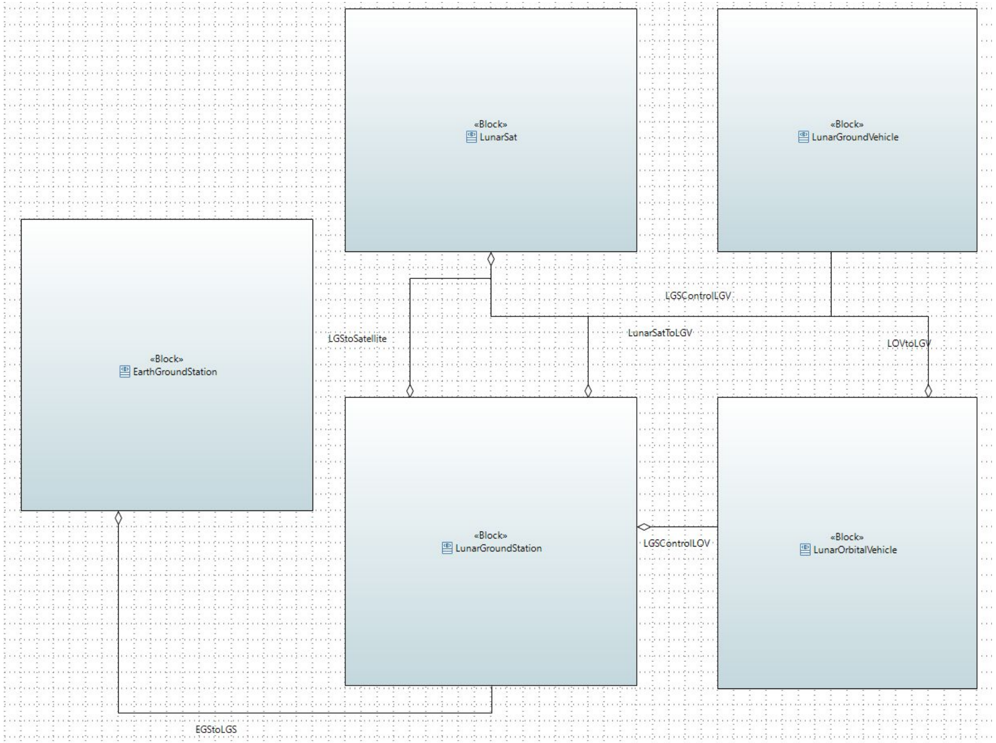
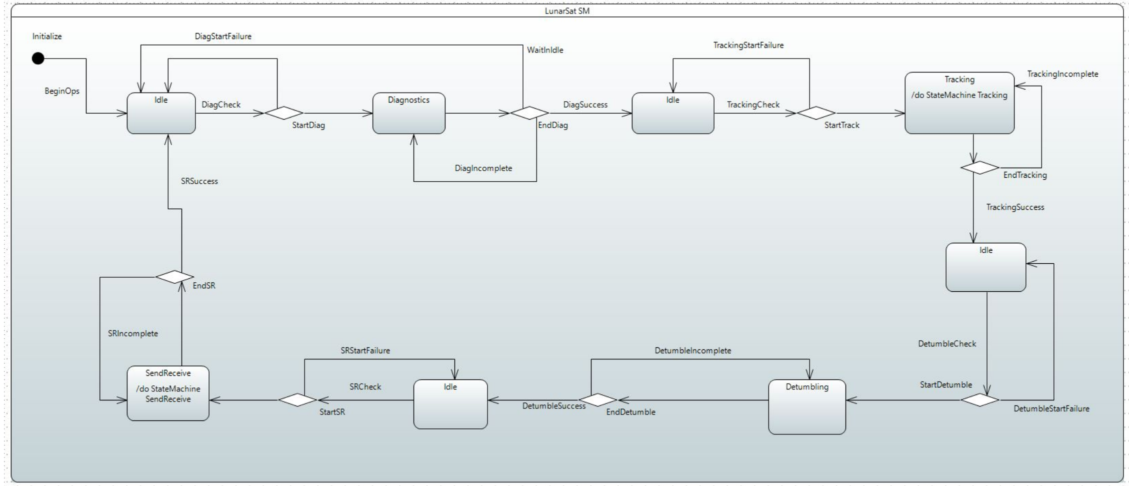
- First pillar of SysML modeling
- Two main forms:
    - Data connections between nodes
    - Internal structure and design of nodes
- Node properties informed via network design (architecture, link budgeting, etc.) and built from SysML palette of connections/structural tools
- Closely mirrors CONOPS as a baseline framework



