



THE UNIVERSITY OF TEXAS AT EL PASO

LDS Design

NG / UTEP Final
Presentation

Agenda

- **Team introduction**
- **Mission Overview**
- **Concept of Operations**
- **Requirements**
 - **Requirement Flow down**
 - **Requirement Verification and Validation**
- **Trade Studies**
- **Design Concept**
- **Integration and Test**
- **Risk Assessment**
- **Proposed Future Work**

Team Introductions

Ryan Flores – Aerospace Engineering

Kelly Gomez – Aerospace Engineering

Luis Salinas – Aerospace Engineering

Sergio Palacios – Industrial & System Engineering

Rodrigo Reynoso – Industrial & System Engineering

Dimitri Bellakis – Industrial & System Engineering

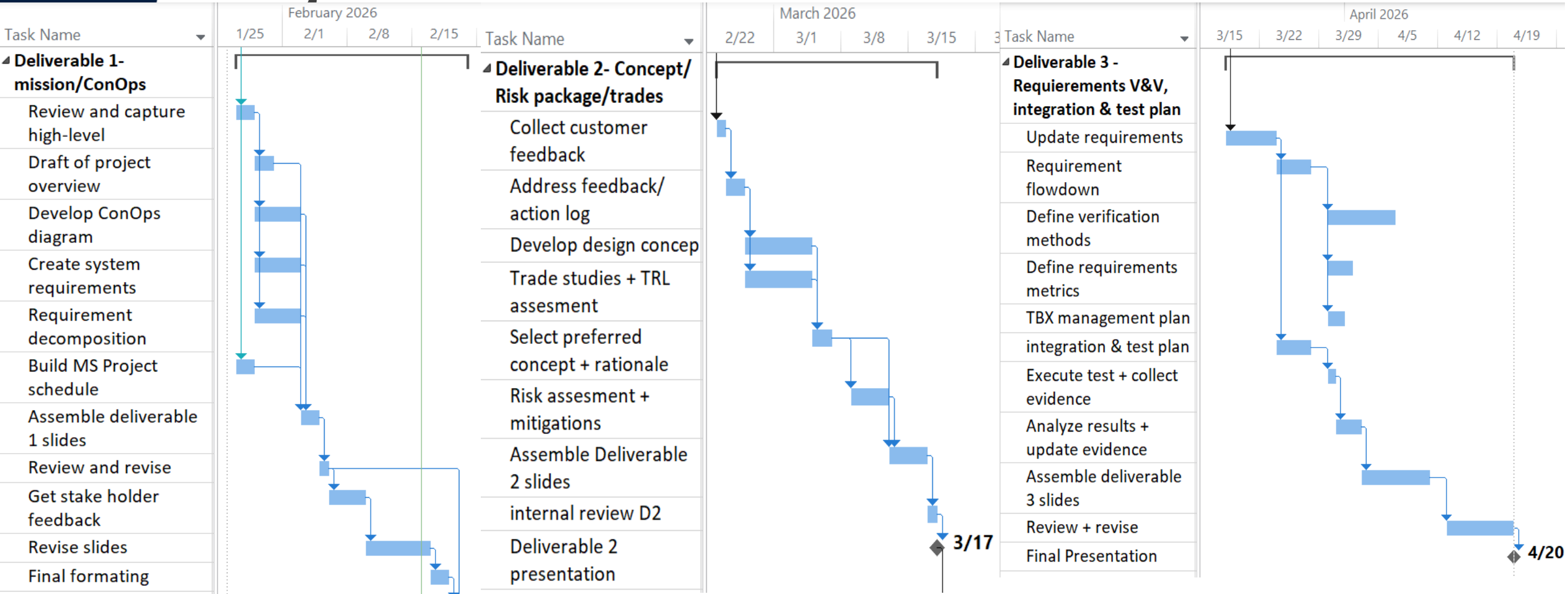
Project Schedule

Project kickoff & team introduction	1 day	Mon 1/26/26	Mon 1/26/26	
Deliverable 1- mission/ConOps	19 days?	Tue 1/27/26	Fri 2/20/26	
Review and capture high-level	2 days	Tue 1/27/26	Wed 1/28/26	1
Draft of project overview	2 days	Thu 1/29/26	Fri 1/30/26	3
Develop ConOps diagram	3 days	Thu 1/29/26	Mon 2/2/26	3
Create system requirements	3 days	Thu 1/29/26	Mon 2/2/26	3
Requirement decomposition	3 days	Thu 1/29/26	Mon 2/2/26	3
Build MS Project schedule	2 days	Tue 1/27/26	Wed 1/28/26	1
Assemble deliverable 1 slides	2 days	Tue 2/3/26	Wed 2/4/26	4,5,6,7,8
Review and revise	1 day?	Thu 2/5/26	Thu 2/5/26	9
Get stake holder feedback	2 days	Fri 2/6/26	Mon 2/9/26	10

Task Name	Duration	Start	Finish	Predecessors
Revise slides	5 days	Tue 2/10/26	Mon 2/16/26	11
Final formating	2 days	Tue 2/17/26	Wed 2/18/26	12
Rehersal for presentation	2 days	Thu 2/19/26	Fri 2/20/26	13
Deliverable 1 Presentation	0 days	Fri 2/20/26	Fri 2/20/26	10,14
Deliverable 2- Concept/ Risk package/trades	17 days	Mon 2/23/26	Tue 3/17/26	
Collect customer feedback	1 day	Mon 2/23/26	Mon 2/23/26	15
Address feedback/ action log	2 days	Tue 2/24/26	Wed 2/25/26	17
Develop design concep	5 days	Thu 2/26/26	Wed 3/4/26	18
Trade studies + TRL assesment	5 days	Thu 2/26/26	Wed 3/4/26	18
Select preferred concept + rationale	2 days	Thu 3/5/26	Fri 3/6/26	19,20
Risk assesment + mitigations	4 days	Mon 3/9/26	Thu 3/12/26	21
Assemble Deliverable 2 slides	2 days	Fri 3/13/26	Mon 3/16/26	21,22

