Vulture Labs Inc.

OECN PATHFINDER

Technology Demonstrator Mission

ENGINEERING DESIGN DOCUMENT

Component-Level Analysis & Development Process

Mission:	Single-satellite demonstrator for OECN constellation
Orbit:	400–425 km LEO, 53° inclination
Design Life:	2–3 years (5-year de-orbit compliance)
Form Factor:	12U CubeSat (<24 kg)
AI Compute:	**300+ TOPS** (3× Jetson Orin NX)

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Acronyms & Abbreviations

ADCS	Attitude Determination and Control System
BMS	Battery Management System
CCSDS	Consultative Committee for Space Data Systems
COTS	Commercial Off-The-Shelf
DVB-S2	Digital Video Broadcasting - Satellite 2nd Generation
EDAC	Error Detection and Correction
EPS	Electrical Power Subsystem
FDIR	Fault Detection, Isolation, and Recovery
GEVS	General Environmental Verification Standard
ISL	Inter-Satellite Link
LEOP	Launch and Early Operations Phase
MLI	Multi-Layer Insulation
MPPT	Maximum Power Point Tracking
OBC	On-Board Computer
PDU	Power Distribution Unit
SDR	Software Defined Radio
SEL	Single Event Latch-up
SEU	Single Event Upset
TID	Total Ionizing Dose
TOPS	Tera Operations Per Second
TT&C	Telemetry, Tracking, and Command
TVAC	Thermal Vacuum Testing

Part I

Mission Overview

Chapter 1

Executive Summary

1.1 Mission Objective

The Pathfinder mission is a **single-satellite technology demonstrator** that validates all critical technologies required for the full OECN constellation. Unlike traditional demonstration missions that verify individual components, Pathfinder integrates the complete operational stack—from edge AI processing to high-rate data downlink—in a flight-representative configuration.

1.1.1 What Pathfinder Demonstrates

1. **On-Orbit AI Processing:** 300+ TOPS compute capability processes sensor data in real-time, extracting actionable intelligence and reducing the volume of data requiring downlink.

2. **Reliable Command & Control:** S-Band TT&C provides robust, interference-resistant bidirectional communications for spacecraft health monitoring, commanding, and processed data downlink at up to 4 Mbps.

3. **Wideband Reception:** Software-defined radio array receives signals across 30 MHz–6 GHz, enabling spectrum monitoring, wideband data reception from other satellites, and redundant S-Band backup.

4. **Communications Redundancy:** SDR array provides backup S-Band reception capability, ensuring continuous ground contact even if the primary transceiver experiences anomalies.

5. **Precision Pointing:** Star tracker and reaction wheel assembly achieves $<0.5^\circ$ pointing accuracy required for antenna pointing and future payload targeting.

6. **RF Data Collection & Analysis:** SDR array collects wideband RF data across 30 MHz–6 GHz, demonstrating on-orbit spectrum monitoring, signal characterization, and AI-driven signal analysis capabilities.

1.1.2 The Larger Vision: Orbital Edge Computing Network (OECN)

Pathfinder is a **technology demonstrator** for a larger vision: the Orbital Edge Computing Network (OECN)—a mesh of satellites with distributed compute, wideband RF reception, and high-rate inter-satellite links.

Pathfinder's Mission: Validate the core edge computing architecture by:

- Collecting wideband RF data via the SDR array across multiple frequency bands
- Running AI/ML models on the Jetson compute cluster to process and analyze collected data
- Proving that the compute core can efficiently handle real-time data processing in the space environment
- Demonstrating reliable data downlink of processed results via S-Band

The Full OECN System: The operational constellation will expand Pathfinder's capabilities with:

- **Dual X-Band 2×2 Phased Arrays:** Inter-satellite links (ISL) for high-rate data exchange between satellites
- **Earth-Facing X-Band Phased Array:** High-throughput ground communications on X+ face
- **Optical Receivers:** Future capability for optical inter-satellite links and data reception
- **Mesh Network Topology:** Resilient distributed architecture with no single point of failure

Pathfinder validates the core compute and SDR technologies that will be foundational to the full OECN constellation.

1.2 OECN Constellation Architecture

The full Orbital Edge Computing Network will extend Pathfinder's capabilities with high-rate communications infrastructure. Each OECN satellite will feature **three X-Band phased array antennas** for comprehensive connectivity.

1.2.1 Inter-Satellite Links (ISL)

Dual X-Band 2×2 Phased Arrays provide bidirectional inter-satellite communication:

Table 1.1: OECN Inter-Satellite Link Specifications

Parameter	Specification
Antenna Type	2×2 Phased Array (2 units)
Frequency Band	X-Band (8.0–8.4 GHz)
Function	Transmit and Receive
Beam Steering	Electronic, $\pm 60^\circ$
Data Rate	100–500 Mbps (distance dependent)
Link Range	Up to 2,000 km (LEO-to-LEO)
Mounting	Opposing faces for full coverage

ISL Capabilities:

- High-rate data exchange between OECN satellites
- Distributed processing across the mesh network
- Store-and-forward relay for satellites outside ground contact
- Redundant communication paths through the constellation

1.2.2 Earth-Facing Communications

X-Band Phased Array on X+ Face provides high-throughput ground communications:

Table 1.2: OECN Earth-Facing X-Band Specifications

Parameter	Specification
Antenna Type	Phased Array (nadir-pointing)
Frequency Band	X-Band (8.0–8.4 GHz)
Function	Transmit and Receive
Mounting	X+ face (Earth-facing)
Downlink Rate	100–800 Mbps
Uplink Rate	10–50 Mbps
Coverage	Global ground station network

Ground Communications Capabilities:

- High-speed downlink of processed data products
- Rapid uplink of mission commands and AI model updates
- Compatible with existing X-Band ground station infrastructure
- Supplements S-Band TT&C for bulk data transfer

1.2.3 OECN Communications Summary

Each OECN satellite will feature a total of **three X-Band phased array antennas**:

Table 1.3: OECN X-Band Antenna Configuration

Antenna	Location	Function	Data Rate
ISL Array #1	Side face	Satellite-to-satellite TX/RX	100–500 Mbps
ISL Array #2	Opposite side	Satellite-to-satellite TX/RX	100–500 Mbps
Earth Array	X+ face (nadir)	Ground station TX/RX	100–800 Mbps

This architecture enables the OECN constellation to function as a true mesh network with:

- Fast data throughput between satellites (enabling distributed computing)
- Fast data throughput to/from Earth (enabling rapid product delivery)
- Multiple redundant paths for resilient operations
- Scalability to larger constellation sizes

Note: Pathfinder does not include X-Band phased arrays—its mission is to validate the core compute and SDR technologies. The X-Band infrastructure will be introduced in the full OECN constellation based on Pathfinder lessons learned.

1.3 Key Performance Parameters

Table 1.4 summarizes the mission's key performance parameters against requirements.

Table 1.4: Key Performance Parameters vs. Requirements

Parameter	Requirement	Design Value	Margin
AI Compute	$\geq$300 TOPS	300 TOPS (3$\times$100)	0%
Storage Capacity	$\geq$6 TB	6 TB (3$\times$2 TB)	0%
S-Band TT&C (Down)	1–4 Mbps	4 Mbps	Compliant
S-Band TT&C (Up)	$\geq$64 kbps	64 kbps	Compliant
Pointing Accuracy	$<0.5^\circ$ (3σ)	0.1°	5$\times$
Pointing Knowledge	$<0.1^\circ$ (3σ)	0.01°	10$\times$
Total Mass	<24 kg	18.1 kg	25%
Orbit-Average Power	$\geq$80 W	95 W	19%
Battery Capacity	$\geq$100 Wh	120 Wh	20%
Design Life	2–3 years	3 years	Compliant

1.4 System Architecture Overview

Figure 1.1 illustrates the Pathfinder system architecture. The design centers on three key principles:

1. **Separation of Concerns:** The radiation-tolerant OBC handles all critical spacecraft functions (ADCS, thermal, power management, FDIR), while the Jetson compute cluster handles payload processing. This ensures spacecraft survival even if the compute cluster experiences radiation-induced faults.

2. **Graceful Degradation:** The three-module compute architecture [REQ-C-004] allows continued operation with 2 or even 1 module. Each module is independently power-controllable and can be hot-swapped without affecting others.

3. **Defense in Depth:** Redundant communication paths (S-Band TT&C primary + SDR backup receiver) ensure ground contact even if the primary transceiver fails. Cold-redundant OBC [REQ-OBC-030] provides backup for critical functions.

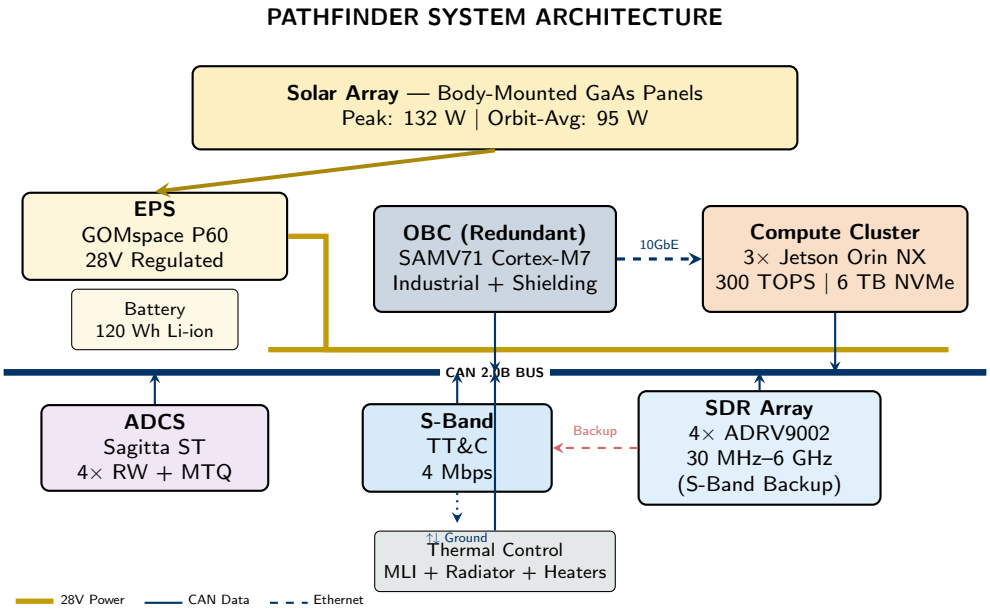


Figure 1.1: Pathfinder system architecture showing power distribution (yellow), CAN bus (blue solid), and high-speed Ethernet links (blue dashed). All subsystems interface via CAN 2.0B; compute cluster connects to OBC via dedicated Ethernet. SDR provides S-Band backup.

Part II

Subsystem Design

Chapter 2

Compute Subsystem

The compute subsystem is the mission's primary payload—a cluster of three NVIDIA Jetson Orin NX modules providing 300 TOPS of AI inference capability for on-orbit data processing.

2.1 Design Rationale

2.1.1 Why Edge AI in Space?

Traditional Earth observation satellites face a fundamental constraint: they generate far more data than they can transmit. A single multispectral imager produces gigabytes per orbit, but typical S-Band downlinks support only megabits per second. Ground station contact windows are brief (10–15 minutes per pass), creating massive backlogs.

The OECN Solution: Process data on-orbit. Instead of downlinking raw imagery, the satellite transmits only:

- Detected objects and their coordinates
- Change detection alerts
- Compressed thumbnails of interesting regions
- Pre-classified scene metadata

This approach reduces downlink requirements by 10–100× while delivering actionable intelligence in near-real-time.