Network Behavior Modeling

- Second pillar of SysML modeling
- Again, two main forms:
  - Network reaction to new connections
  - Data packet behavior through network nodes
- Behavioral properties of nodes informed through study of existing structure
- Some behavior left “high-level” due to dependency on established network hardware design (e.g. satellite pointing control)



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Requirement Verification

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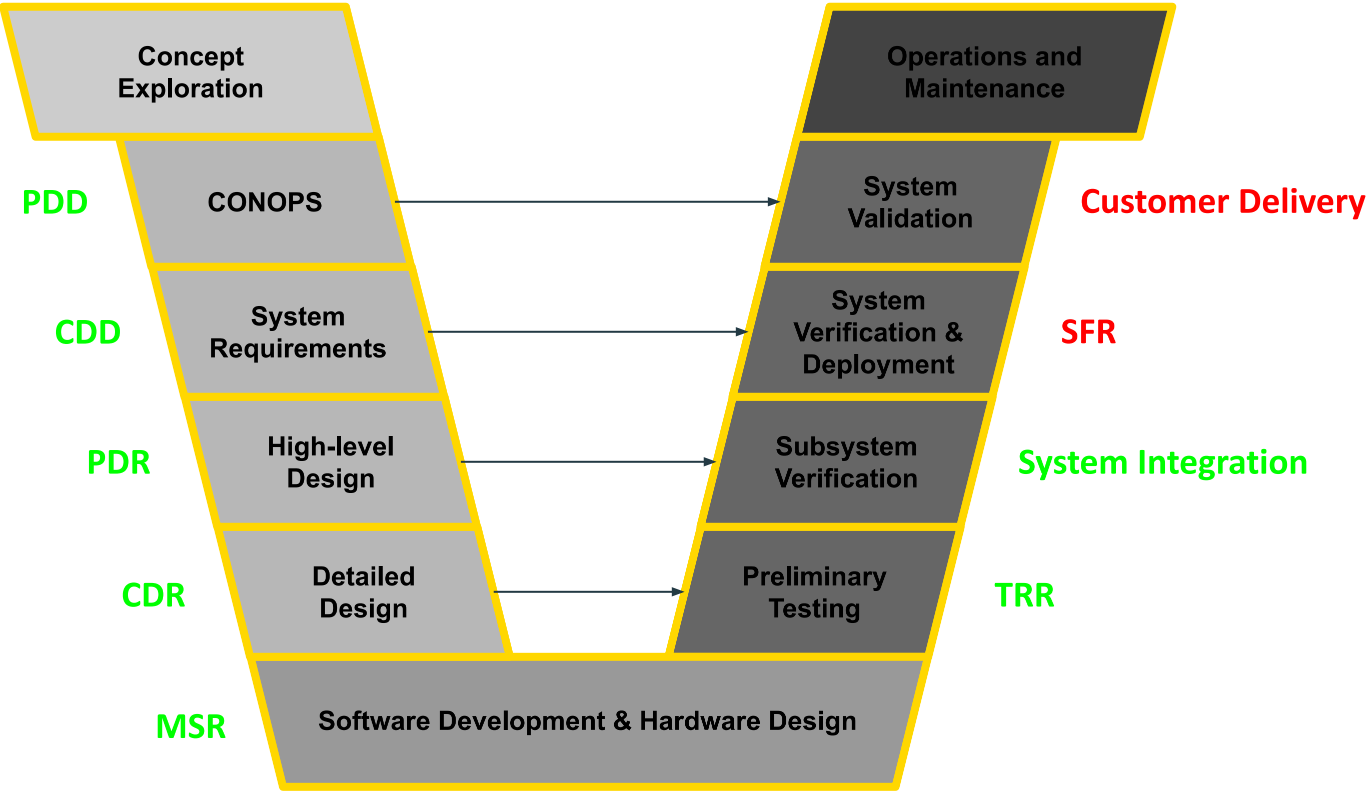
- Verification through MBSE/SysML required as per GA directives
- Requirement matrices allow "checking off" of system requirements
- Compliance drawn from various test results & simulation vs. performance targets