Task Name	Duration	Start	Finish	Predecessors
Assemble Deliverable 2 slides	2 days	Fri 3/13/26	Mon 3/16/26	21,22
internal review D2	1 day	Tue 3/17/26	Tue 3/17/26	23
Deliverable 2 presentation	0 days	Tue 3/17/26	Tue 3/17/26	24
Deliverable 3 - Requierements V&V, integration & test plan	24 days?	Wed 3/18/26	Mon 4/20/26	
Update requirements	4 days	Wed 3/18/26	Mon 3/23/26	25
Requirement flowdown	4 days	Tue 3/24/26	Fri 3/27/26	27
Define verification methods	6 days	Mon 3/30/26	Mon 4/6/26	28
Define requirements metrics	3 days	Mon 3/30/26	Wed 4/1/26	28
TBX management plan	2 days	Mon 3/30/26	Tue 3/31/26	28
integration & test plan	4 days	Tue 3/24/26	Fri 3/27/26	27
Execute test + collect evidence	1 day?	Mon 3/30/26	Mon 3/30/26	32
Analyze results + update evidence	3 days	Tue 3/31/26	Thu 4/2/26	33
Assemble deliverable 3 slides	6 days	Fri 4/3/26	Fri 4/10/26	34
Review + revise	6 days	Mon 4/13/26	Mon 4/20/26	35
Final Presentation	0 days	Mon 4/20/26	Mon 4/20/26	36

Project Schedule



Mission Overview

The goal of this project is to design a spacecraft optimized for deep space missions while ensuring the ability to reliably communicate with Earth's ground stations.

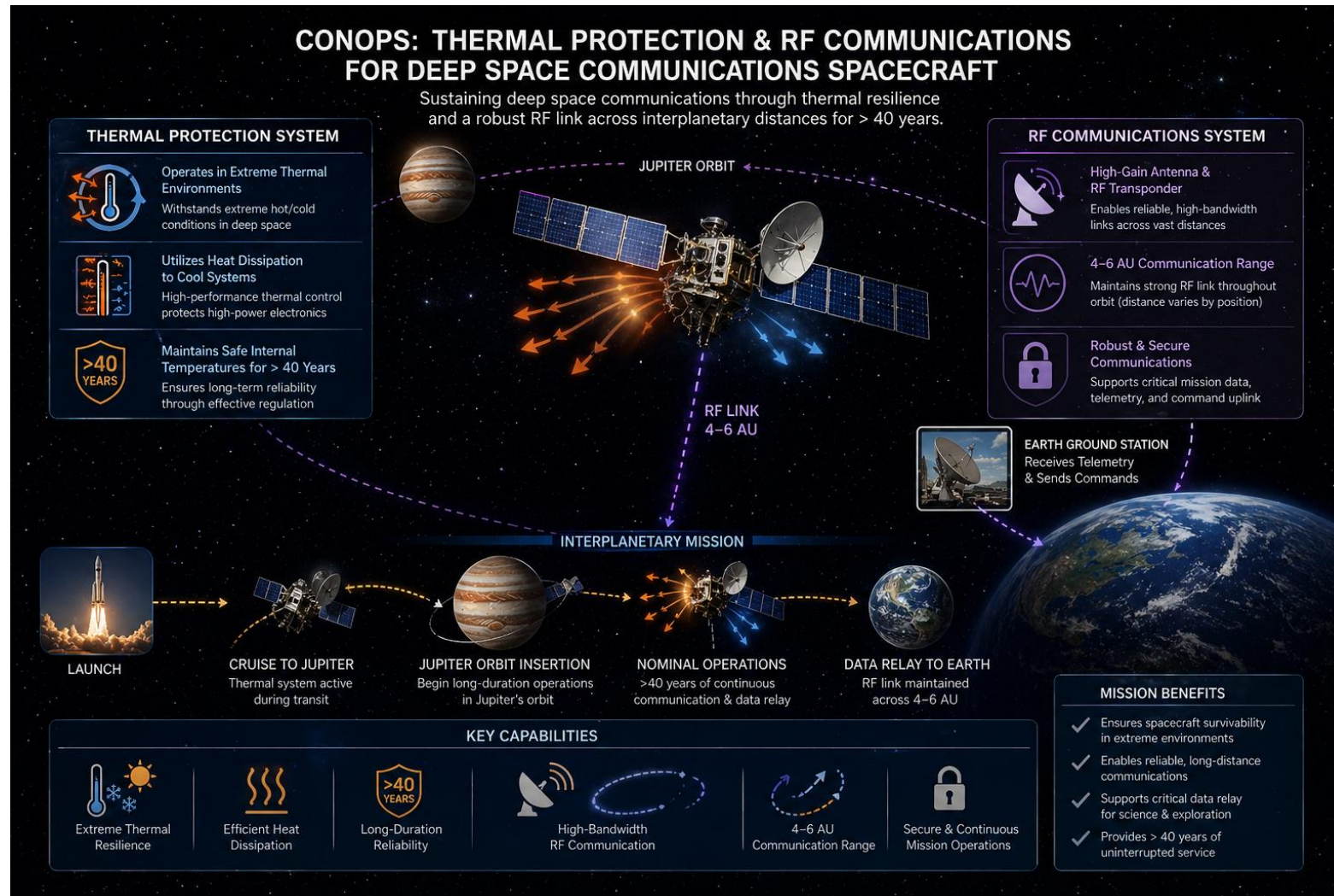
Objective:

Design a communication system capable of deep space communications to ground stations supporting reliable, long-duration data transmission between the satellite and Earth.