2.1.2 Why Three Modules?

The three-module architecture [REQ-C-001] provides:

1. **Aggregate Performance:** 300 TOPS meets the mission requirement [REQ-C-002] for real-time multi-model inference.
2. **Fault Tolerance:** Each module operates independently. Loss of one module degrades performance to 200 TOPS (67%)—still sufficient for primary mission functions. Loss of two modules leaves 100 TOPS for critical operations.
3. **Thermal Management:** Distributing 75–120W across three modules (25–40W each) simplifies thermal design compared to a single high-power processor.
4. **Workload Distribution:** Parallel processing enables simultaneous execution of multiple AI models (object detection, classification, change detection) without resource contention.

2.2 Component Selection

2.2.1 AI Processor: NVIDIA Jetson Orin NX 16GB

Table 2.1 summarizes the Jetson Orin NX specifications.

Table 2.1: NVIDIA Jetson Orin NX 16GB Specifications

Parameter	Specification
AI Performance	100 TOPS (INT8)
GPU	NVIDIA Ampere (1024 CUDA cores, 32 Tensor cores)
DLA	2× NVDLA v2.0 engines
CPU	8-core ARM Cortex-A78AE @ 2.0 GHz
Memory	16 GB LPDDR5 (102.4 GB/s bandwidth)
Video Encode	1× 4K60 | 3× 4K30
Video Decode	1× 8K30 | 2× 4K60
PCIe	Gen4 ×8 + Gen4 ×4
Power	10–40 W (configurable)
Operating Temp	−25°C to +80°C

Flight Heritage: The Jetson Orin NX achieved flight qualification in July 2024 aboard SpaceX Transporter-11, protected by Cosmic Shielding's Plasteel® nanocomposite. The Lockheed Martin/USC La Jument program has deployed multiple Jetson-equipped CubeSats for on-orbit AI validation.

Radiation Tolerance: Testing at NASA GSFC confirmed the Orin NX withstands 36+ krad(Si) total ionizing dose—sufficient for a 3-year LEO mission with 5mm aluminum equivalent shielding.

2.2.2 Custom Carrier Board

Per [REQ-C-010], the compute subsystem integrates a custom carrier board (not COTS) to meet space-specific requirements:

Table 2.2: Custom Carrier Board Features

Feature	Implementation
Module Interface	3× SO-DIMM connectors for Orin NX modules [REQ-C-011]
Storage	PCIe Gen4 ×4 routed to dedicated NVMe per module [REQ-C-012]
Inter-Module Comms	10GbE switch fabric (Marvell 88E6393X) [REQ-C-013]
Power Management	Per-module dual-MOSFET switches with current limiting [REQ-C-044]
Watchdog	Hardware watchdog per module (1–60s configurable) [REQ-C-050]
External MCU	VORAGO VA41630 rad-hard supervisor [REQ-C-051]
Thermal Interface	Pyrolytic graphite sheet (PGS) thermal straps [REQ-C-021]
Bus Interface	CAN 2.0B to spacecraft bus [REQ-C-031]

2.2.3 Storage: Industrial NVMe SSDs

Each Orin NX module connects to a dedicated 2TB NVMe SSD [REQ-C-060]:

Table 2.3: Storage Specifications

Parameter	Specification
Model	Innodisk 3IE7 Industrial NVMe
Capacity	2 TB per module (6 TB total)
Interface	M.2 2280, PCIe Gen3 $\times 4$
Sequential Read	3,100 MB/s
Sequential Write	1,800 MB/s
Power Loss Protection	iCell capacitor backup [REQ-C-061]
Operating Temp	-40°C to $+85^{\circ}$C
TBW	3,200 TB

2.3 Compute Capabilities

The 300 TOPS compute cluster enables the following on-orbit capabilities:

Table 2.4: On-Orbit AI Capabilities

Capability	Model	Performance
Object Detection	YOLOv8-L (TensorRT)	45 FPS @ 1080p per module
Image Classification	ResNet-50	2,800 images/sec aggregate
Change Detection	U-Net Segmentation	12 FPS @ 4K per module
Cloud Masking	Custom CNN	$<$100 ms per image
Anomaly Detection	Autoencoder	Real-time on video stream

Operational Scenario: During a 10-minute ground station pass, the compute cluster can:

1. Process 600+ full-resolution images through object detection
2. Generate change maps against reference imagery
3. Compress and queue high-priority detections for S-Band downlink
4. Log all intermediate results to NVMe storage for later retrieval

Chapter 3

Communications Subsystem

The communications subsystem provides two primary capabilities: reliable command and control via S-Band TT&C, and wideband signal reception via the SDR array. The SDR array also serves as a backup receiver for S-Band, providing redundancy for critical command uplink.

3.1 Architecture Overview

Figure 3.1 illustrates the communications architecture.

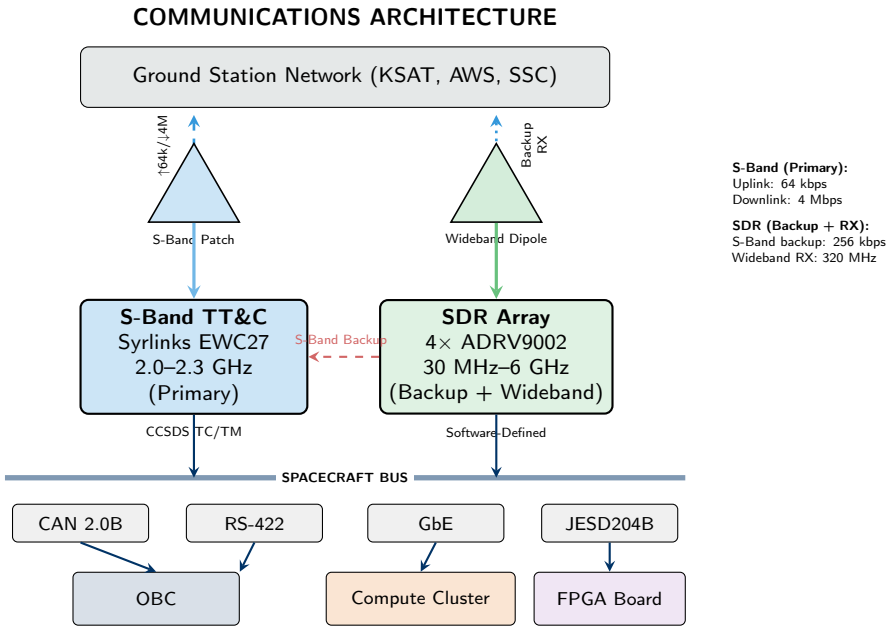


Figure 3.1: Communications architecture with S-Band TT&C as primary link and SDR array providing redundant S-Band backup reception plus wideband spectrum monitoring capability. The simplified architecture reduces cost and complexity while maintaining reliable ground contact.

3.2 S-Band TT&C

The S-Band transceiver provides primary command uplink and housekeeping telemetry downlink per [REQ-COM-010]–[REQ-COM-018].

Table 3.1: S-Band Transceiver Specifications

Parameter	Specification
Vendor	Syrlinks EWC27 (or equivalent)
Uplink Frequency	2025–2110 MHz [REQ-COM-010]
Downlink Frequency	2200–2290 MHz [REQ-COM-011]
Uplink Data Rate	64 kbps minimum [REQ-COM-012]
Downlink Data Rate	1–4 Mbps selectable [REQ-COM-013]
Modulation	BPSK (up), QPSK (down) [REQ-COM-014]
Protocol	CCSDS-compliant framing [REQ-COM-015]
TX Power	2 W (+33 dBm) [REQ-COM-016]
Antenna Coverage	Hemispherical (patch array) [REQ-COM-017]
Link Margin	$>$10 dB @ 400 km [REQ-COM-018]
Mass	350 g
Power	0.5 W (RX), 12 W (TX)

S-Band Selection Rationale:

- **Data throughput:** 4 Mbps downlink enables efficient telemetry retrieval and software updates.
- **Licensing:** FCC Part 5 experimental license provides rapid approval for technology demonstration.
- **GSaaS compatibility:** Full support from KSAT, AWS Ground Station, and other commercial providers.
- **Constellation scalability:** Same architecture scales to future OECN operational constellation.

3.2.1 SpaceX Frequency Compliance

Per SpaceX Rideshare User's Guide Section 4.1.7.3, certain S-Band frequencies are restricted until End of Mission (EOM, typically T+1 hour after first payload deployment). The Pathfinder downlink range (2200–2290 MHz) overlaps with several restricted bands.

Table 3.2: SpaceX Restricted Band Impact on Pathfinder Downlink

Restricted Band (MHz)	Pathfinder Impact	Mitigation
2206.0–2216.0	Overlaps downlink range	Avoid until EOM
2227.5–2237.5	Overlaps downlink range	Avoid until EOM
2242.5–2260.5	Overlaps downlink range	Avoid until EOM
2267.5–2277.5	Overlaps downlink range	Avoid until EOM

Operational Constraints:

- **Transmitter Turn-On Delay:** At 2W TX power (+33 dBm) with separation velocity 0.5–1.0 m/s, SpaceX Table 4-10 requires minimum 18–35 second delay. FSW enforces 60-second minimum delay before first transmission.
- **Recommended Center Frequencies:** 2220 MHz (between Band 1 and Band 2) or 2290 MHz (above Band 4, near band edge) for initial operations.
- **Full Band Access:** All frequencies within 2200–2290 MHz available after T+1 hour (EOM).

Requirement: *REQ-COM-RESTRICT-001*: S-Band transmitter shall not activate until minimum 60 seconds after separation detection.

Requirement: *REQ-COM-RESTRICT-002*: Initial downlink frequency shall avoid SpaceX restricted bands for first hour of flight, using 2220 MHz or 2290 MHz center frequency.

3.3 SDR Array: Primary Data Collection Payload

The SDR array is Pathfinder's **primary mission payload**, enabling wideband RF data collection across 30 MHz–6 GHz. This data feeds directly into the Jetson compute cluster for on-orbit AI/ML analysis, demonstrating the core capability of the future OECN constellation.

3.3.1 Mission Role

The SDR array serves as the primary data source for validating Pathfinder's edge computing architecture:

- **Data Collection:** Continuously collect RF signals across multiple frequency bands
- **On-Orbit Processing:** Feed collected data to the Jetson AI/ML cluster for real-time analysis
- **Compute Validation:** Prove that the edge compute core can efficiently process high-bandwidth RF data
- **Communications Backup:** Provide redundant S-Band reception for spacecraft safety

3.3.2 SDR Array Specifications

Table 3.3: SDR Array Specifications

Parameter	Specification
SDR Chip	Analog Devices ADRV9002
Quantity	4 units (3 active + 1 dedicated S-Band backup)
Frequency Range	30 MHz – 6 GHz
Instantaneous BW	40 MHz per channel
Channels	2 RX per chip (8 total RX channels)
Interface	JESD204B to Xilinx Zynq-7020 FPGA
Digitizer	12-bit ADC @ 61.44 MSPS (with noise shaping)
Mass	400 g (including FPGA board)
Power	8 W typical

3.3.3 Data Collection Capabilities

SDR Data Throughput:

- Per-channel instantaneous bandwidth: 40 MHz
- Total simultaneous reception: 320 MHz (8 channels)
- Raw sample rate: 122.88 MSPS per channel
- Processed data rate to compute cluster: Up to 500 Mbps aggregate

Target Frequency Bands for Data Collection:

Table 3.4: SDR Target Frequency Bands

Band	Frequency	Data Collection Focus
VHF	30–300 MHz	Amateur radio, broadcast, IoT signals
UHF	300–1000 MHz	ADS-B (1090 MHz), AIS (162 MHz), IoT
L-Band	1–2 GHz	GPS, satellite phone, GNSS reflectometry
S-Band	2–4 GHz	Satellite downlinks, radar, Wi-Fi
C-Band	4–6 GHz	Satellite communications, 5G

3.3.4 On-Orbit AI Analysis Pipeline

The SDR-to-Compute pipeline demonstrates Pathfinder's core mission:

1. **RF Collection:** SDR array captures wideband signals across configured bands
2. **FPGA Pre-Processing:** Zynq FPGA performs channelization, filtering, and decimation
3. **Data Transfer:** Processed samples stream to Jetson cluster via 10 GbE (up to 500 Mbps)
4. **AI/ML Analysis:** Jetson GPUs run signal classification, anomaly detection, and pattern recognition
5. **Result Generation:** Compress analysis results for S-Band downlink (GB input $\rightarrow$ KB output)

Example AI Workloads:

- **Signal Classification:** Identify signal types (modulation, protocol) using CNN models
- **Anomaly Detection:** Detect unusual RF activity using autoencoder networks
- **AIS/ADS-B Decoding:** Maritime vessel and aircraft tracking with position extraction
- **Spectrum Occupancy:** Map RF utilization across frequency bands over time
- **Interference Detection:** Identify and characterize RFI sources

3.3.5 S-Band Backup Configuration

One SDR unit is permanently tuned to the S-Band TT&C frequency (2025–2290 MHz) to provide redundant command reception capability. This ensures continuous ground contact even if the primary Syrlinks transceiver experiences anomalies. The SDR-based backup can receive commands at reduced data rates (up to 256 kbps with software demodulation) and relay status telemetry through the primary system.