	R-005: Data relay between ...	R-008: Simultaneous comm...	R-009: Non-simultaneous co...	R-010: Simultaneous comm...
LunarOrbitalVehicle	☐	☐	☐	☐
LOVtoLGV	☐	☐	☐	☐
LGStoSatellite	☐	☐	☐	☐
LunarSatToLGV	☐	☑	☑	☐
lunargroundvehicle : LunarGro...	☐	☐	☑	☐
lunarsat : LunarSat [6]	☐	☐	☑	☐
EGStoLGS	☑	☐	☐	☐
lunargroundstation : LunarGro...	☐	☐	☐	☐
earthgroundstation : EarthGro...	☐	☐	☐	☐
LGSControlLOV	☐	☐	☐	☑
LGSControlLGV	☐	☐	☐	☐
Earth Segment	☐	☐	☐	☐
MoonSegment	☐	☐	☐	☐
LunarSatDTNHistory	☐	☐	☑	☐
LunarGroundStationDTNHistory	☐	☐	☐	☐

Systems Engineering

Project Overview | Design Description | Test Overview | Test Results | **Systems Engineering** | Project Management

Systems Engineering V



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Key Challenges

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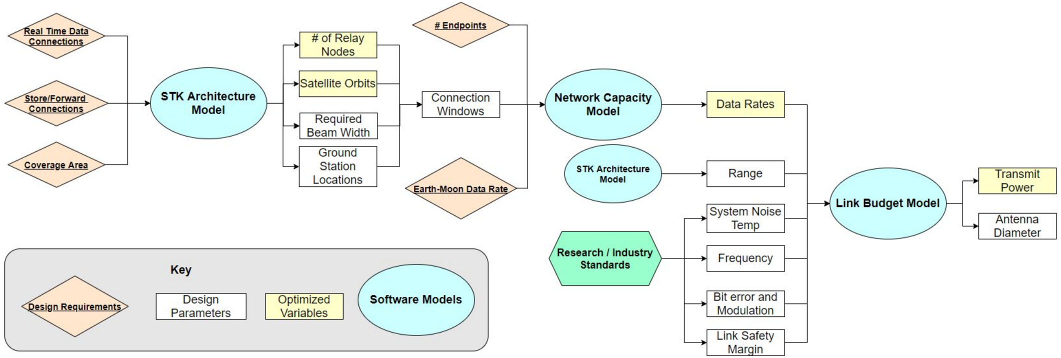
1. MBSE Cross-team Integration (**CTI**)
   a. Link Budget interface with MBSE
2. Raspberry Pi DTN Integration (**RPI**)
3. Network Capacity Model (**NCP**)

CDR Risk Assessment:

Likelihood \ Severity	Negligible	Minor	Moderate	Major	Cata-strophic
Almost Certain					
Likely			**RPI**		
Possible				**NCP**	
Unlikely					
Rare					**CTI**

Systems Engineering - Key Lessons

1. Trade studies at the research level
2. Infrastructure management
3. Limiting design requirement scope



Project Management

Project Overview → Design Description → Test Overview → Test Results → Systems Engineering → **Project Management**