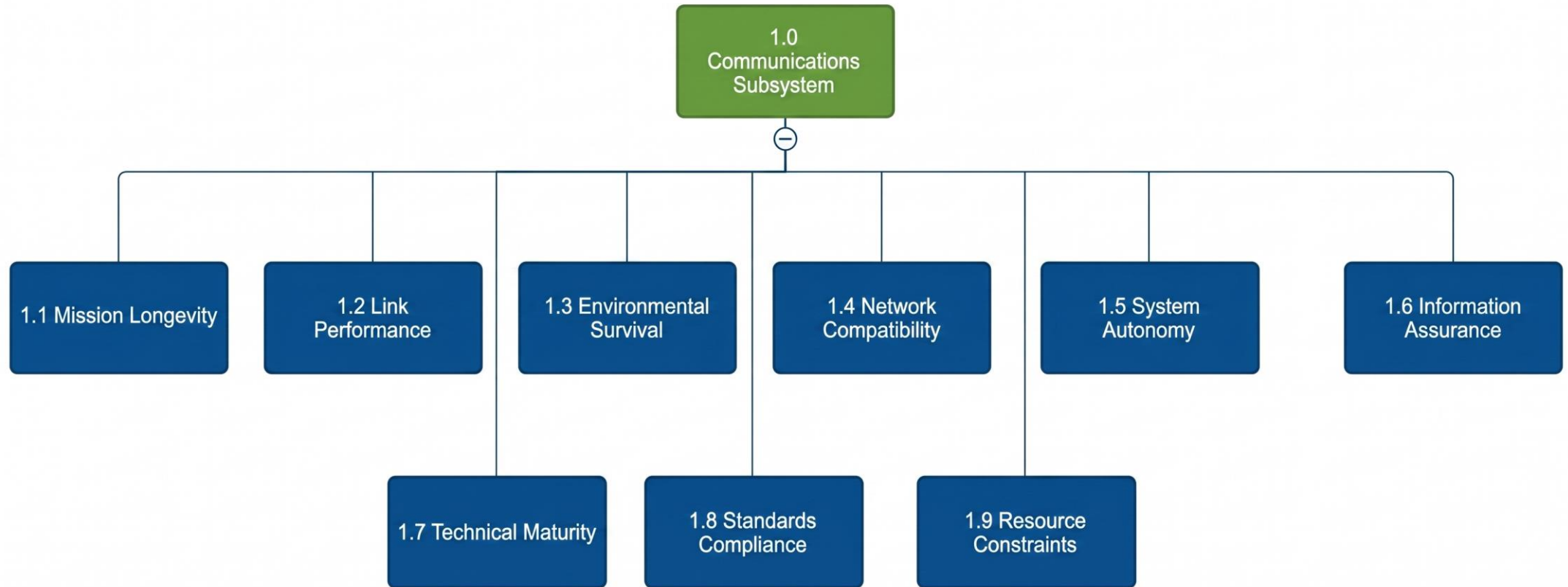
The spacecraft should:

- Operate effectively in a harsh deep space environment.
- interface with power, thermal and structural subsystems.

Concept of Operations



Requirement Overview



Requirements Flowdown

1.0 Communications Subsystem

1.1 Mission Longevity	The subsystem shall maintain full operational functionality for a minimum mission duration of 40 years.
1.1.1	The subsystem shall maintain a cumulative Probability of Success (P_s) of ≥ 0.95 over the 40-year life.
1.1.2	The pointing mechanism shall support a minimum of 14,600 discrete tracking duty cycles.
1.1.3	The integrated electronics shall maintain a Mean Time Between Failures (MTBF) of $\geq 350,000$ hours.
1.1.4	Articulating interfaces shall remain free of stiction/cold-welding in a vacuum for 40 years.
1.1.5	Internal structural connections shall withstand a minimum of 15,000 cumulative thermal cycles.
1.1.6	The system shall maintain software execution integrity for $\geq 8,760$ hours between scheduled resets.
1.1.7	The subsystem shall maintain $\geq 90\%$ functional capability at End-of-Life (EOL).
1.1.8	The subsystem shall utilize a fault-tolerant, cross-strapped redundant architecture for all active electronic paths to eliminate single-point failures

1.2 Link Performance The subsystem shall sustain high-rate science data and command links at distances up to 1 AU.

1.2.1 The system shall sustain a science data downlink rate of ≥ 25 kbps at a distance of 6.0 AU.

1.2.2 The system shall support a command uplink reception rate of ≥ 2 kbps.

1.2.3 The system shall provide a minimum boresight gain of ≥ 45 dBi in the Ka-band.

1.2.4 The system shall maintain a Bit Error Rate (BER) for telemetry of $\leq 10^{-6}$.

1.2.5 The system shall achieve a receiver Figure of Merit (G/T) of ≥ 2.5 dB/K.

1.2.6 The system shall limit signal loss due to boresight misalignment to a maximum of 3 dB.

1.2.7 The system shall maintain a minimum link margin of ≥ 3 dB during nominal operations.

1.2.8 The system shall support an emergency command uplink at a rate of ≥ 10 kbps.

Environmental Survival The subsystem shall maintain structural and electrical integrity within the deep-space environment.

1.3.1 The system shall remain operational after exposure to a cumulative TID of ≥ 300 krad.

1.3.2 The system shall perform within specs across a temperature gradient of -180°C to $+120^{\circ}\text{C}$.

1.3.3 All subsystem materials shall exhibit a Total Mass Loss (TML) of $< 1.0\%$.

1.3.4 The system shall maintain structural integrity during cold-soak periods of $\geq -230^{\circ}\text{C}$.

1.3.5 The system shall withstand launch Random Vibration Loads per NASA-STD-7001B.

1.3.6 The subsystem shall mitigate molecular and particulate contamination on all RF-sensitive surfaces to maintain signal degradation within ± 0.5 dB of nominal.

1.4 Network Compatibility The subsystem shall be fully interoperable with NASA Deep Space Network (DSN) infrastructure.

1.4.1 The system shall utilize telemetry/telecommand protocols compliant with CCSDS 401.0-B.

1.4.2 The system shall be compatible with DSN 34m and 70m Beam Waveguide (BWG) architectures.

1.4.3 The system shall support two-way coherent Doppler and ranging per Standard DSN Ranging.

1.4.4 Radiated emissions shall stay within the SFCG masks of -60 dBc.

System Autonomy The subsystem shall manage autonomous link acquisition and fault recovery without ground intervention.

1.5.1 The system shall re-establish the Earth-link after a Loss of Signal (LOS) within ≤ 300 seconds.

1.5.2 The system shall transition to a "Safe Mode" (broad-beam) upon critical fault within ≤ 10 seconds.

1.5.3 The system shall report internal health metrics to the flight computer at a frequency of ≥ 1.0 Hz.

1.5.4 The system shall execute closed-loop corrections if boresight drifts by $\geq 0.05^\circ$.

1.5.5 The system shall store/execute time-tagged commands for periods of ≥ 168 hours.

Information Assurance

The subsystem shall provide secure, encrypted, and untampered data transport for all mission segments.

1.6.1

All telecommand data shall be decrypted using the AES-256 bit hardware-level standard.

1.6.2

The system shall reject command packets failing a cryptographic handshake in $< 10\text{ms}$.

1.6.3

The system shall utilize Reed-Solomon ECC to prevent bit-level corruption.

1.6.4

The subsystem shall lockout "Privileged Commands" without Multi-factor (MFA) authorization.

1.6.5

The system shall utilize time-stamped nonces within a $\pm 1\text{s}$ window to prevent duplicate commands.

Technical Maturity

The subsystem shall utilize flight-proven architectures with a minimum TRL 6 at the time of PDR.

1.7.1

All critical sub-components shall achieve a minimum maturity level of TRL 6 prior to PDR.

1.7.2

The core transponder architecture shall have documented flight heritage of ≥ 1 Mission.