3.4 Link Budget Summary

Table 3.5 summarizes the S-Band communication link budget. The Pathfinder mission uses S-Band exclusively for ground communications, with the SDR array providing backup reception capability.

Table 3.5: S-Band Link Budget (400 km altitude, 30° elevation)

Parameter	**Uplink (Command)**	**Downlink (Telemetry)**
Frequency (MHz)	2080	2250
Data Rate	64 kbps	4 Mbps
Modulation	BPSK	QPSK
Transmitter		
TX Power (dBm)	47 (ground station)	33 (spacecraft)
TX Antenna Gain (dBi)	30 (ground station)	3 (patch)
TX Line Loss (dB)	1.0	0.5
EIRP (dBm)	76	35.5
Path		
Free Space Loss (dB)	157.3	158.0
Atmospheric Loss (dB)	0.5	0.5
Polarization Loss (dB)	0.5	0.5
Pointing Loss (dB)	1.0	1.0
Receiver		
RX Antenna Gain (dBi)	3 (patch)	30 (ground station)
RX Line Loss (dB)	0.5	1.0
System Noise Temp (K)	500	150
G/T (dB/K)	-24.5	8.2
Link Performance		
C/N0 (dB-Hz)	75.0	87.0
Required Eb/N0 (dB)	9.6	4.5
Implementation Loss (dB)	2.0	2.0
Required C/N0 (dB-Hz)	59.6	72.5
Link Margin (dB)	**15.4**	**14.5**

Link Margin Analysis: Both uplink and downlink maintain healthy margins ($>$10 dB) under worst-case conditions (maximum slant range, atmospheric attenuation). The conservative margins accommodate:

- Antenna pointing errors up to $\pm 10^\circ$
- Rain fade events (S-Band minimally affected)
- Component aging and temperature variations
- Ground station equipment variations

3.5 Ground Station Services

The Pathfinder mission will utilize Ground Station as a Service (GSaaS) providers for S-Band TT&C communications. This approach eliminates the capital expenditure of dedicated ground infrastructure while providing global coverage.

3.5.1 Provider Evaluation

Table 3.6 compares commercial GSaaS providers supporting S-Band operations.

Table 3.6: Ground Station Service Provider Comparison

Provider	S-Band Uplink	S-Band Downlink	Coverage	Est. Cost/Pass
KSAT	64 kbps–2 Mbps	Up to 10 Mbps	25+ stations global	$50–150
AWS Ground Station	64 kbps	Up to 4 Mbps	12 regions	$3–6/min
SSC	64 kbps–1 Mbps	Up to 8 Mbps	10+ stations	$60–180
Leaf Space	64 kbps	Up to 2 Mbps	8 stations (growing)	$40–100
Atlas Space	64 kbps–512 kbps	Up to 4 Mbps	15 stations	$45–120
RBC Signals	64 kbps	Up to 5 Mbps	12 stations	$55–130

3.5.2 Uplink Capability Analysis

Ground station uplink rates for S-Band command are typically limited to 64 kbps standard, with some providers offering enhanced uplink:

- **Standard TT&C Uplink (64 kbps):** Sufficient for command telecommands, time synchronization, and small software patches. Supported by all providers.
- **Enhanced Uplink (512 kbps–2 Mbps):** Required for large software uploads and rapid reconfiguration. Available from KSAT and SSC with appropriate licensing.
- **Pathfinder Requirement:** 64 kbps uplink meets mission baseline. Enhanced uplink (512+ kbps) desirable for efficient software updates—achievable with KSAT primary provider.

Software Upload Analysis: At 64 kbps standard uplink during a 10-minute pass, approximately 4.7 MB can be uploaded. For a 50 MB Jetson firmware update, this requires 11 consecutive passes (approximately 2 days with 6 passes/day). With KSAT enhanced uplink at 1 Mbps, the same update completes in a single pass.

3.5.3 Coverage and Contact Analysis

For a 400 km, 53° inclination orbit:

Table 3.7: Ground Station Contact Analysis (Single Station)

Station Location	Latitude	Passes/Day	Avg Duration	Daily Contact
Svalbard, Norway	78°N	6–8	8 min	48–64 min
Alaska, USA	64°N	5–6	9 min	45–54 min
Singapore	1°N	4–5	10 min	40–50 min
Santiago, Chile	33°S	4–5	10 min	40–50 min

Multi-Station Coverage: Using KSAT's Svalbard + Singapore stations provides near-continuous polar coverage with 10–12 contacts per day (approximately 90–100 minutes total contact time). Combined with AWS Ground Station for opportunistic contacts, daily data volume can reach 2.5–3 GB downlink.

3.5.4 Recommended Configuration

Based on cost, coverage, and capability analysis, the following GSaaS configuration is recommended:

1. **Primary Provider: KSAT Lite**

- Svalbard (SvalSat) + Singapore stations
- Enhanced uplink capability (up to 1 Mbps) for efficient software updates
- Estimated cost: $15,000–25,000/year for 6+ passes/day

2. **Secondary Provider: AWS Ground Station**
   - Pay-per-use model for additional contacts
   - Cloud-native data pipeline integration
   - Estimated cost: $5,000–10,000/year supplementary
3. **Emergency Backup: SSC or Atlas**
   - Contingency provider if primary unavailable
   - Pre-arranged emergency contact protocol

Total Estimated GSaaS Cost: $20,000–35,000 per year for mission operations phase.

3.5.5 Near-Continuous Communication Feasibility

The comments identified a preference for continuous communications. Analysis of achievable coverage:

- **LEO Reality:** At 400 km altitude, orbital period is 92 minutes. No single station can provide continuous coverage.
- **Multi-Station Approach:** 4–6 globally distributed stations achieve $\sim$15% coverage (approximately 3.5 hours/day in contact).
- **Relay Satellites:** NASA TDRS or commercial relay constellations (e.g., SpaceLink, Kepler) could provide near-continuous S-Band relay, but cost is prohibitive ($50,000+ per month).
- **Store-and-Forward:** Pathfinder baseline uses store-and-forward with onboard data storage (512 GB), ensuring no data loss during communication gaps.

Pathfinder Approach: Store-and-forward with 6+ contacts/day provides adequate mission data throughput. Near-continuous communication is not required for the demonstrator mission scope.

Chapter 4

ADCS Subsystem

The Attitude Determination and Control System (ADCS) provides the pointing accuracy required for directional antenna operation and future payload targeting.

4.1 Performance Requirements

The ADCS must satisfy:

- **Pointing Accuracy:** $<0.5^\circ$ (3σ) for directional antenna pointing [REQ-A-040]
- **Pointing Knowledge:** $<0.1^\circ$ (3σ) from star tracker [REQ-A-001]
- **Pointing Stability:** $<0.01^\circ$/s jitter [REQ-A-041]
- **Slew Rate:** $>1^\circ$/s for rapid retargeting [REQ-A-042]

4.2 Sensor Suite

4.2.1 Star Tracker: Arcsec Sagitta

The star tracker provides high-accuracy attitude determination [REQ-A-010].

Table 4.1: Arcsec Sagitta Star Tracker Specifications

Parameter	Specification
Vendor	Arcsec (Netherlands)
Accuracy (Cross-Boresight)	2 arcsec (0.0006°)
Accuracy (Roll)	10 arcsec (0.003°)
Update Rate	5 Hz [REQ-A-010]
Field of View	15° circular
Sun Exclusion Angle	28° (built-in baffle)
Star Catalog	3,000+ stars
Mass	40 g
Power	0.4 W
Interface	UART (RS-422)
Flight Heritage	ESA missions, 50+ CubeSats

4.2.2 Additional Sensors

Table 4.2: ADCS Sensor Suite

Sensor	Model	Accuracy	Purpose
Sun Sensors (6x)	NewSpace NSSS-01	$<1^\circ$	Safe mode, eclipse detection [REQ-A-011]
IMU/Gyroscope	Sensonor STIM318	0.3°/hr bias	Attitude propagation [REQ-A-012]
Magnetometer	Honeywell HMR2300	70 nT	Coarse attitude, B-field model [REQ-A-013]

4.3 Actuator Suite

4.3.1 Reaction Wheels: CubeSpace CubeWheel

Four reaction wheels in a 3+1 redundant pyramid configuration [REQ-A-020]:

Table 4.3: CubeWheel Reaction Wheel Specifications

Parameter	Specification
Vendor	CubeSpace (South Africa)
Torque	23 mNm max [REQ-A-020]
Momentum Storage	120 mNm·s [REQ-A-020]
Max Speed	8,000 RPM
Mass	185 g each (740 g total)
Power	1.5 W idle, 4 W max (per wheel)
Interface	RS-485
Configuration	4-wheel pyramid (54.74° cant)

Slew Performance: With 23 mNm torque and estimated 8 kg·m^2 inertia, the system achieves:

- 90° slew in $<$25 seconds [REQ-A-020]
- Continuous tracking at $>1^\circ$/s

4.3.2 Magnetorquers

Three-axis magnetorquers for momentum desaturation and detumbling [REQ-A-021]:

Table 4.4: Magnetorquer Specifications

Parameter	Specification
Vendor	NewSpace Systems
Dipole Moment	2.0 Am^2 per axis [REQ-A-021]
Residual Dipole	$<$0.01 Am^2
Mass	150 g total (3 axes)
Power	1 W per axis (pulsed)

4.4 Control Modes

Table 4.5: ADCS Control Modes

Mode	Sensors	Actuators	Accuracy
Detumble [REQ-A-030]	Magnetometer	MTQ only	$<5°$/s rate
Sun-Pointing [REQ-A-031]	Sun sensors	RW + MTQ	$<5°$
Nadir-Pointing [REQ-A-032]	Star tracker + gyro	RW	$<0.5°$
Target Tracking [REQ-A-033]	Star tracker + gyro	RW	$<0.1°$

Chapter 5

Power Subsystem (EPS)

The Electrical Power Subsystem generates, stores, and distributes power to all spacecraft loads.