Management Summary

- Approach: Agile, Sub-Team Driven
- Difficulties:
  - Initial task breakdowns and scheduling (Gantt Chart)
  - Completing spin-off projects
  - Balancing Customer and PAB requirements
- Successes:
  - Amount of scope covered
  - Initial organization
  - Growth between Team & PAB
- Lessons Learned:
  - No such thing as over-communication
  - Use resources as much as possible
  - Bigger project = longer planning

Costs

Initial Budget (CDR)
Raspberry Pi (7)
Monitors (7)
Keyboards (7)
SD cards (7)
Ethernet Cables (14)
HDMI Cables (7)
Power Cables (7)
Total: $1,528.45

Final Budget
Raspberry Pi (3)
Monitors (2)
SD Cards (3)
Keyboards (2)
HDMI Cables (2)
Ethernet Cables (2)
Total: $645.83

Industry Cost	
Aerospace Engineers	$28,656
Overhead	$57,312
Materials	$646
Total	$86,614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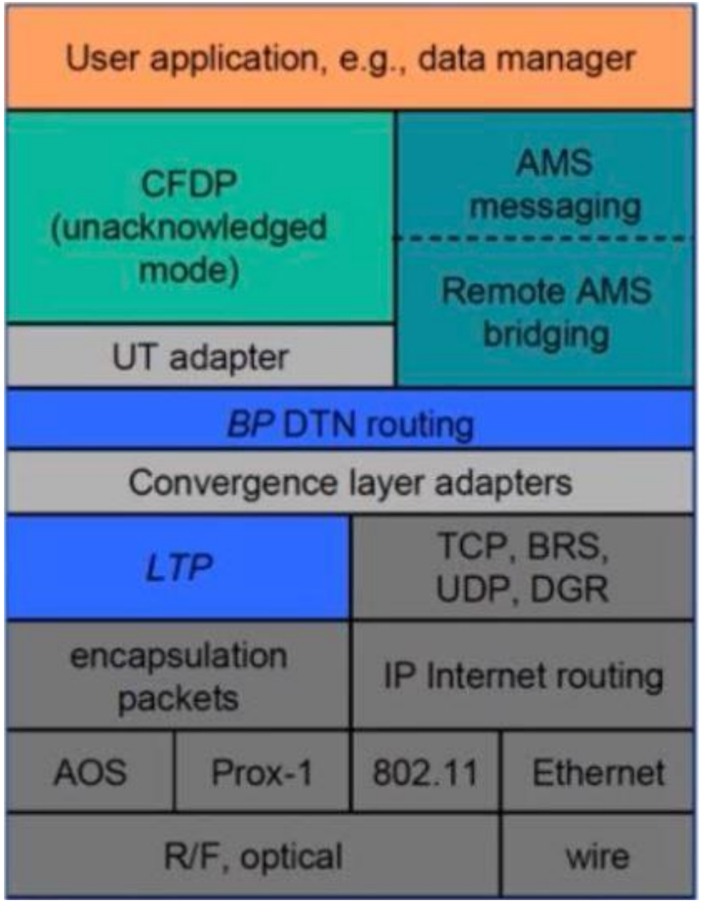
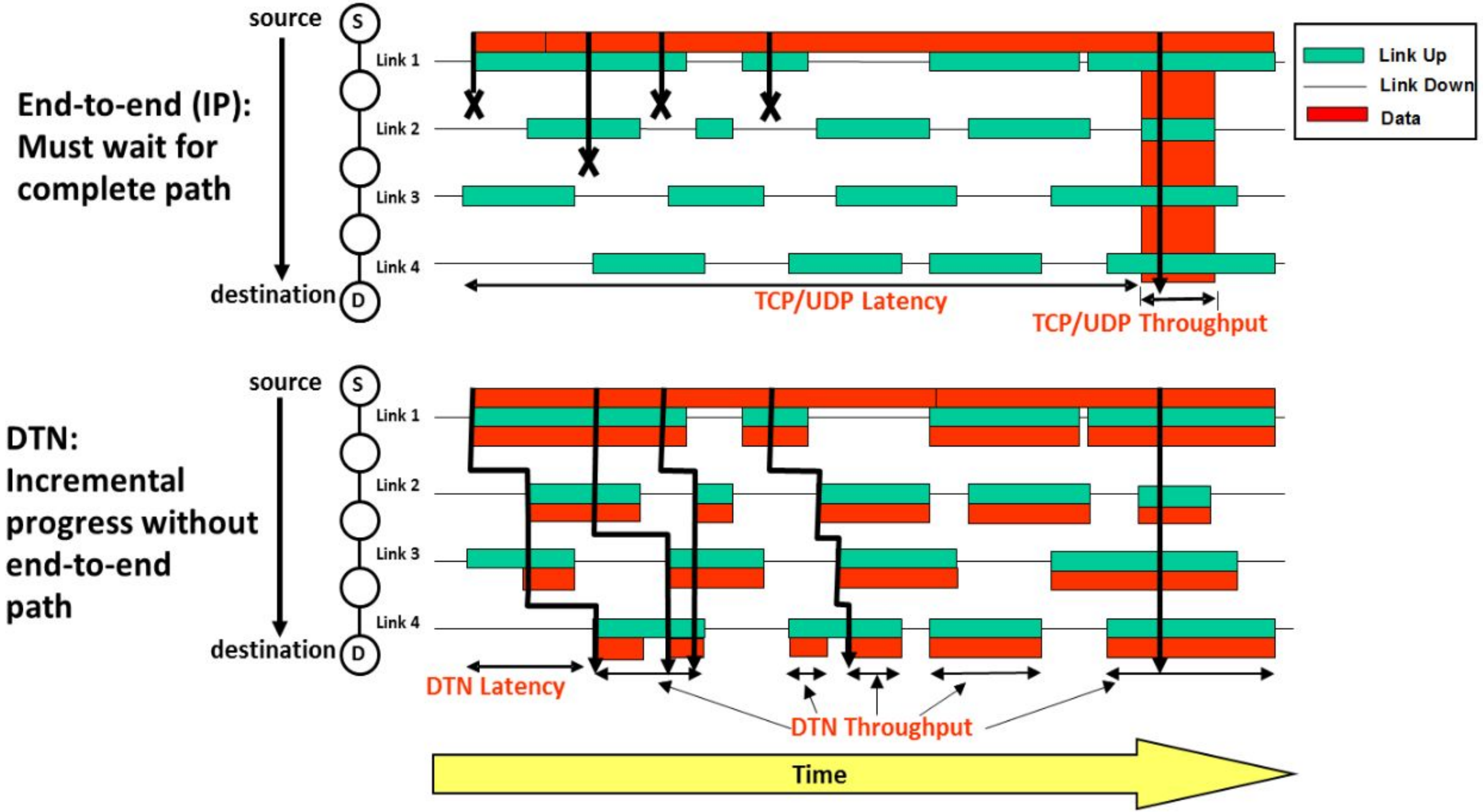
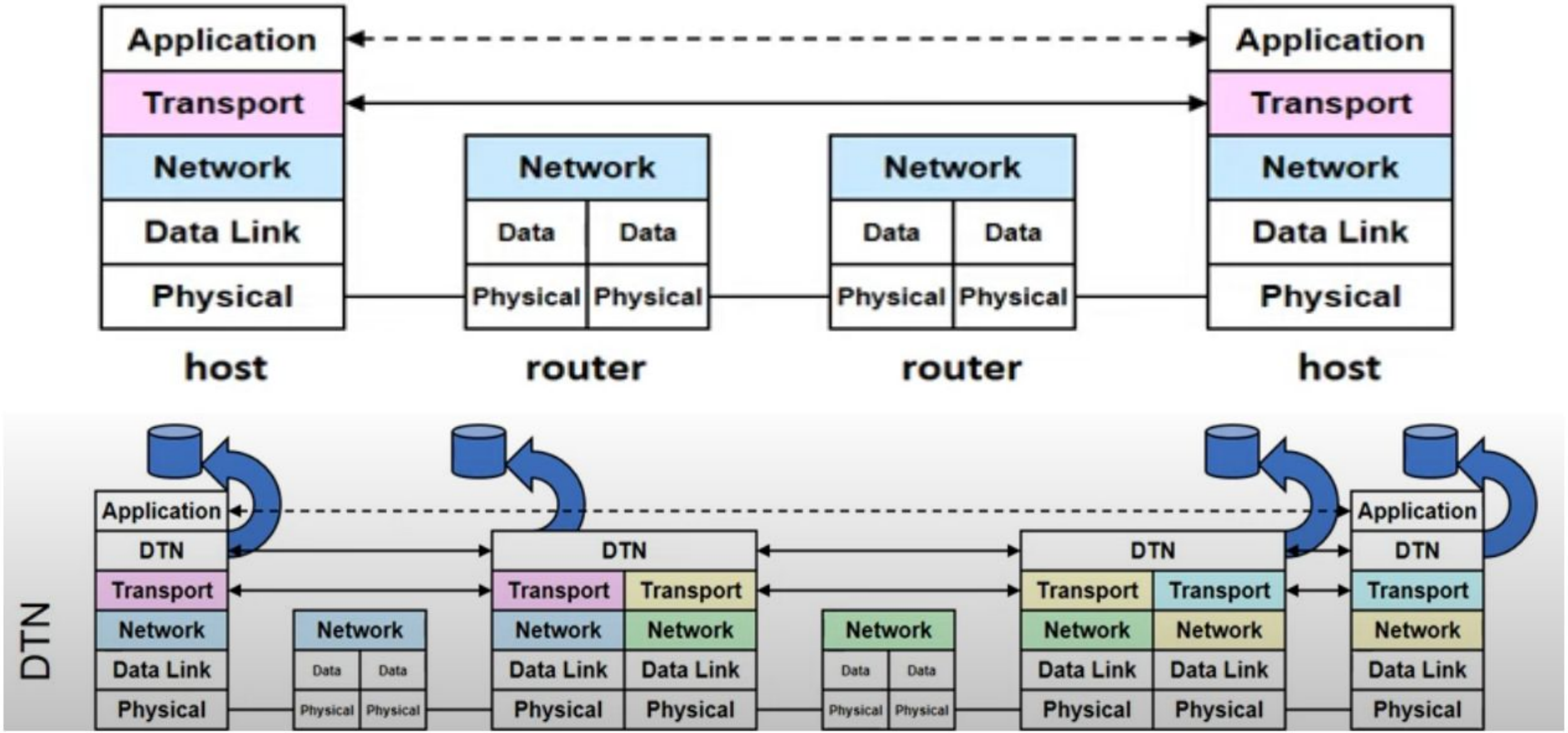
Questions?