1.7.3

Any component below TRL 6 shall require a formal Maturation Plan per NPR 7123.1C.

Standards Compliance All engineering processes shall comply with applicable NASA Procedural Requirements (NPRs).

1.8.1 All moving parts shall comply with NASA design safety factors per NASA-STD-5017A.

1.8.2 All transmissions shall comply with NASA frequency control per NASA-STD-4003.

1.8.3 Flight software development shall follow NASA procedural requirements per NPR 7150.2.

1.8.4 The project shall utilize the NASA Systems Engineering Engine model per NPR 7123.1.

1.9 Resource Constraints The subsystem shall operate within the allocated Mass, Power, and Volume (SWaP) budgets.

1.9.1 The total dry mass of the COMM subsystem shall not exceed 45 kg.

1.9.2 The system shall not exceed a maximum peak power allocation of 75W during downlink.

1.9.3 The subsystem shall fit within a stowed dynamic launch envelope of 1.5m x 1.5m x 2m.

1.9.4 The subsystem shall incorporate a software-controllable Power Management Mode capable of reducing average power draw by > 50% during non-transmission cycles

1.9.5 The subsystem shall operate within a peak transmit power range of 5W to 20W.

Vibrations trade studies table

Method	Vibration Protection	Reliability (40 yr)	Mass/Volume	Mechanical Complexity	Trade Score
Rigid Mount	2: No isolation (8–12 g RMS transmitted)	5: High reliability, no moving parts	5: Low mass (2-3 Kg)	5: Very simple few components	3.8 / 5 = 76%
Elastomeric Isolators (Rubber Mounts)	4: Moderate damping (3–6 g RMS)	3: Material degradation risk of rubber failure	3: Moderate mass (4-6 Kg)	3: Moderate complexity	3.4 / 5 = 68%
Spring-Damper Isolators	5: High isolation (2–5 g RMS)	3: More parts higher failure from springs and dampers failing	2: Higher mass (7 – 10 Kg)	2: High complexity	3.3 / 5 = 66%
Weighting	0.40	0.25	0.20	0.15	

Conclusion:

Rigid antenna mounts are simpler and lighter, making them attractive for many missions. However, vibration-isolated mounts can significantly reduce launch loads on sensitive communication hardware and may improve reliability for large or delicate antennas but is complex to implement. Based on the trade studies, the rigid mount is best for its simpler/ lower mechanical complexity.

Antenna-Type Trade Studies Table

Criteria	Data Rate	Gain	Mass/Size Efficiency	Power Efficiency	Trade Score
Parabolic Dish	5; excellent Deep space (300Mbps-10Gbps)	5; excellent (30-50dBi)	2; poor (10 kg – 900kg)	5; Excellent	4.4/5 = 88%
Helical Antenna	4; good Medium-Long range (100Mbps- 2Gbps)	4; good (10—20dBi)	4; good (800g – 1.7kg)	3; Average	3.8/5 = 76%
Active Phased Array	5; excellent Deep space (varies due to array sizes, can exceed 1Gbps)	3; average Varies by size	5; excellent (Typically around 8 to 15kg/m ² , some can achieve up to 2kg/m ²)	2; Poor	3.8/5 = 76%
Weight	0.3	0.3	0.2	0.2	

Conclusion:

The parabolic dish antenna offers the highest gain making it crucial for the long-distance spacecraft. This antenna also provides high-data-rate downlink from deep space to the remote stations needed as well as high reliability in vacuum conditions. However, its size can impact the overall volume of the spacecraft. Based on the trade studies, the parabolic dish antenna is best for our deep space mission whilst maintaining high power efficiency.

Total Mass Trade Studies Table

Criteria	Mass Efficiency	Strength-to-weight Ratio	Stiffness-to-weight Ratio	Manufacturability	Integration/Assembly	Trade Score
Aluminum Structure	2- Heavier material increases mass (2.7g/cm ³)	3- Good strength, not optimal for low-mass	3- Adequate stiffness, but still heavier than composites(25.6 specific units)	5- Easy to manufacture	5- Easier to assemble and mount	3.3/5 = 66%
Composite Structure	5- Much lighter. Reduces total system mass(1.6g/cm ³ , 30%-50% lighter than aluminum)	5- Excellent strength for its lower weight	5- High stiffness with low mass (about 43.8 specific)	2- More difficult to manufacture	3- More complex integration	4.25/ 5 = 85%
Weighting	0.30	0.20	0.20	0.15	0.15	

Conclusion:

Aluminum Structures are simpler to manufacture and easier to integrate, making them a good option for lower cost and simpler missions. However, composite structures provide much better mass efficiency, strength-to-weight ratio, and stiffness. The composite structure is the better choice because reducing total antenna mass is more important for spacecraft performance and launch.

Data Rate Trade Studies

Frequency Bands: S-Band / X-Band / K-Band / Ka-Band

Criteria	Power Required (100 MB / 8hr)	Dish Size (diameter)	Rain-fade Resistance (heavy rain)	Interference	Data Loss Risk	Power Handling (EIRP)	Trade Score
S-Band 2-4 GHz	4; good 5-10 W	2; poor >2m	5; excellent	3; average (radar, weather)	5; excellent <1%	3; average 30-45 dBW	3.5/5 = 70%
X-Band 8-12 GHz	4; average 5-10 W	3; average 1-3 m	4; good	4; good (military reserved)	4; good 1-3%	4; good 45-55 dBW	3.75/5 = 75%
K-Band 18-27 GHz	3; average 10-15 W	4; good 0.5-2 m	2; poor	3; average (TV)	3; average 3-10%	4; good 50-60 dBW	3.25/5 = 65%
Ka-Band 27-40 GHz	2; poor 15-20 W	5; excellent <1m	1; very poor	3; average (Broadband)	2; poor 5-15%	5; good 55-65 dBW	3.15/5 = 63%
Weight	0.25	0.25	0.15	0.1	0.1	0.15	

Conclusion

While higher frequency bands like the K-band or Ka-band can maximize data rates and precision, it lacks reliability for data transmission in a harsh environment like thick clouds or rain; thus, lower frequency bands such as X-band will translate to more reliability, thus using X-Band.