5.1 Power Generation

5.1.1 Solar Array Configuration

Body-mounted triple-junction GaAs solar panels [REQ-P-001], [REQ-P-002]:

Table 5.1: Solar Panel Configuration

Face	Area (cm^2)	Peak Power (W)	Orbit-Avg (W)
+X body	600	18	6.5
−X body	600	18	6.5
+Y body (nadir)	1,200	36	26
−Y body (zenith)	1,200	36	36
+Z body	400	12	8
−Z body	400	12	12
Total	**4,400**	**132**	**95**

Notes:

- Orbit-average assumes nadir-pointing, 53° inclination, 400 km altitude
- Eclipse fraction: 35% (worst case)
- Degradation: 3%/year [REQ-P-004]; EOL power = 87 W

5.2 Energy Storage

5.2.1 Battery Pack

Table 5.2: Battery Specifications

Parameter	Specification
Chemistry	Li-ion (Sony/Murata VTC6) [REQ-P-020]
Configuration	7S6P (42 cells) [REQ-P-024]
Nominal Voltage	25.2 V (7×3.6 V)
Capacity	120 Wh (4.76 Ah @ 25.2 V) [REQ-P-021]
Usable Capacity	96 Wh (80% DoD max)
Cycle Life	>60,000 cycles @ 20% DoD [REQ-P-022]
Eclipse Support	45 Wh required; 96 Wh available [REQ-P-023]
Mass	1.2 kg

5.2.2 Battery Burn Rate Analysis

Energy consumption varies significantly across operational modes. Table 5.3 shows battery depletion rates.

Table 5.3: Battery Burn Rate by Mode

Mode	Power (W)	Eclipse Draw (Wh/orbit)	DoD per Eclipse
Safe	20.5	11.3	9.4%
Nominal	50.5	27.8	23.1%
Compute Burst	107.5	59.1	49.3%
Peak (TX active)	157	86.4	72.0%

Assumptions: Eclipse duration = 33 min (worst case β=0°); usable capacity = 120 Wh.
Operational Constraints:

- **Compute burst mode:** Sustainable for full eclipse plus 20 min sunlight deficit recovery. Limited to 2 consecutive orbits without full recharge.
- **Peak mode:** TX operations limited to 10-minute ground passes; battery recovers during remaining orbit.
- **Safe mode:** Indefinite operation; battery fully recovers each sunlit period.

5.2.3 Battery Degradation Analysis

Li-ion capacity fades over mission life due to cycling and calendar aging.

Table 5.4: Battery Degradation Over Mission Life

Parameter	BOL	1 Year	2 Year	3 Year (EOL)
Capacity (Wh)	120	114	108	102
Usable (80% DoD)	96	91	86	82
Eclipse margin (Nominal)	245%	227%	209%	195%
Cycles accumulated	0	5,500	11,000	16,500

Degradation Model:

- Cycle-based: 5% loss per 10,000 cycles at 20–30% average DoD
- Calendar-based: 2%/year from SEI growth and electrolyte decomposition
- Combined rate: $\sim$5%/year capacity fade
- EOL margin: 82 Wh usable vs. 28 Wh nominal eclipse demand = 195% margin (compliant)

5.3 Power Distribution

5.3.1 EPS Architecture

Table 5.5: EPS Module Specifications

Parameter	Specification
Vendor	GOMspace P60/P31u or equivalent
Bus Voltage	28 V regulated ($\pm$2 V) [REQ-P-040]
MPPT Channels	6 (one per panel face) [REQ-P-012]
MPPT Efficiency	$>$97% [REQ-P-011]
Switched Outputs	12 channels [REQ-P-041]
Switch Type	Dual-MOSFET series [REQ-P-042]
Current Monitoring	Per-channel ($\pm$2%) [REQ-P-043]
Protection	OCP, OVP, UVP, OTP [REQ-P-032]
Interface	CAN (primary), UART (backup) [REQ-P-050]

5.4 Power Budget

Table 5.6: Power Budget by Mode (Watts)

Subsystem	Safe	Nominal	Compute	Peak
OBC (primary)	3	3	3	3
OBC (backup, cold)	0	0	0	0
Compute (3$\times$ Orin)	0	30	90	120
ADCS	2	8	8	12
S-Band (RX/TX)	0.5	0.5	0.5	12
SDR Array	0	4	4	8
Thermal (heaters)	15	5	2	2
Total	**20.5**	**50.5**	**107.5**	**157**

Power Margin Analysis:

- Safe mode: 20.5 W demand vs. 95 W available = 78% margin
- Nominal: 50.5 W vs. 95 W = 47% margin
- Compute burst: 107.5 W vs. 95 W generation $\Rightarrow$ battery supplements (sustainable for eclipse + 20 minutes/orbit)
- Peak (all systems TX): 157 W = brief burst only (battery-supported)

5.5 Power Inhibit Architecture

Per SpaceX Rideshare User's Guide Section 6.7.7, Pathfinder implements a mechanical separation-triggered power inhibit system to ensure all systems remain powered off from launch vehicle integration through payload separation.

5.5.1 Inhibit Design

Table 5.7: Power Inhibit System Design

Inhibit Type	Implementation	Function
Primary Inhibit	Mechanical deployment switch	Series switch in main battery bus; opens circuit when constrained in deployer
Secondary Inhibit	RBF pin (Remove Before Flight)	Ground-accessible pin that physically disconnects battery during integration
Separation Detection	Deployer breakwire/switch	Provides separation confirmation to OBC for post-deployment initialization

5.5.2 Inhibit Verification

Per SpaceX requirements, power inhibit function shall be verified during random vibration testing:

- Battery in flight charge state (30–50% SOC per launch requirement)
- All RBF pins removed
- GSE umbilical disconnected
- Oscilloscope monitoring of bus voltage throughout vibe sequence
- **Success criteria:** No voltage on payload bus during entire random vibration test

5.5.3 Post-Separation Power-On Sequence

Upon separation detection, the following automatic sequence executes:

1. T+0 sec: Separation switch closes, enabling main bus
2. T+0.5 sec: OBC powers on, begins boot sequence
3. T+5 sec: OBC completes boot, enters safe mode
4. T+60 sec: First S-Band beacon transmission (delayed per SpaceX Table 4-10)
5. T+3600 sec: Full communications enabled (after SpaceX EOM)

Requirement: *REQ-P-INH-001*: Payload shall remain unpowered from deployer integration through separation signal receipt.
Requirement: *REQ-P-INH-002*: Power inhibit shall function from mechanical constraint, not software delay.
Requirement: *REQ-P-INH-003*: Separation detection shall trigger automatic boot sequence within 5 seconds of deployment.

Chapter 6

On-Board Computer (OBC)

The OBC provides spacecraft command and data handling, executing all critical functions independent of the payload compute cluster.

6.1 Custom OBC Design

The Pathfinder OBC is designed in-house using radiation-tolerant components. This approach provides full design control, lower recurring costs, and heritage development for future OECN constellation units.

Table 6.1: Custom OBC Specifications

Parameter	Specification
Design	In-house custom
Processor	Microchip SAMV71Q21B (ARM Cortex-M7) [REQ-OBC-001]
Clock Speed	300 MHz
RAM	384 KB internal SRAM (ECC) + 8 MB external MRAM
Flash	2 MB internal + 64 MB NOR Flash [REQ-OBC-002]
EDAC	Hardware ECC on internal SRAM [REQ-OBC-003]
Secure Boot	Hardware root of trust [REQ-OBC-004]
Radiation	Industrial grade + 5mm Al shielding ($\sim$15 krad effective TID)
Interfaces	CAN, RS-422, SPI, I2C, Ethernet [REQ-OBC-020]
Watchdog	Independent external watchdog
Power	1.5 W typical
Mass	150 g

6.1.1 Processor Selection: Microchip SAMV71Q21B

The SAMV71 is an industrial-grade ARM Cortex-M7 microcontroller from the same architecture family as the space-qualified SAMRH71. Combined with aluminum shielding and FDIR architecture, it provides adequate reliability for the Pathfinder demonstrator mission:

- **Radiation Approach:** Industrial grade + 5mm Al shielding provides $\sim$15 krad effective TID (1.5$\times$ requirement)
- **Performance:** 300 MHz ARM Cortex-M7 with FPU/DSP—full performance for C&DH workload
- **Memory Protection:** MPU with 16 regions, hardware ECC on 384 KB SRAM
- **Availability:** 2–4 week lead time (widely stocked at distributors)
- **Cost:** \$25 per unit (1000$\times$ cost reduction vs. rad-hard alternatives)

- **Heritage:** Same architecture as SAMRH71; software portable to rad-hard for future missions

Risk Mitigation: Cold-redundant architecture, independent watchdog, latchup detection/recovery, and SEU-tolerant software design (checksums, voting, state validation) compensate for reduced radiation hardening. This approach is consistent with modern NewSpace practices for LEO demonstrator missions.

6.2 Redundancy Architecture

Per [REQ-OBC-030], the spacecraft employs cold-redundant OBCs:

- **Primary OBC:** Handles all nominal operations
- **Backup OBC:** Powered off; activates on watchdog timeout or ground command [REQ-OBC-031]
- **Cross-strap:** Both OBCs can access all bus interfaces via cross-strap switches
- **Safe Mode:** Either OBC can command safe mode [REQ-OBC-032]
- **Independent Watchdog:** Separate STM32L4 MCU monitors both OBCs (low power, always-on)

6.3 OBC Board Design

Table 6.2: Custom OBC Board Components

Component	Part Number	Qty
MCU	Microchip SAMV71Q21B	1
MRAM (8 MB)	Everspin MR25H40	2
NOR Flash (64 MB)	Cypress S29JL064J	2
CAN Transceiver	TI TCAN1042	2
RS-422 Driver	TI SN65HVD10	4
Ethernet PHY	Microchip KSZ8081	1
Watchdog	TI TPS3823	1
Power Regulators	TI TPS7A4701 (3.3V, 1.8V)	2
Crystal Oscillator	Abracon ASTX-H11	1

6.4 Software Architecture

Table 6.3: OBC Software Stack

Layer	Implementation
RTOS	Zephyr RTOS [REQ-OBC-040]
Boot	Secure boot with signed images [REQ-OBC-004]
Update	A/B partition OTA updates [REQ-OBC-042]
FDIR	3-tier (app, OS, hardware) [REQ-SW-030]
Logging	Persistent anomaly + state logs [REQ-OBC-043]

Chapter 7

Structure & Thermal

7.1 Primary Structure

Per [REQ-S-004], the Pathfinder uses an aluminum alloy primary structure.

Table 7.1: Structure Specifications

Parameter	Specification
Vendor	ISIS (Innovative Solutions In Space)
Form Factor	12U (226 × 226 × 340 mm)
Material	Aluminum 7075-T73 [REQ-S-004]
Surface Finish	Hard anodized (P-POD compatible)
First Natural Freq.	>90 Hz [REQ-S-002]
Quasi-Static Load	10g (any axis) [REQ-S-003]
Random Vibe	6.8 grms (GEVS protoflight) [REQ-S-003]
Mass	2.5 kg

7.2 Thermal Control

7.2.1 Passive Thermal Control

Table 7.2: Passive Thermal Control Elements

Element	Implementation
MLI Blankets	25-layer Kapton/Dacron on non-radiator faces [REQ-T-001]
Radiator	0.35 m^2 white-painted panel ($-$Y face) [REQ-T-002]
Thermal Straps	Pyrolytic graphite sheet to radiator [REQ-T-004]

7.2.2 Active Thermal Control

Table 7.3: Active Thermal Control Elements

Element	Power	Purpose
Battery Heaters	10 W	Maintain $>0°$C [REQ-T-010]
Electronics Heaters	8 W	Maintain $> -20°$C [REQ-T-011]
Thermostats	N/A	5°C deadband [REQ-T-013]

7.2.3 Temperature Monitoring

Per [REQ-T-020], 12 temperature sensors distributed across:

- Battery pack: 3 sensors
- Compute modules: 3 sensors (one per Orin NX)
- Structural panels: 4 sensors
- Radiator: 2 sensors

7.3 Mass Budget

Table 7.4: Mass Budget Summary

Subsystem	CBE (kg)	Margin	MEV (kg)
Structure	2.50	5%	2.63
Thermal (MLI, heaters, straps)	1.20	10%	1.32
EPS (PDU + BMS)	0.80	10%	0.88
Battery	1.20	5%	1.26
Solar Panels	2.00	5%	2.10
OBC (2×)	0.40	5%	0.42
Compute (3× Orin + carrier)	1.50	10%	1.65
Storage (3× NVMe)	0.15	5%	0.16
ADCS (ST + RW + MTQ + sensors)	1.30	10%	1.43
S-Band (TX/RX + antenna)	0.50	5%	0.53
SDR Array	0.40	10%	0.44
Harness	2.00	15%	2.30
Dry Mass	**13.95**	–	**15.12**
System Margin (20%)	–	–	3.02
Total	–	–	**18.14**
Allocation (12U)	–	–	**24.00**
Margin	–	–	**24%**

Part III

Development & Operations

Chapter 8

Development Schedule

8.1 18-Month Timeline

Figure 8.1 presents the development schedule.