APPENDIX


User application, e.g., data manager
CFDP (unacknowledged mode)
AMS messaging
Remote AMS bridging
UT adapter
BP DTN routing
Convergence layer adapters
LTP
TCP, BRS, UDP, DGR
encapsulation packets
IP Internet routing
AOS
Prox-1
802.11
Ethernet
R/F, optical
wire



End-to-end (IP): Must wait for complete path
source
destination
S
D
Link 1
Link 2
Link 3
Link 4
Link Up
Link Down
Data
TCP/UDP Latency
TCP/UDP Throughput
DTN: Incremental progress without end-to-end path
DTN Latency
DTN Throughput
Time


Application
Transport
Network
Data Link
Physical
host
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Data
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router
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router
Application
Transport
Network
Data Link
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Application
DTN
Transport
Network
Data Link
Physical

Network Capacity Model

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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

Link Budget Validation Tests

- Study on Intersatellite Link Antenna
- AMSAT IARU Link Budget Calculator
  - Trade off of satellite antennas with associated link budgets

Variable	Satellite Study Results	Link Budget Model Calculations
C/N_O	87.04 dbHz	85.04 dbHz
Link Margin	37.99 dBHz	35.99 dBHz

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

Walker-Delta Constellation Configuration

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

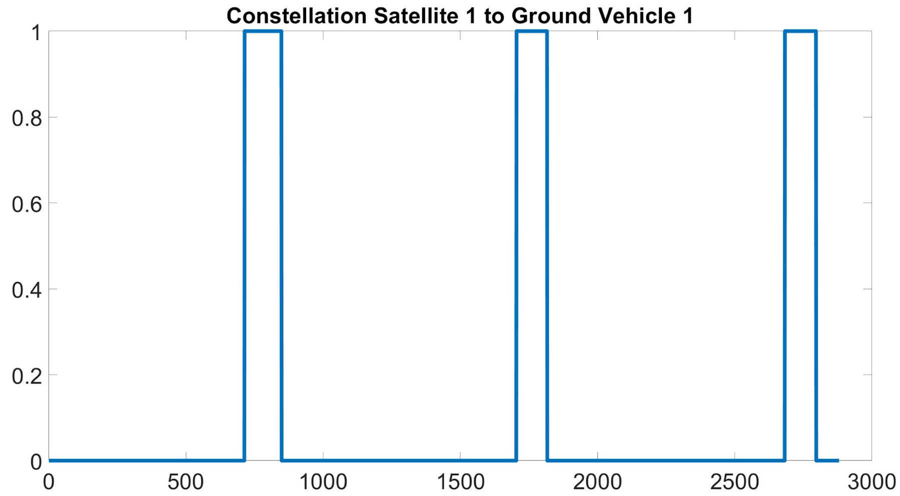
Configuration has format T/P/F

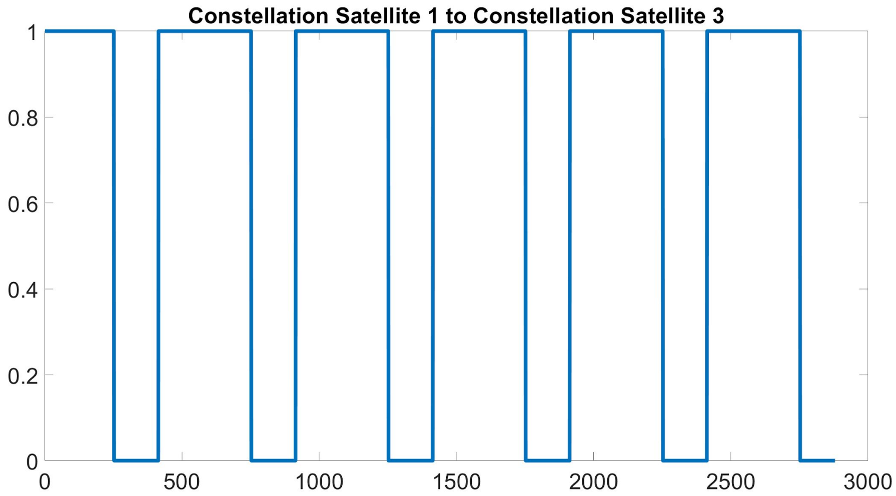
RAAN separation = 360°/P

v separation = F * RAAN separation

i = 60° = constant

Connection Window Examples





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.