Pointing Trade Studies

Trade Study: Antenna Steering & Integration					
Method	TRL	Power Efficiency	Reliability (40yr)	Mass/Volume	Trade Score
Mechanical Gimbal	5 - TRL 4	5 – Low draw (10W); only uses power when rotating	3 - Risk of gear wear/seizure over 40 years	4 - Lightweight harmonic drives (Expected 22kg)	4.2 / 5 = 84%
Phased Array	3 – TRL 3	2- High draw(150W); needs constant power for electronic beam steering.	5 - No moving parts to fail over long durations.	2 - Heavy electronics and thermal cooling needed for arrays. (Expected 65kg)	3.2 / 5 = 64%
Weighting	0.2	0.3	0.3	0.2	

5: Great, 4: Very Good, 3: Good, 2: Fair, 1: Bad

Conclusion: Pointing manipulated via two-axis harmonic drives and dry-film lubricants ensures high-precision tracking and structural durability for the required 40-year mission duration. This TRL 9 technology fits within a Falcon 9 fairing while providing superior weight and battery efficiency.

Requirements V&V

Req ID	Requirement	Verification	Validation	V&V Method
1.1	Mission Longevity: The subsystem shall maintain full operational functionality for a minimum mission duration of 40 years	Perform reliability analysis (MTBF, redundancy modeling) and parts lifetime analysis	Validate through comparison to heritage missions and long-life component qualification data	Analysis (A), Inspection (I)
1.2	Link Performance: The subsystem shall sustain high-rate science data and command links at distances up to 1 AU	Perform link budget analysis and RF performance testing (gain, SNR, BER)	Validate communication performance meets mission data needs in end-to-end testing	Analysis (A), Test (T)
1.3	Environmental Survival: The subsystem shall maintain structural and electrical integrity within the deep-space environment	Conduct vibration, thermal vacuum ("shake and bake"), and structural analysis	Validate functionality before and after environmental testing	Test (T), Analysis (A)

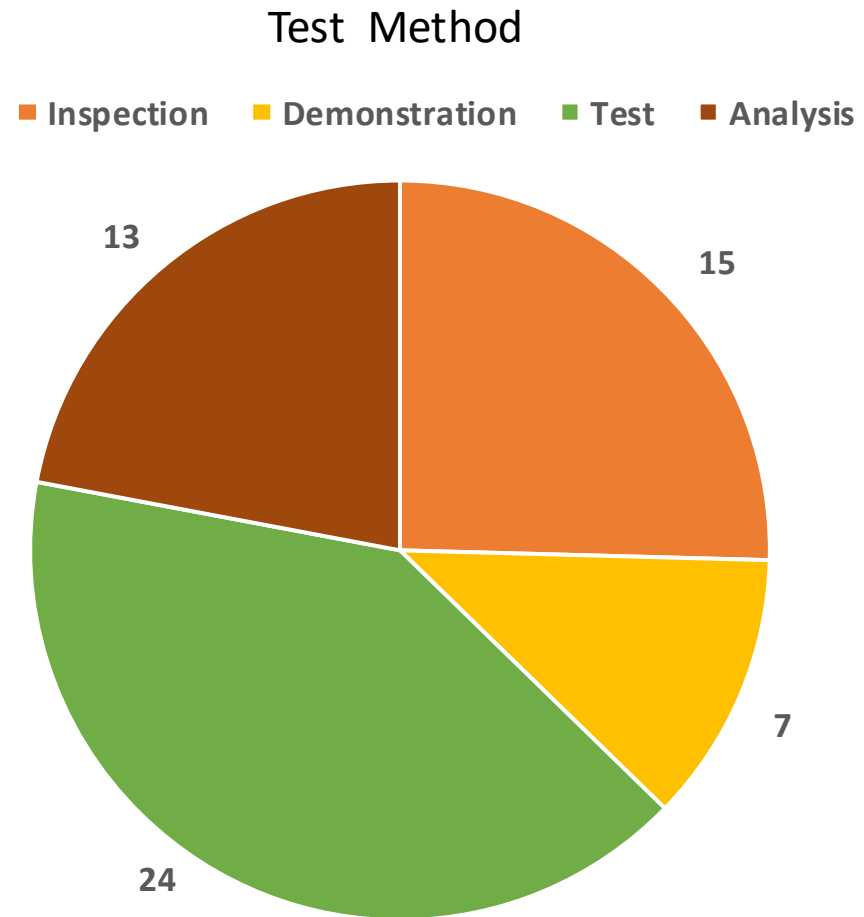
Requirements V&V

Req ID	Requirement	Verification	Validation	V&V Method
1.4	Network Compatibility: The subsystem shall be fully interoperable with NASA Deep Space Network (DSN) infrastructure	Verify compliance with DSN frequency bands and protocols (CCSDS standards)	Validate successful communication with simulated DSN ground station	Inspection (I), Test (T)
1.5	System Autonomy: The subsystem shall manage autonomous link acquisition and fault recovery without ground intervention	Simulate fault scenarios and autonomous recovery logic	Demonstrate successful fault detection and recovery without operator input	Analysis (A), Demonstration (D)
1.6	Information Assurance: The subsystem shall provide secure, encrypted, and untampered data transport	Verify encryption algorithms and data integrity protocols	Validate secure transmission through simulated cyber/communication tests	Inspection (I), Test (T)

Requirements V&V

Req ID	Requirement	Verification	Validation	V&V Method
1.7	Technical Maturity: The subsystem shall utilize flight-proven architectures with a minimum TRL 6 at the time of PDR	Review component heritage and TRL documentation	Validate selection against known flight-proven systems	Inspection (I)
1.8	Standards Compliance: All engineering processes shall comply with applicable NASA Procedural Requirements (NPRs)	Review documentation and processes against NPR guidelines	Validate compliance through design reviews (PDR/CDR)	Inspection (I)
1.9	Resource Constraints: The subsystem shall operate within allocated mass, power, and volume (SWaP) budgets	Perform mass, power, and volume analysis	Validate compliance against system-level allocations	Analysis (A)