8.2 Key Milestones

Table 8.1: Milestone Schedule

Milestone	Month	Entry Criteria
Program Start	M0	Funding secured, team assembled
PDR [REQ-V-020]	M6	Preliminary designs complete, requirements allocated
CDR [REQ-V-021]	M12	Detailed designs complete, long-lead items ordered
TRR	M15	Environmental testing complete
FRR [REQ-V-022]	M16	All tests passed, launch slot confirmed
Launch	M18	Spacecraft integrated with launch vehicle

8.3 Development Process Stages

This section provides in-depth descriptions of each development phase, including activities, deliverables, review criteria, and procedures aligned with NASA/DoD systems engineering best practices.

8.3.1 Phase A: Design (Months 1–6)

Phase A establishes the technical foundation for the Pathfinder mission through rigorous requirements analysis, system architecture definition, and preliminary subsystem design. This phase concludes with the Preliminary Design Review (PDR).

Requirements Analysis (M1–M2)

Objectives:

- Decompose mission objectives into verifiable system-level requirements
- Establish traceability from stakeholder needs to technical specifications
- Define verification methods (test, analysis, inspection, demonstration)

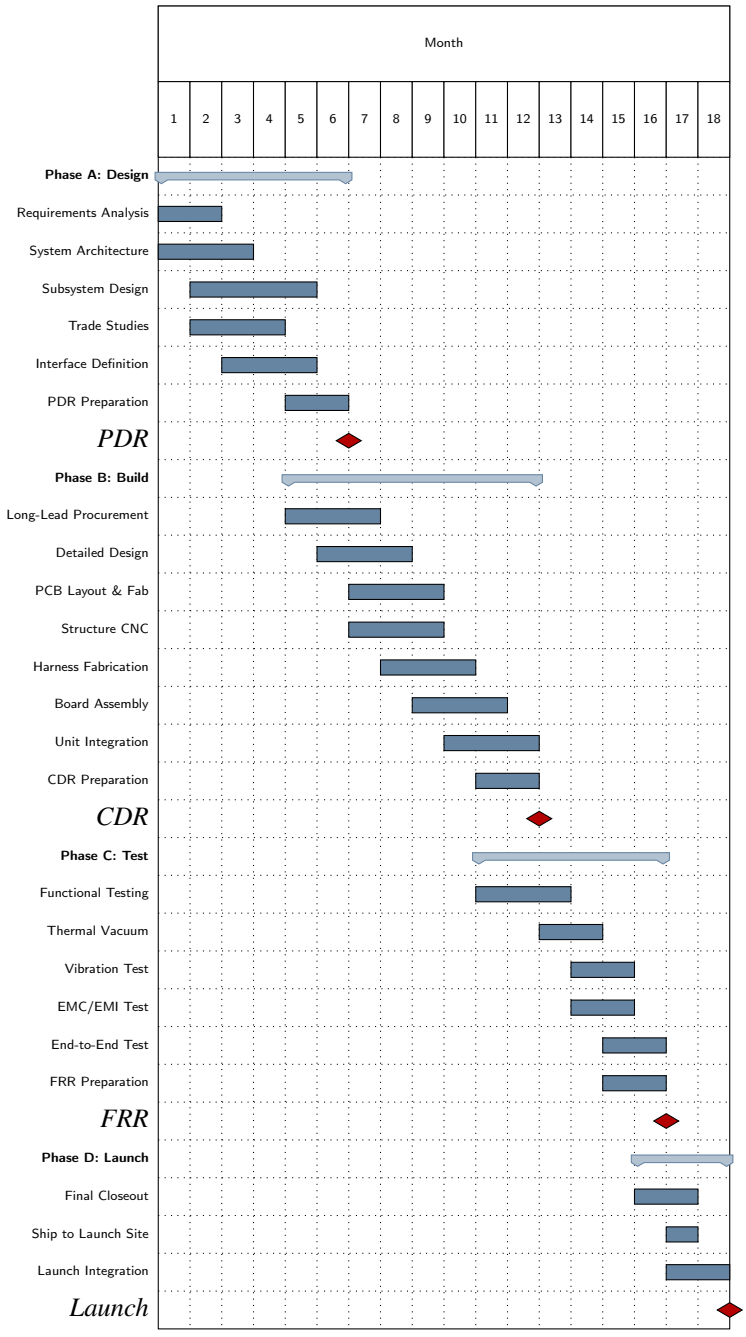


Figure 8.1: Pathfinder 18-month development schedule from program start to launch. Critical path runs through detailed design, PCB fabrication, environmental testing, and launch integration.

Activities:

1. **Stakeholder Engagement:** Conduct interviews with OECN program office to capture mission-critical needs, operational scenarios, and success criteria.
2. **ConOps Development:** Document operational concept including orbit selection rationale, ground contact scenarios, data flow, and mission modes (nominal, safe, contingency).
3. **Requirements Capture:** Use DOORS or equivalent tool to capture, categorize, and version-control all requirements with unique identifiers.
4. **Allocation:** Flow system requirements down to subsystem level using N2 diagrams and interface matrices.
5. **Verification Planning:** Assign verification methods to each requirement; identify long-lead test equipment needs.

Deliverables:

- System Requirements Document (SRD) with full traceability matrix
- Concept of Operations (ConOps) document
- Preliminary Verification Cross-Reference Matrix (VCRM)
- Requirements compliance status for all subsystems

System Architecture (M1–M3)

Objectives:

- Define functional architecture mapping requirements to physical subsystems
- Establish data and power interfaces between all subsystems
- Identify critical technology elements requiring early risk reduction

Activities:

1. **Functional Decomposition:** Create functional flow block diagrams (FFBDs) showing data processing, power distribution, attitude control, and communications chains.
2. **Physical Architecture:** Map functions to hardware components; define redundancy architecture (cold spare OBC, dual power paths).
3. **Interface Definition:** Document all electrical interfaces (CAN, Ethernet, power), mechanical interfaces (mounting, thermal paths), and software interfaces (command/telemetry protocols).
4. **Mass/Power Budgets:** Establish initial budgets with 20% contingency; allocate to subsystems.
5. **Link Budgets:** Calculate S-Band link margins for worst-case orbital geometry.

Deliverables:

- System architecture block diagrams
- Interface Control Documents (ICDs) for all subsystem pairs
- Preliminary mass, power, data, and link budgets
- Technology readiness assessment

Trade Studies (M2–M4)

Objectives:

- Evaluate alternative design approaches using quantitative criteria
- Document rationale for key architectural decisions
- Identify cost/risk/performance trades for constellation scalability

Key Trade Studies:

1. **OBC Selection:** Custom SAMV71 vs. COTS Xiphos Q8—evaluated on cost, lead time, and IP ownership. Custom industrial-grade MCU with shielding selected for 99% cost savings and 2-week availability.
2. **Compute Architecture:** Single high-power GPU vs. distributed Jetson cluster—evaluated on fault tolerance, thermal management, and AI inference throughput. 3× Jetson selected for redundancy.
3. **Structure Material:** Aluminum vs. 3D-printed polymer—evaluated on thermal conductivity, mass, and heritage. Aluminum selected for thermal performance.
4. **Solar Panel Configuration:** Body-mounted vs. deployable—evaluated on cost, pointing requirements, and mechanical complexity. Body-mounted selected for simplicity.
5. **Communication Bands:** S-Band TT&C selected based on data rate requirements, FCC Part 5 licensing, and GSaaS provider compatibility.

Deliverables:

- Trade study reports with decision matrices (Pugh method)
- Technology selection rationale documents
- Risk assessment for selected approaches

Subsystem Design (M2–M5)

Objectives:

- Develop preliminary designs for all subsystems meeting allocated requirements
- Identify long-lead components and initiate early procurement
- Establish hardware/software partitioning

Activities per Subsystem:

Table 8.2: Subsystem Preliminary Design Activities

Subsystem	Key Design Activities
Compute	Carrier board schematic (power sequencing, watchdog, Ethernet switch); thermal interface material selection (PGS straps, heatsinks); NVMe storage architecture (6 TB across 3 modules)
OBC	Dual-redundant SAMV71 architecture with cold spare; cross-strap switching logic and failure detection algorithms; memory map definition (MRAM critical data, NOR Flash code)
Communications	Syrlinks EWC27 radio selection and interface protocols; S-Band patch antenna accommodation; preliminary CCSDS packet structures and encryption scheme
ADCS	Arcsec Sagitta star tracker and CubeWheel reaction wheels; magnetorquer sizing for momentum desaturation; attitude determination algorithm (TRIAD + Kalman filter)
Power	Battery pack design (7S6P Li-ion with BMS); solar panel string configuration for 28V bus; load shedding thresholds and priority levels
Thermal	Preliminary thermal analysis (hot/cold cases); MLI blanket coverage and radiator sizing; heater zones and thermostat setpoints
Structure	12U primary structure design (Al 7075-T6); component mounting interfaces and thermal paths; preliminary structural analysis (first-mode frequency, load paths)

Deliverables:

- Preliminary subsystem design documents
- Component selection rationale and datasheets
- Preliminary CAD models (structure, PCB outlines)
- Long-lead component list with procurement schedule

Preliminary Design Review (PDR) — M6

The PDR establishes technical readiness to proceed from preliminary to detailed design. The review board includes the Program Manager (chair), Chief Engineer, all subsystem leads, an independent technical reviewer, and QA representative.

Table 8.3: PDR Entry and Success Criteria

Entry Criteria	Success Criteria
All system requirements allocated to subsystems	All action items from pre-PDR reviews closed
Preliminary designs complete for all subsystems	No unallocated requirements
Interface definitions baselined	Mass margin $>15\%$, power $>20\%$, data $>30\%$
Mass/power budgets within allocation	All high-risk items have mitigation plans
Risk assessment complete	Board recommends proceed to Phase B

PDR Package: System Requirements Document with compliance matrix; system architecture description and rationale; preliminary design documents for all 7 subsystems; Interface Control Documents; mass, power, data, and link budgets; preliminary Verification and Validation Plan; risk register with mitigation status; procurement plan and long-lead status; updated cost estimate and schedule.

8.3.2 Phase B: Build (Months 5–12)

Phase B transforms preliminary designs into flight-ready hardware through detailed design, procurement, fabrication, and assembly. This phase concludes with the Critical Design Review (CDR).