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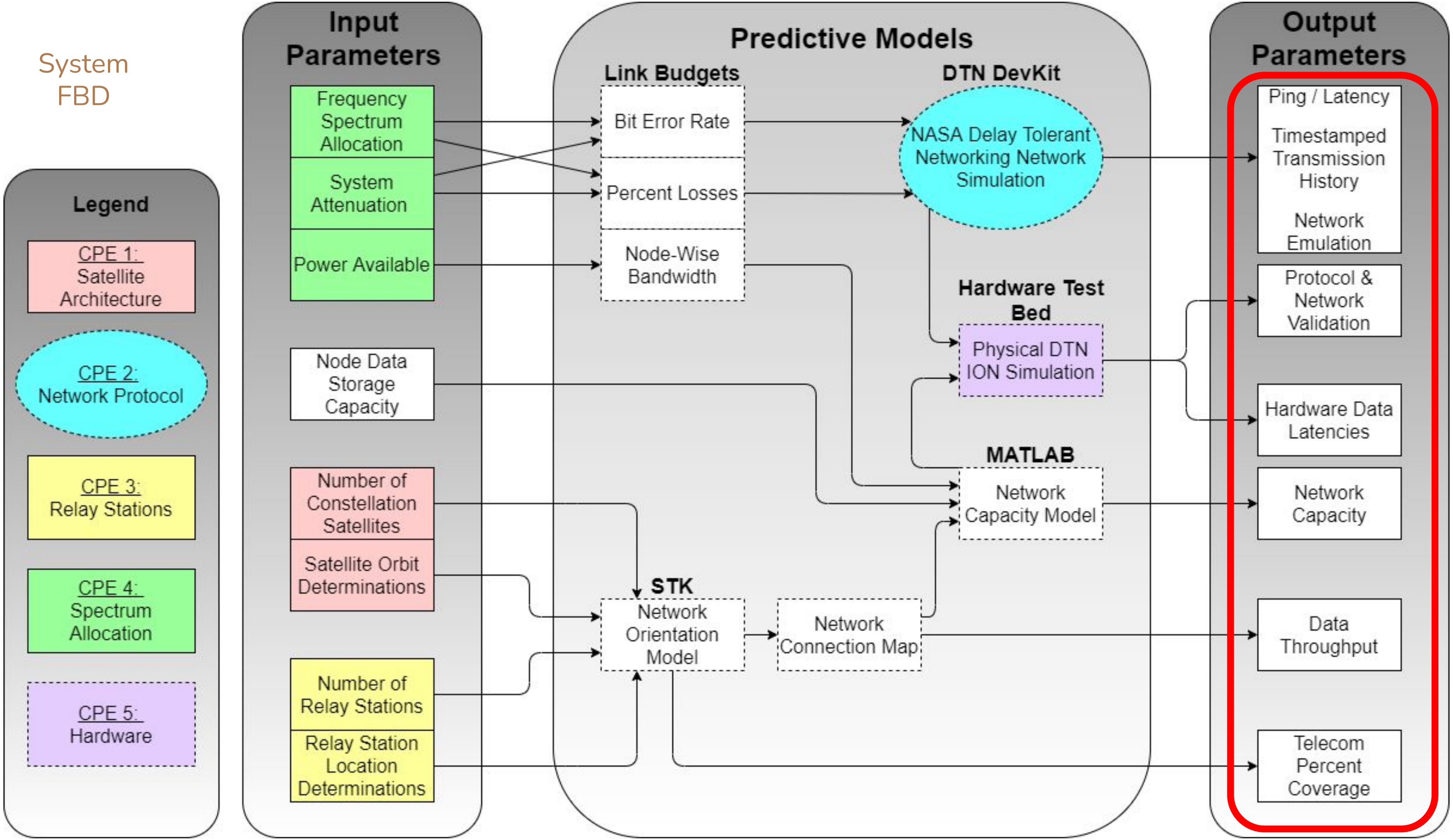
		A	B
		name : String [0..1]	/satisfiedBy : NamedElement [*]
0	/ownedElement		
1	FR-1: Comms must have transmit/receive capability simultaneously & non-simultaneously between Earth, Moon, Mars.	FR-1: Comms must have transmit/receive capability simultaneously & non-simultaneously between Earth, Moon, Mars.	x
2	/ownedElement		
3	R-001: Real time data relay between environments	R-001: Real time data relay between environments	AntennalO, AntennalO, AntennalO
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

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

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