Verification metrics

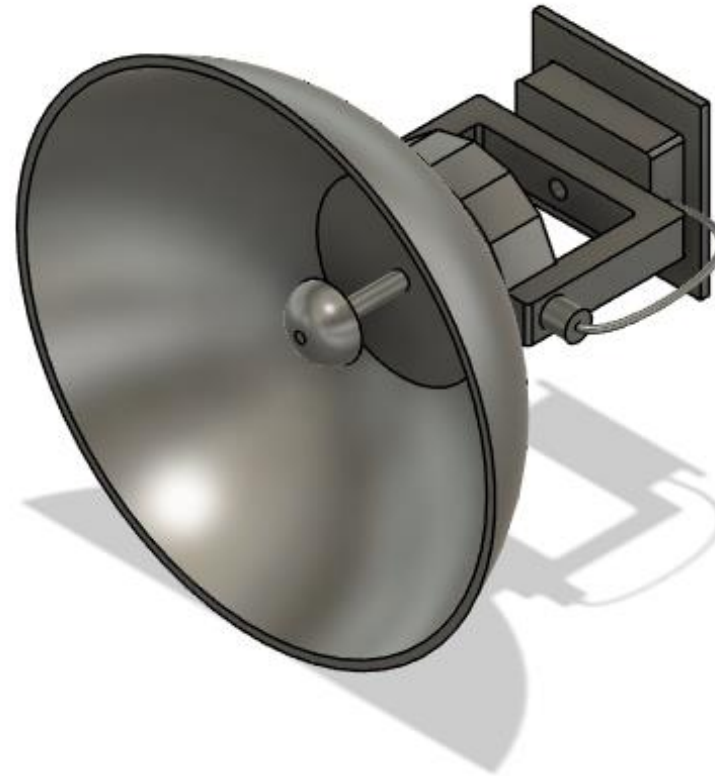


Design Concept

Parabolic dish antenna with central feed point.

Two-axis gimbal movement in azimuth and elevation angles.

Room for transmitter and receiver electronics box to incorporate in the satellite



Risk Assessment

Risk ID	Risk Description	Likelihood (1-5)	Consequence (1-5)	Risk Level	Mitigation Strategies	Consequences
R1	Mechanical Failure (Gimbal Seizure)	4	5	CRITICAL	<ul style="list-style-type: none"> Utilizes solid-state Molybdenum Disulfide to prevent "cold-welding" and outgassing in a 40-year vacuum. Prevents mechanical "binding" by maintaining gear tolerances during extreme deep-space temperature swings. Provides electrical redundancy, ensuring backup torque is available if a primary motor phase fails. Implementation of physical maze-like barriers to isolate gear teeth from internal wear particles and external micro-debris. Scheduled micro-movements to prevent static friction ("stiction") from building up during long periods of inactivity. 	If the gimbal seizes Communication is lost permanently once the spacecraft moves out of the current beam-width.
R2	Mechanical Alignment Drift	3	4	HIGH	<ul style="list-style-type: none"> Post-launch recalibration to lock onto DSN beacon. Minimize dimensions of lever arms in the gimbal system. Maximize stiffness in bearings and supports. Use materials of low Coefficient of Thermal Expansion such as titanium alloys in the gimbal structure. 	Degraded signal leads to significantly increased downlink times for scientific data.
R3	Radiation Hardening Comm Boxes	3	5	CRITICAL	<ul style="list-style-type: none"> Redundant Comm Boxes and Rad-Hard components for the Transponders. Perform radiation analysis and testing Use radiation hardened electronics and enclosures Implement error detection and correction timers Add localized shielding around the most radiation-sensitive electronics 	A Single Event could cause the transponder to stop transmitting or enter an infinite reboot loop until a ground-commanded reset.
R4	Lubricant Outgassing	2	3	MEDIUM	<ul style="list-style-type: none"> Use of Dry-Film Lubricants like molybdenum disulfide and labyrinth seals to prevent vapor migration. Subjecting the entire antenna assembly and its moving parts to Thermal Vacuum (TVAC) Bake-outs. The hardware is heated in a vacuum chamber to temperatures higher than it will see in flight. 	In a vacuum, standard oils can evaporate and settle on the antenna feed horn, creating a "film" that partially blocks signals and reduces total antenna gain.
R5	Actuator Fatigue	3	4	HIGH	Dual-Winding Actuators to provide electrical redundancy within the gimbal.	The internal motor coils degrade over 40 years.

Risk Assessment

Risk ID	Risk Description	Likelihood (1-5)	Consequence (1-5)	Risk Level	Mitigation Strategies	Consequences
R5	Actuator Fatigue	3	4	HIGH	<ul style="list-style-type: none"> • Use dual-winding motors or redundant actuator paths so the gimbal can still maintain antenna pointing if one motor winding or drive path degrades over the mission lifetime. • Use dry lubricants or long-life space-qualified lubrication systems, along with vacuum-rated bearings, to reduce wear, cold welding, and seizure during decades of operation in vacuum and thermal cycling. • Use radiation-tolerant motor drivers, encoders, and control electronics to prevent long-term degradation from ionizing radiation exposure in cis-lunar or interplanetary space. • Design the gimbal with thermal shielding, heaters if needed, and materials with compatible thermal expansion properties so misalignment, cracking, or binding do not occur over repeated hot-cold cycles. • Include continuous monitoring of motor current, torque demand, temperature, vibration, and pointing accuracy so early degradation can be detected and the system can shift into reduced-load or backup operating modes instead of failing completely. 	The internal motor coils degrade over 40 years.

Risk Matrix

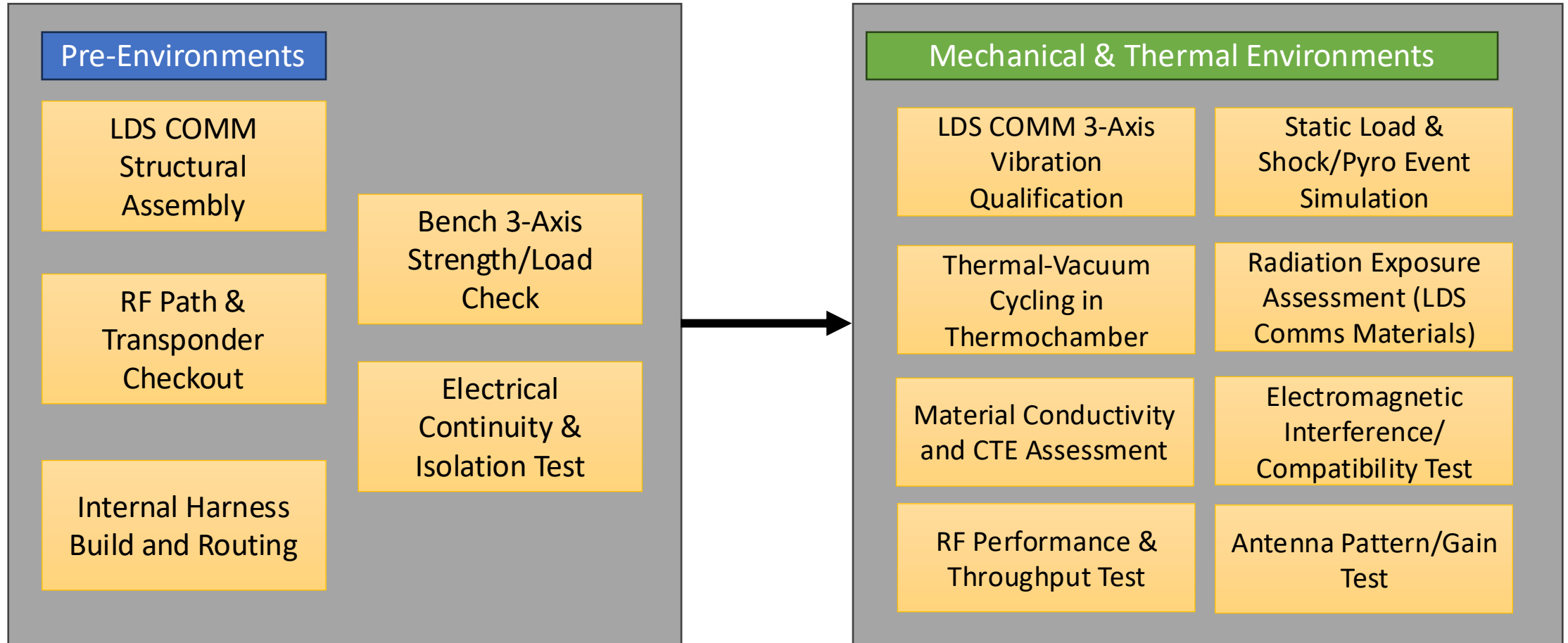
R1 and R3 are categorized as Critical Risk, with high likelihood and mission impact.