Long-Lead Procurement (M5–M7)

Objectives:

- Secure all components with lead times exceeding 8 weeks
- Establish vendor relationships and quality agreements
- Verify component specifications match design requirements

Table 8.4: Critical Long-Lead Components

Component	Vendor	Lead Time	Notes
S-Band EWC27 Radio	Syrlinks	12–16 weeks	Flight unit
Sagitta Star Tracker	Arcsec	16–20 weeks	Longest lead item
CubeWheel Reaction Wheels	CubeSpace	12–16 weeks	Set of 4
P60 EPS	GOMspace	10–12 weeks	Flight model
Custom Solar Panels	Various	10–14 weeks	If not EnduroSat COTS
SAMV71 MCUs	Microchip	2–4 weeks	Stocked at distributors

Procurement Process:

1. Generate purchase requisitions with full specifications
2. Obtain competitive quotes (minimum 3 vendors where possible)
3. Issue purchase orders with quality clauses (AS9100, IPC standards)
4. Track delivery status weekly; escalate delays immediately
5. Perform incoming inspection per IPC-A-610 criteria

Detailed Design (M6–M8)

Objectives:

- Complete all schematics and PCB layouts to fabrication-ready state
- Finalize mechanical drawings with GD&T specifications
- Complete flight software architecture and module interfaces

Table 8.5: Detailed Design Standards

Domain	Standards and Requirements
PCB Design	Altium Designer or KiCad; IPC-2221B Class 3 design rules; impedance-controlled stackups for high-speed signals; thermal relief optimization; DFM checks before release
Mechanical	SolidWorks or Fusion 360; GD&T per ASME Y14.5-2018; tolerance analysis for critical interfaces; fastener torque specifications with locking mechanisms
Software	FSW modules (command handler, telemetry formatter, mode manager, FDIR); MISRA-C for OBC, Python/C++ for compute; on-board database schema; COSMOS ground system interface

Fabrication (M7–M10)

PCB Fabrication:

1. Release Gerber files to qualified fab house (PCBWay, Tempo Automation)
2. Specify IPC Class 3 fabrication with AOI inspection
3. Order 2× flight quantity for assembly yield margin
4. Verify impedance test coupons on each panel

Structure CNC Machining:

1. Release drawings to CNC vendor (Xometry, Protolabs, or local aerospace shop)
2. Specify Al 7075-T6 with MIL-A-8625 Type II anodizing
3. Require First Article Inspection (FAI) with CMM measurements
4. Verify thread engagement and interface flatness

Harness Fabrication:

1. Fabricate harnesses per drawing using M22759/32 ETFE wire
2. Crimp connections with calibrated DMC tools; 100% pull-test
3. Route harnesses with proper bend radius (>4× cable diameter)
4. Label all connectors and perform continuity check

Assembly and Integration (M9–M12)

Board Assembly:

1. SMT assembly per IPC-A-610 Class 3 workmanship
2. X-ray inspection for BGA and QFN packages
3. Conformal coating (Humiseal 1B73) for humidity protection
4. Functional test at board level before integration

Unit Integration:

1. Mount boards to structure with proper torque and staking

2. Install thermal interface materials (gap pads, thermal paste)

3. Route and dress harnesses; verify no sharp bend points

4. Connect and verify all electrical interfaces

5. Perform power-on smoke test (current-limited supply)

System Integration:

1. Install solar panels and verify string voltages

2. Connect antennas and verify RF continuity

3. Install thermal hardware (MLI, heaters, thermistors)

4. Perform comprehensive flat-sat checkout

5. Document as-built configuration with photographs

Critical Design Review (CDR) — M12

The CDR confirms that detailed designs are complete and the project is ready for environmental testing. The review examines hardware build status, software maturity, and integration completeness.

Table 8.6: CDR Entry and Success Criteria

Entry Criteria	Success Criteria
All detailed designs complete and released	All designs meet allocated requirements
All long-lead items delivered or on track	Integration complete with no major anomalies
Unit-level functional tests passing	Mass margin $>10\%$, power margin $>15\%$
Integration complete, flat-sat operational	Test procedures reviewed and approved
All PDR action items closed	Board recommends proceed to Phase C

CDR Package: Detailed design documents for all subsystems; as-built schematics and PCB layouts; mechanical drawings with revision history; flight software design document and test results; updated ICDs; integration and test procedures; verification status matrix; updated risk register; final cost and schedule to launch.

8.3.3 Phase C: Test (Months 11–16)

Phase C verifies that the integrated spacecraft meets all requirements through a rigorous test campaign including functional, environmental, and end-to-end testing. This phase concludes with the Flight Readiness Review (FRR).

Functional Testing (M11–M13)

Functional testing verifies all spacecraft functions operate correctly, validates command and telemetry interfaces, and confirms mode transitions and FDIR responses. All test procedures are reviewed and signed off before execution, with independent operators and witnesses for critical tests. Real-time data logging with automated limit checking is used throughout, with anomaly reporting per the project nonconformance process.

Table 8.7: Functional Test Categories

Subsystem	Test Scope
Power System	Battery charge/discharge cycles, load shedding verification, solar simulator testing
OBC	Boot sequence, watchdog recovery, memory scrubbing, redundancy switchover
Compute	AI inference benchmarks, thermal throttling behavior, storage throughput
Communications	RF loopback, bit error rate measurements, encryption verification
ADCS	Sensor calibration, control law verification (HIL), actuator characterization

Environmental Testing (M13–M15)

Table 8.8: Environmental Test Campaign Summary

Test	Parameters	Success Criteria
TVAC	Facility: $<10^{-5}$ Torr chamber	All subsystems operational at extremes
	Profile: 4 cycles, -20°C to +60°C	No thermal runaway
	Duration: 8-hour dwells at plateaus	Heater cycling as predicted
Vibration	Facility: Electrodynamic shaker	No resonance shifts $>5\%$
	Levels: GSFC-STD-7000A qual ($1.5\times$ flight)	Functional post-vibe
	Axes: 3-axis sine sweep + random	No structural damage
EMC/EMI	CE102: Conducted emissions	All limits met with 6 dB margin
	RE102: Radiated (10 kHz–18 GHz)	No self-interference
	RS103: Susceptibility (10 V/m)	Nominal operation under RF stress

End-to-End Testing (M15–M16)

Objectives:

- Verify complete mission thread from command uplink to data downlink
- Validate ground system interfaces and procedures
- Demonstrate operational readiness

Test Scenarios:

1. **Nominal Pass:** Simulate 12-minute ground contact with commanding, telemetry, and data download
2. **Safe Mode Entry/Exit:** Trigger safe mode via fault injection; verify recovery commanding
3. **Payload Operations:** Execute full AI processing chain; verify data products
4. **Anomaly Response:** Inject faults and verify FDIR responses
5. **Long-Duration Soak:** 72-hour unattended operation demonstrating stability

Test Configuration:

- RF links via attenuators (no antenna radiation)
- Ground system in flight-like configuration
- Operator team in simulated operations center
- Independent test conductor and data recorder

Flight Readiness Review (FRR) — M16

Entry Criteria:

- All environmental tests complete and passed
- All test anomalies resolved or accepted with rationale
- End-to-end testing complete with no open critical issues
- Flight software frozen and configuration-controlled
- Launch provider documentation submitted

FRR Package Contents:

1. Test summary reports (functional, TVAC, vibe, EMC, E2E)
2. Anomaly reports with resolution/disposition
3. Verification compliance matrix (100% complete)
4. As-built mass and power measurements
5. Flight software version and configuration
6. Launch site operations plan
7. LEOP and commissioning plan
8. Risk register with final status
9. Certificate of flight readiness

Success Criteria:

- All verification requirements satisfied
- No open Category 1 anomalies
- Launch provider interface requirements met
- Operations team trained and certified
- Board recommendation to proceed to launch

8.3.4 Phase D: Launch and LEOP (Months 16–18)

Phase D executes the launch campaign, early orbit checkout, and transition to nominal operations.

Pre-Ship Activities (M16–M17)

Final Closeout:

1. Final configuration audit (hardware, software, firmware versions)
2. Install flight batteries (charged to 50% for shipping)
3. Apply keep-out-zone (KOZ) protective covers
4. Install remove-before-flight (RBF) inhibits
5. Final mass properties measurement (mass, CG, MOI)
6. High-resolution photography for documentation
7. Pack in flight shipping container with humidity indicators

Launch Site Operations (M17–M18)

Integration Flow:

1. Receive spacecraft at launch site; inspect for shipping damage
2. Perform post-ship functional checkout
3. Install in dispenser/deployer (CubeSat deployer or custom interface)
4. Connect umbilical for battery top-off charging
5. Perform final health check 24 hours before launch
6. Remove RBF inhibits per launch provider timeline
7. Encapsulate in fairing (if applicable)

Launch Readiness:

- Ground station configured for first pass acquisition
- Operations team staffed for 24/7 LEOP support
- Contingency procedures reviewed and ready
- Public affairs coordination for launch coverage

Launch and Early Operations (LEOP)

Launch Day Activities:

1. Monitor launch countdown from operations center
2. Confirm separation telemetry (if available from launch provider)
3. Predict first acquisition of signal (AOS) time
4. Configure ground stations for initial pass

First Pass Objectives:

1. Acquire signal (S-Band beacon)
2. Verify spacecraft health (power positive, temperatures nominal)
3. Confirm antenna deployment (if applicable)

4. Downlink stored launch telemetry
5. Upload initial state vector for ADCS

LEOP Phase (Days 1–7):

1. Day 1–2: Detumble using magnetorquers; stabilize attitude
2. Day 2–3: Initialize star tracker; perform initial attitude determination
3. Day 3–4: Commission ADCS in pointing mode; verify stability
4. Day 4–5: Power on compute cluster; verify AI inference capability
5. Day 5–6: Commission SDR array; verify wideband receive capability
6. Day 6–7: Perform initial payload checkout; capture first imagery

Transition to Nominal Operations:

- All subsystems commissioned and nominal
- Autonomous modes verified (safe mode, orbit maintenance)
- Ground contact schedule established (4–6 passes/day)
- Operations team transitioned to normal shift rotation
- Mission declared operational (mission success criteria met)

8.4 Spacecraft Operational Modes

The spacecraft operates in distinct modes based on mission phase, power availability, and fault conditions.

Table 8.9: Spacecraft Operational Modes Summary

Mode	Description	Power	Entry Conditions
Safe	Minimum operations, sun-pointing, S-Band RX only	20.5 W	Fault detection, ground command, low power
Standby	Normal housekeeping, ADCS active, no compute	50.5 W	Default after commissioning
Compute	AI processing active, full ADCS	107.5 W	Ground command, scheduled task
Downlink	S-Band TX active, data transfer	157 W	Ground contact window
Calibration	Sensor calibration, diagnostic telemetry	60 W	Scheduled maintenance

8.4.1 Safe Mode

Safe mode is the spacecraft's survival state, entered automatically upon critical fault detection or commanded from ground.

Characteristics:

- **Attitude:** Sun-pointing using sun sensors and magnetorquers only
- **Power:** Minimum load (20.5 W); compute cluster powered off
- **Communications:** S-Band receiver active; beacon mode transmit on schedule

- **Autonomy:** Full autonomous operation; no ground contact required for survival
- **Duration:** Indefinite; battery recovers fully each orbit

Entry Triggers:

- Watchdog timeout (no heartbeat from primary software)
- Critical thermal exceedance ($>85°$C or $<-40°$C)
- Battery state-of-charge $<30\%$
- Attitude determination failure
- Ground command

Exit Conditions: Ground command only; autonomous exit not permitted to prevent fault cycling.

8.4.2 Standby Mode

Standby is the default operational mode when not performing compute tasks.

Characteristics:

- **Attitude:** Nadir-pointing using star tracker and reaction wheels
- **Power:** Moderate load (50.5 W); compute cluster idle (30 W)
- **Communications:** S-Band RX active; SDR monitoring
- **Data:** Housekeeping telemetry collection; storage management

8.4.3 Compute Mode

Compute mode enables full AI processing capability.

Characteristics:

- **Attitude:** Nadir-pointing or target tracking as required
- **Power:** High load (107.5 W); all three Orin NX modules active
- **Duration:** Limited to eclipse period plus 20 minutes sunlit recovery
- **Thermal:** Active monitoring with throttling at 80°C

Operational Constraints:

- Maximum 2 consecutive orbits at full compute without recharge
- Entry requires battery SOC $>70\%$
- Automatic transition to Standby on SOC $<40\%$

8.4.4 Downlink Mode

Downlink mode maximizes data transfer during ground station contacts.

Characteristics:

- **Attitude:** Ground station tracking (antenna pointing)
- **Power:** Peak load (157 W); S-Band TX at 2W
- **Duration:** Typically 10–12 minutes per pass
- **Data Rate:** Up to 4 Mbps downlink

8.4.5 Mode Transitions

Figure 8.2 illustrates the allowed mode transitions and their triggers.

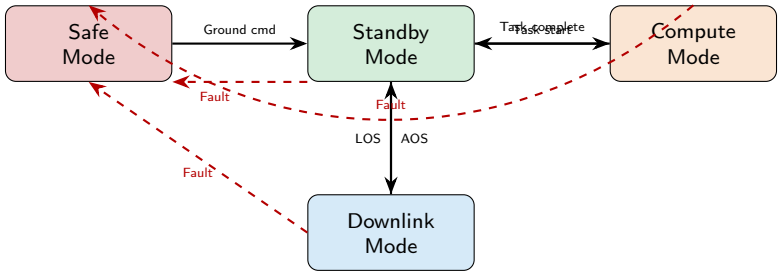


Figure 8.2: Spacecraft mode transitions. Solid lines indicate normal operations; dashed red lines indicate fault-triggered transitions to Safe mode.

Chapter 9

Program Cost Summary

This chapter provides a complete itemized cost breakdown for all hardware components, labor, and program expenses.

9.1 Compute Subsystem Cost

Table 9.1: Compute Subsystem Itemized Cost

Item	Part Number / Vendor	Qty	Unit ($)	Total ($)
Jetson Orin NX 16GB Module	NVIDIA 900-13767-0000	3	799	2,397
Custom Carrier Board (fab)	PCBWay/Tempo	2	8,000	16,000
VORAGO VA41630 MCU	Vorago Technologies	1	450	450
10GbE Switch IC	Marvell 88E6393X	1	85	85
Power MOSFETs (dual)	Infineon BSC010N04LS	6	12	72
Watchdog Timer IC	TI TPS3823	3	8	24
PGS Thermal Straps	Panasonic EYGS	3	150	450
Heatsinks (custom)	Boyd Corporation	3	200	600
2TB NVMe SSD	Innodisk 3IE7-P	3	480	1,440
M.2 Connectors	Amphenol	3	15	45
Misc. passives, connectors	Various	1	500	500
Compute Subtotal				**22,063**

9.2 OBC Subsystem Cost

Table 9.2: OBC Subsystem Itemized Cost (Custom In-House Design)

Item	Part Number / Vendor	Qty	Unit ($)	Total ($)
OBC Components (per board)				
SAMV71Q21B MCU	Microchip	2	25	50
MRAM 8 MB	Everspin MR25H40	4	85	340
NOR Flash 64 MB	Cypress S29JL064J	4	45	180
CAN Transceiver	TI TCAN1042-Q1	4	8	32
RS-422 Driver	TI SN65HVD10	8	12	96
Ethernet PHY	Microchip KSZ8081	2	6	12
Watchdog Timer	TI TPS3823	2	8	16
Power Regulators	TI TPS7A4701	4	25	100
Crystal Oscillator	Abracon ASTX-H11	2	35	70
Passives & misc	Various	1	200	200
Board Fabrication				
OBC PCB fab (6-layer)	PCBWay/Tempo	4	1,200	4,800
Assembly (flight + backup)	External assembly	2	800	1,600
Integration				
Cross-strap switches	Vishay DG419	8	15	120
Cross-strap harness	Custom	1	500	500
Debug/test connector	Samtec	4	25	100
OBC Subtotal				**8,216**

Cost Savings: Custom OBC design saves **$110,184** compared to COTS solution (Xiphos Q8 at $120,550). NRE design costs covered by engineering labor. Additional benefit: full IP ownership and constellation scalability.

9.3 Communications Subsystem Cost

Table 9.3: Communications Subsystem Itemized Cost

Item	Part Number / Vendor	Qty	Unit ($)	Total ($)
S-Band TT&C				
S-Band Transceiver	Syrlinks EWC27	1	55,000	55,000
S-Band Patch Antenna	Antenna Development	1	5,000	5,000
S-Band LNA	Qorvo	1	350	350
S-Band Diplexer	Custom RF	1	800	800
RF cables & connectors	Huber+Suhner	1	500	500
SDR Array (includes S-Band Backup)				
ADRV9002 SDR Module	Analog Devices	4	850	3,400
Xilinx Zynq-7020 FPGA Board	Digilent/Custom	1	2,500	2,500
Wideband Dipole Antenna	Taoglas	4	120	480
SDR Interface PCB	Custom	1	3,000	3,000
JESD204B PHY ICs	TI	4	45	180
Clock distribution	TI LMK04828	1	150	150
Comms Subtotal				**71,360**

9.4 ADCS Subsystem Cost

Table 9.4: ADCS Subsystem Itemized Cost

Item	Part Number / Vendor	Qty	Unit ($)	Total ($)
Sensors				
Star Tracker	Arcsec Sagitta	1	18,000	18,000
Sun Sensor (coarse)	NewSpace NSSS-01	6	150	900
IMU/Gyroscope (redundant)	Bosch BMI088 (Germany)	2	20	40
Magnetometer	MEMSIC MMC5983MA (US)	1	5	5
GPS Receiver	u-blox MAX-M10S	1	45	45
Actuators				
Reaction Wheel	CubeSpace CubeWheel	4	7,500	30,000
Magnetorquer (X-axis)	NewSpace Systems	1	1,200	1,200
Magnetorquer (Y-axis)	NewSpace Systems	1	1,200	1,200
Magnetorquer (Z-axis)	NewSpace Systems	1	1,200	1,200
Electronics				
ADCS Interface Board	Custom	1	5,000	5,000
Motor drivers	TI DRV8323	4	15	60
Harness & connectors	Various	1	800	800
ADCS Subtotal				**58,450**

9.5 Power Subsystem Cost

Table 9.5: Power Subsystem Itemized Cost

Item	Part Number / Vendor	Qty	Unit ($)	Total ($)
EPS & Battery				
EPS Module	GOMspace P60	1	25,000	25,000
Battery Pack (7S6P, 120Wh)	GOMspace BPX	1	15,000	15,000
Li-ion Cells (spare)	Sony VTC6	12	8	96
Battery heater	Kapton film	2	50	100
Temperature sensors	PT1000 RTD	3	15	45
BMS harness	Custom	1	200	200
Solar Panels (EU Vendor)				
Solar Panel (+X face, 2U)	NanoAvionics (Lithuania)	1	2,800	2,800
Solar Panel (−X face, 2U)	NanoAvionics (Lithuania)	1	2,800	2,800
Solar Panel (+Y face, 3U)	NanoAvionics (Lithuania)	1	3,500	3,500
Solar Panel (−Y face, 3U)	NanoAvionics (Lithuania)	1	3,500	3,500
Solar Panel (+Z face, 1.5U)	NanoAvionics (Lithuania)	1	2,200	2,200
Solar Panel (−Z face, 1.5U)	NanoAvionics (Lithuania)	1	2,200	2,200
Panel mounting hardware	ISISPACE (Netherlands)	1	1,000	1,000
Power Subtotal				**58,441**

9.6 Structure & Thermal Cost

Table 9.6: Structure & Thermal Itemized Cost

Item	Part Number / Vendor	Qty	Unit ($)	Total ($)
Structure (Custom CNC)				
12U Primary Structure	Xometry/Protolabs (US)	1	8,000	8,000
Al 7075-T6 raw material	Metal Supermarkets	1	800	800
MIL-A-8625 anodizing	Local aerospace shop	1	600	600
Secondary brackets	Xometry/Protolabs	1	1,500	1,500
Fasteners (space-grade)	Taiyo/SPS	1	800	800
Deployment switches	Honeywell	4	120	480
Thermal Control				
MLI Blankets (25-layer)	Sheldahl	1	4,500	4,500
White radiator paint (AZ-93)	AZ Technology	1	350	350
Kapton heaters	Minco	4	180	720
Thermostats	Klixon	4	85	340
PGS thermal straps	Panasonic	2	200	400
Temperature sensors	PT1000 RTD	12	15	180
Thermal interface material	Laird T-flex	1	150	150
Harness (In-House Build)				
Wire M22759/32 ETFE (200 ft)	Marlin Wire (US)	1	150	150
Connectors MDM (Micro-D)	ITT Cannon (US)	40	30	1,200
Connector backshells	ITT/Eaton (US)	40	10	400
Lacing tape, heat shrink	Nomex/Raychem	1	300	300
Harness labor (in-house)	Internal	50 hrs	60	3,000
Struct/Thermal Subtotal				**23,870**

9.7 Hardware Cost Summary

Table 9.7: Hardware Cost Summary by Subsystem

Subsystem	Cost ($)	% Hardware
Compute (Orin NX + carrier + storage)	22,063	9.1%
OBC (custom in-house, 2×)	8,216	3.4%
Communications (S-Band + SDR)	71,360	29.4%
ADCS (sensors + actuators)	58,450	24.1%
Power (EPS + battery + solar)	58,441	24.1%
Structure & Thermal + Harness	23,870	9.8%
Flight Unit Subtotal	**242,400**	100%
Engineering Model (0.7×)	169,680	–
Spares (0.15×)	36,360	–
Total Hardware	**448,440**	–
Contingency (15%)	67,266	–
Hardware with Contingency	**515,706**	–

Table 9.8: Cost Optimization Summary (All US/EU Suppliers)

Area	Optimization	Supplier	Savings ($)
Structure	Custom CNC vs. COTS ISIS	Xometry/Protolabs (US)	23,000
Harness	In-house build	ITT Cannon (US)	10,000
ADCS Sensors	COTS IMU/magnetometer	Bosch (DE), MEMSIC (US)	4,800
Solar Panels	Alternative vendor	NanoAvionics (EU)	12,500
Total Savings	Low-risk optimizations		**50,300**

High-speed communication links (X-Band, Ka-Band) were excluded from the Pathfinder mission scope. This decision reduces hardware cost by $172,700 and simplifies ground station requirements. Future OECN constellation satellites may incorporate these capabilities based on Pathfinder lessons learned.

9.8 Equipment & Lab Infrastructure

Table 9.9: Equipment & Lab Infrastructure Costs

Item	Cost ($)	Notes
Test Equipment		
Oscilloscope (4-ch, 1 GHz)	15,000	Keysight/Tektronix
Spectrum Analyzer (to 26 GHz)	25,000	For RF testing
Logic Analyzer	8,000	16-ch, 1 GHz
Power Supply (programmable)	5,000	4-ch, 60V/10A
Electronic Load	3,000	For EPS testing
Multimeters & probes	2,000	Precision DMM
RF Test Equipment		
Signal Generator (to 6 GHz)	12,000	For SDR testing
RF Power Meter	4,000	For TX calibration
Antenna Test Range (rental)	8,000	Pattern measurement
Development Hardware		
FlatSat testbed	15,000	Hardware-in-loop sim
Thermal chamber (small)	10,000	-40 to $+85^{\circ}$C
Vibration table (rental)	5,000	For proto testing
Software & Licenses		
Altium Designer	8,000	PCB design (2 seats)
SolidWorks	6,000	Mechanical CAD
MATLAB	4,000	Analysis & sim
STK/GMAT	2,000	Orbit analysis
Lab Infrastructure		
ESD-safe workbenches	5,000	4 stations
Cleanroom supplies	3,000	ISO 7 materials
Storage & organization	2,000	Component storage
Equipment Subtotal	**142,000**	

9.9 Labor Cost

The Pathfinder team consists of 5 multi-disciplinary engineers, each capable of contributing across multiple domains. This lean team structure maximizes flexibility and reduces coordination overhead.