R2 and R5 fall into high-risk

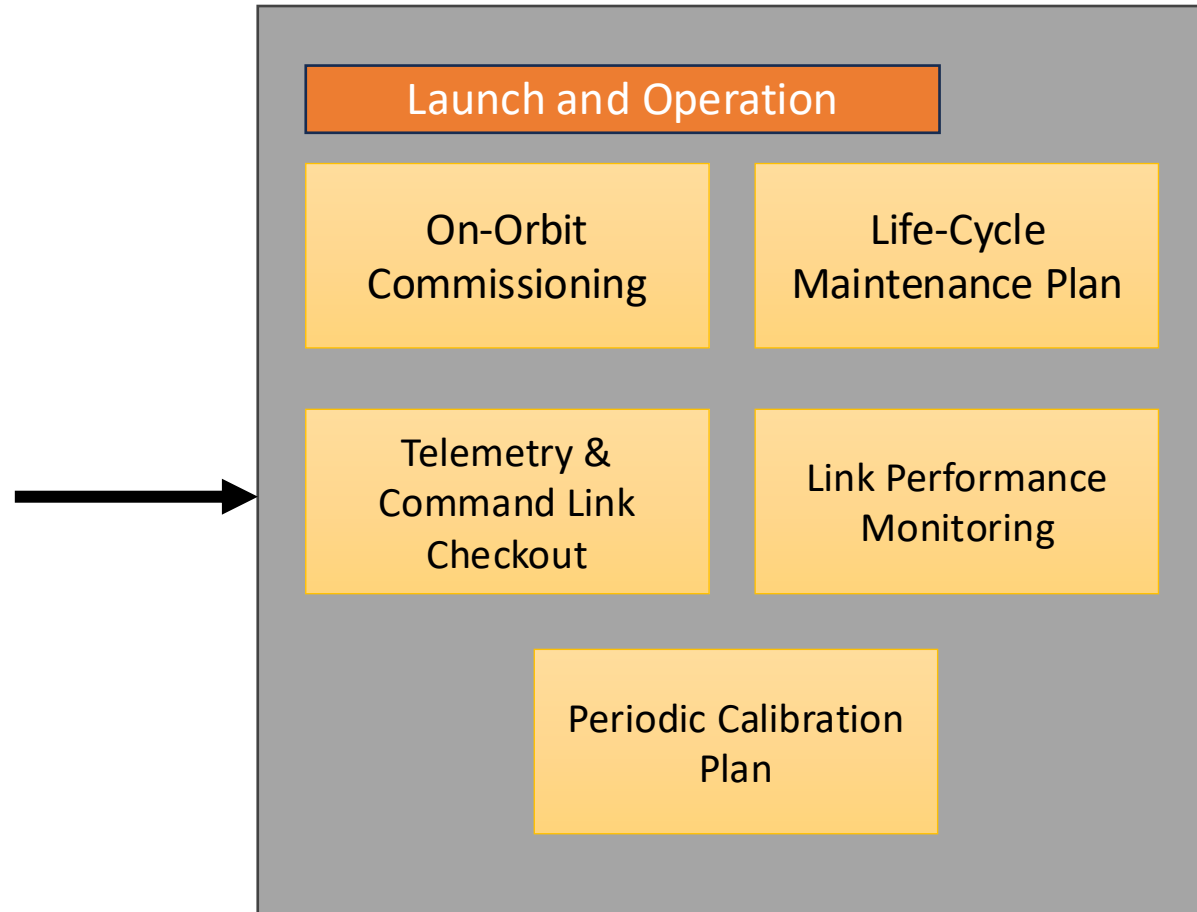
R4 was assessed as medium risk

	Very Likely (5)					
Likelihood	Likely (4)					R1
	Possible (3)				R5,R2	R3
	Unlikely (2)			R4		
	Rare (1)					
		Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Catastrophic (5)
	Consequence					

Integration and Test Flow Diagram



Integration and Test Flow Diagram



Proposed Future Work

- Perform structural analysis of the comms system
- Perform Link budget analysis for the antenna
- Build a prototype and perform tests for gimbals and environmental tests
- Power team design power system to deliver power to the communications system
- Computer design and software development for communications control and cybersecurity.



THE UNIVERSITY OF TEXAS AT EL PASO

Q&A

Supplementary material: V&V

Req ID	Requirement	Verification	Validation	V&V Method
1.1.1	$P_s \geq 0.95$ over 40 years	Reliability block diagram & Monte Carlo analysis	Compare with heritage mission reliability data	A
1.1.2	$\geq 14,600$ tracking cycles	Mechanical life-cycle simulation + actuator testing	Demonstrate repeatability over duty cycles	A, T
1.1.3	MTBF $\geq 350,000$ hrs	Reliability prediction (MIL-HDBK-217)	Validate against component qualification data	A
1.1.4	No stiction/cold welding	Materials inspection & vacuum compatibility review	Validate via vacuum material certification	I
1.1.5	$\geq 15,000$ thermal cycles	Thermal cycling test in chamber	Validate no structural degradation	T
1.1.6	Software integrity $\geq 8,760$ hrs	Long-duration software simulation	Demonstrate stable execution without faults	D, T
1.1.7	$\geq 90\%$ EOL functionality	Degradation modeling (radiation, wear)	Validate using heritage mission data	A
1.1.8	Fault-tolerant architecture	Design inspection + redundancy test	Demonstrate failover operation	I, D

Req ID	Requirement	Verification	Validation	V&V Method
1.2.1	≥ 25 kbps downlink at 6 AU	RF throughput testing	Validate science data transmission	T
1.2.2	≥ 2 kbps uplink	RF receiver testing	Validate command reception	T
1.2.3	Gain ≥ 45 dBi	Antenna gain measurement (anechoic chamber)	Validate link performance	T
1.2.4	$BER \leq 10^{-6}$	BER simulation + RF testing	Validate data integrity	A, T
1.2.5	$G/T \geq 2.5$ dB/K	Link analysis (noise temp, gain)	Validate receiver sensitivity	A
1.2.6	≤ 3 dB misalignment loss	Pointing error simulation	Validate impact on signal strength	A
1.2.7	≥ 3 dB link margin	Link budget + RF testing	Validate robustness of link	A, T
1.2.8	≥ 10 kbps emergency uplink	RF testing under degraded conditions	Validate emergency communication	T

Req ID	Requirement	Verification	Validation	V&V Method
1.3.1	≥300 krad radiation tolerance	Radiation analysis + component certs	Validate performance post-exposure	A, T
1.3.2	−180°C to +120°C operation	Thermal vacuum (TVAC) testing	Validate system functionality	T
1.3.3	TML < 1.0%	Material inspection (NASA database)	Validate outgassing compliance	I
1.3.4	Structural integrity at −230°C	Thermal stress analysis + testing	Validate no cracking/failure	A, T
1.3.5	Launch vibration survival	Vibration test (shaker table)	Validate structural integrity	T
1.3.6	Contamination ≤ ±0.5 dB loss	Cleanliness inspection & surface analysis	Validate RF performance stability	I

Req ID	Requirement	Verification	Validation	V&V Method
1.4.1	X/Ka-band compliance	Frequency allocation inspection	Validate RF operation in band	I
1.4.2	CCSDS compliance	Protocol inspection	Validate interoperability with ground system	I
1.4.3	DSN compatibility	Link analysis with DSN models	Validate communication with DSN simulation	A
1.4.4	Doppler & ranging	RF testing with simulated DSN signals	Validate navigation capability	T
1.4.5	Emissions ≤ -60 dBc	Spectrum analyzer testing	Validate compliance with masks	T

Req ID	Requirement	Verification	Validation	V&V Method
1.5.1	LOS recovery ≤ 300 sec	Simulation of signal loss	Demonstrate reacquisition	D
1.5.2	Safe mode ≤ 10 sec	Fault injection testing	Validate response time	T
1.5.3	≥ 1 Hz health reporting	Software timing test	Validate telemetry output	T
1.5.4	$\geq 0.05^\circ$ drift correction	Control system simulation	Validate pointing correction	A
1.5.5	≥ 168 hr time-tag commands	Software test	Demonstrate command execution	T, D

Req ID	Requirement	Verification	Validation	V&V Method
1.6.1	AES-256 encryption	Software inspection	Validate secure transmission	I
1.6.2	Reject invalid commands <10 ms	Timing test	Validate response speed	T
1.6.3	Reed-Solomon ECC	Algorithm inspection	Validate error correction	I
1.6.4	MFA lockout	Security demonstration	Validate restricted access	D
1.6.5	Nonce timing ± 1 s	Timing analysis	Validate anti-replay protection	A

Req ID	Requirement	Verification	Validation	V&V Method
1.7.1	TRL \geq 4 components	TRL documentation review	Validate readiness level	I
1.7.2	Flight heritage \geq 1 mission	Heritage documentation review	Validate prior use	I
1.7.3	Maturation plan for <TRL 6	Documentation analysis	Validate risk mitigation plan	A

Req ID	Requirement	Verification	Validation	V&V Method
1.8.1	NASA structural standards	Design inspection	Validate safety factors	I
1.8.2	Frequency compliance	RF testing	Validate frequency use	T
1.8.3	Software NPR compliance	Process inspection	Validate development lifecycle	I
1.8.4	Systems engineering NPR	Documentation inspection	Validate process compliance	I

Req ID	Requirement	Verification	Validation	V&V Method
1.9.1	Mass \leq 45 kg	Mass properties analysis	Validate against budget	I
1.9.2	Power \leq 75 W	Power testing	Validate consumption	T
1.9.3	envelope	Dimensional inspection	Validate fit	I
1.9.4	Power reduction \geq 50%	Power mode testing	Validate energy savings	T, D
1.9.5	5–20 W transmit power	RF power testing	Validate operating range	T

TBX Management

TBX	Requirement	TBX Type	Pending Detail	Current Assumption	Status
TBX-001	1.1.1-Probability of success	TBR	Final reliability target	$P_s \geq 0.95$	Open
TBX-002	1.2.1-Science data Downlink Rate	TBR	Final downlink rate	≥ 150 Mbps at 1.0 AU	Open
TBX-003	1.2.4-Bit Error Rate	TBR	Final BER limit	$\leq 10^{-6}$	Open
TBX-004	1.3.1-Radiation Exposure	TBR	Final radiation dose	≥ 300 Krad	Open
TBX-005	1.4.1-Frequency Band Operation	TBD	Final frequency band selection	X-band and Ka-band assumed	Open
TBX-006	1.9.5-Peak Transmit Power Range	TBR	Final transmit power range	5W to 100W	Open

TBX Management Resolution

TBX	Requirement	How it will be resolved
TBX-001	1.1.1-Probability of success	Perform reliability analysis using component failure rate and mission lifetime assumptions.
TBX-002	1.2.1- Science data downlink	Confirm required science data volume and downlink window availability
TBX-003	1.2.4- Bit error Rate	Run communication performance analysis or BER simulation
TBX-004	1.3.1-Radiation Exposure	Complete radiation dose analysis for the mission environment and compare with component
TBX-005	1.4.1- Frequency Band operation	Review DSN compatibility, antenna performance, and mission data needs.
TBX-006	1.9.5- Peak Transmit power range	Complete power budget and RF link budget analysis.