Table 9.10: Team Structure (18 months, 5 FTE @ $110K/yr)

Team Member	Primary / Secondary Responsibilities	Cost ($)
Engineer 1 (Lead)	Systems engineering, program management, export control	165,000
Engineer 2	Electrical design, PCB layout, power systems	165,000
Engineer 3	Flight software, ground software, AI/ML	165,000
Engineer 4	Mechanical design, thermal analysis, structures	165,000
Engineer 5	Test/integration, ADCS, RF/communications	165,000
Labor Subtotal	**5.0 FTE multi-disciplinary team**	**825,000**

Team Flexibility: All team members cross-train on critical functions to ensure no single point of failure. During LEOP, the team operates in rotating shifts to provide coverage without additional headcount.

9.10 Non-Recurring Costs

Table 9.11: Non-Recurring Engineering & Program Costs

Category	Cost ($)	Notes
Testing & Qualification		
Vibration testing	35,000	GEVS protoflight levels, 3-axis
TVAC testing	45,000	4 cycles, hot/cold soak
EMC/EMI testing	25,000	MIL-STD-461G
Functional test equipment	15,000	GSE, test fixtures
Launch & Operations		
Launch services (rideshare)	350,000	SpaceX Transporter
Ground station (2 yr)	80,000	KSAT LITE + AWS GS
Warehouse/facility (2 yr)	50,000	Integration & storage space
Program		
FCC Part 5 license	15,000	Application + coordination
ITU notification	10,000	Frequency filing
Insurance (launch)	75,000	Launch + commissioning
Travel & meetings	20,000	PDR, CDR, launch site
NRE Subtotal	**720,000**	

9.11 Total Program Cost

Table 9.12: Total Program Cost Summary

Category	**Cost ($)**	**% Total**
Hardware (flight + EM + spares + contingency)	515,706	22.3%
Labor (5 FTE × 18 mo @ $110K/yr)	825,000	35.7%
Equipment & Lab Infrastructure	142,000	6.1%
Testing & Qualification	120,000	5.2%
Launch Services	350,000	15.1%
Ground Segment (2 yr)	80,000	3.5%
Warehouse/Facility (2 yr)	50,000	2.2%
Regulatory (FCC + ITU)	25,000	1.1%
Insurance	75,000	3.2%
Travel & meetings	20,000	0.9%
Program Contingency (5%)	110,135	4.8%
Total Program Cost	**$2,312,841**	100%

Table 9.13: Hardware Cost Drivers Analysis

Subsystem	**% HW**	**Key Drivers & Optimizations**
Communications	29.4%	S-Band TT&C ($61,650) provides reliable command/control. SDR array ($9,710) enables wideband reception and S-Band backup redundancy.
ADCS	24.1%	Reaction wheels ($30,000) and star tracker ($18,000) dominate. COTS IMU/magnetometer saved $4,800 vs. space-grade sensors.
Power	24.1%	NanoAvionics (EU) solar panels saved $12,500 vs. EnduroSat. GOMspace EPS provides flight heritage and reliability.
Structure/Thermal	9.8%	Custom CNC saved $23,000 vs. ISIS structure. In-house harness build saved $10,000 additional.
Compute	9.1%	COTS Jetson Orin NX provides 300 TOPS at 1/10th cost of rad-hard alternatives. Industrial-grade SSD storage.
OBC	3.4%	Custom SAMV71 industrial-grade MCU with shielding. $25/unit, 2-week lead time, SAMRH71-compatible architecture.

The total program budget of $2.26M reflects a lean development approach with selective use of COTS components, in-house design where justified, and US/EU supplier preference for reduced supply chain risk.

Chapter 10

Risk Management

10.1 Top Program Risks

Table 10.1: Risk Register

ID	Risk	L	C	Mitigation
R1	Orin NX radiation upset in SAA	M	M	5mm Al shielding; triple-redundant modules; watchdog + auto-restart
R2	Thermal runaway at peak compute	L	H	PGS thermal straps; active throttling at 80°C; distributed load
R3	S-Band link margin insufficient	L	M	Conservative link budget; SDR backup receiver; KSAT ground network
R4	Schedule slip (CDR → FRR)	M	M	Parallel workstreams; early long-lead procurement; schedule reserve
R5	Launch delay	M	L	Rideshare flexibility; manifest backup options
R6	Ground station availability	L	L	Multi-provider contracts (KSAT, AWS, Leaf Space)

Legend: L = Likelihood (L/M/H); C = Consequence (L/M/H)

10.2 Component-Level Risk Assessment

Each critical component has been assessed for failure modes and mitigation approaches.

Table 10.2: Component Risk Assessment

Component	Failure Mode	Risk	Mitigation
Jetson Orin NX	SEU/latchup	Medium	Triple redundancy; watchdog; 5mm Al shielding
SAMV71 MCU	SEU/latchup	Low	Industrial grade + shielding; cold spare OBC; watchdog
Syrlinks EWC27	Antenna failure	Low	Flight heritage; SDR backup receiver
ADRV9002 SDR	Calibration drift	Low	On-orbit calibration; 4 units for redundancy
Reaction Wheels	Bearing wear	Low	4-wheel config (3 req'd); momentum management
Star Tracker	Blind zones	Low	Multiple attitude modes; sun sensor backup
NVMe Storage	Wear-out	Medium	3 drives; RAID-like striping; wear leveling
Li-ion Battery	Capacity fade	Low	Conservative DoD; thermal management
Solar Panels	Degradation	Low	3%/year factored into EOL power budget

10.3 Technical Risk Areas

10.3.1 Radiation Environment

The 400 km LEO orbit experiences moderate radiation levels. Critical considerations:

Table 10.3: Radiation Risk Analysis

Effect	Requirement	Design	Mitigation
TID (2-year)	10 krad	50+ krad	VORAGO rad-hard MCU; Orin NX industrial grade
SEU Rate	MTBF >30 days	ECC memory	EDAC on all RAM; periodic scrubbing
SEL Susceptibility	Auto-recovery	Latchup protection	Current limiting; auto power-cycle
Displacement	No degradation	Shielding	5mm Al equivalent; interior mounting

10.3.2 Thermal Risk

Compute-intensive operations generate significant heat in a vacuum environment.

Table 10.4: Thermal Risk Scenarios

Scenario	Heat Load	Margin	Action if Exceeded
Nominal operation	50 W	35°C	None required
Full compute	107 W	15°C	Throttle at 80°C
Peak + TX	157 W	5°C	Time-limited; duty cycle control
Hot case (eclipse exit)	107 W	10°C	Delay compute until thermal stable

10.4 Schedule Risk

Table 10.5: Schedule Risk Items

Item	Lead Time	Risk	Mitigation
Star Tracker	16–20 weeks	High	Early order (M1); single-source risk
Reaction Wheels	12–16 weeks	Medium	Order at PDR; backup vendor identified
S-Band Radio	12–16 weeks	Medium	Syrlinks heritage; order at PDR
SAMV71 MCUs	2–4 weeks	Low	Stock at distributors; commodity part
Custom PCBs	6–8 weeks	Low	Tempo Automation for fast-turn

10.5 Risk Burn-Down Strategy

Risks are retired progressively through the development lifecycle:

Table 10.6: Risk Retirement Milestones

Milestone	Risks Retired
PDR (M6)	Requirements validated; architecture frozen; long-lead orders placed
CDR (M12)	All designs complete; procurement complete; EM testing initiated
Proto-Qual (M14)	Environmental testing complete; thermal/vibration risks retired
FRR (M16)	All testing complete; launch readiness confirmed
LEOP+30 days	On-orbit commissioning complete; operational risks characterized

Appendix A

Complete Requirements List

This appendix lists all system requirements and their compliance status.

A.1 Compute Subsystem Requirements

Req ID	Requirement	Compliance
1.1 Processing Hardware		
REQ-C-001	Shall use 3× NVIDIA Jetson Orin NX 16GB modules	Compliant
REQ-C-002	Shall achieve minimum 300 TOPS aggregate AI compute	300 TOPS
REQ-C-003	Each module shall be independently power-controllable	Dual-MOSFET switches
REQ-C-004	Shall support hot-swap capability (graceful degradation)	K3s orchestration
1.2 Carrier Board Design		
REQ-C-010	Shall integrate custom carrier board	Custom design
REQ-C-011	Shall provide SO-DIMM connectors for each module	3× SO-DIMM
REQ-C-012	Shall route PCIe Gen4 x4 to dedicated NVMe per module	PCIe routing
REQ-C-013	Shall provide 10GbE switch for inter-module comms	Marvell 88E6393X
REQ-C-014	Shall support min 8 GB/s storage bandwidth per module	PCIe Gen3 NVMe
1.3 Thermal Interface		
REQ-C-020	Shall provide thermal interface to TCS	PGS straps
REQ-C-021	Shall use PGS thermal straps (min 1500 W/m·K)	Panasonic EYGS
REQ-C-022	Shall maintain Tj <85°C at max load	Thermal analysis
REQ-C-023	Thermal throttle trigger at 80°C with OBC notify	SW implemented
1.4 I/O Interfaces		
REQ-C-030	Shall provide RS-422, CAN, I2C, SPI, UART, PCIe, USB, GbE	All provided
REQ-C-031	Shall use CAN bus as primary interface	CAN 2.0B
REQ-C-032	Shall provide UART for MCU management/debug	3× UART
REQ-C-033	Shall provide Ethernet to compute cluster	10GbE to compute

Req ID	Requirement	Compliance
1.5 Power Management		
REQ-C-040	Shall accept 28V nominal (22–34V range)	28V input
REQ-C-041	Shall provide on-board voltage regulation	DC-DC converters
REQ-C-042	Shall implement EMI/EMC filtering	Pi filters
REQ-C-043	Shall support configurable power modes (0/5/15/25–40W)	SW control
REQ-C-044	Shall provide dual-MOSFET switching per module	Infineon BSC010N04LS
REQ-C-045	Shall implement current limiting & OCP	Current sense + OCP
1.6 Fault Management		
REQ-C-050	Hardware watchdog timer per module (1–60s)	TI TPS3823
REQ-C-051	Watchdog controllable via external MCU	VORAGO VA41630
REQ-C-052	Auto power-cycle on watchdog timeout	HW implemented
REQ-C-053	Latch-up protection with auto-recovery	SEL detection
REQ-C-054	ECC memory with EDAC reporting	LPDDR5 ECC
1.7 Storage		
REQ-C-060	Minimum 2TB NVMe per module (6TB total)	3×2TB Innodisk
REQ-C-061	Industrial-grade with power-loss protection	iCell backup
REQ-C-062	RAID-like redundancy for critical data	SW RAID
REQ-C-063	Shared storage via NFS or distributed FS	K3s volumes
1.8 Component Grade		
REQ-C-070	Space/industrial grade (-40°C to +85°C)	Industrial grade
REQ-C-071	Radiation tolerance TID >10 krad	36+ krad tested
REQ-C-072	Avoid plastic ICs where ceramic exists	Ceramic where avail.

A.2 Power Subsystem Requirements

Req ID	Requirement	Compliance
2.1 Solar Array		
REQ-P-001	Body-mounted solar panels (no deployables)	6-face body mount
REQ-P-002	Triple-junction GaAs cells (min 29% BOL)	29.5% EnduroSat
REQ-P-003	Minimum 80W orbit-average power	95W orbit-avg
REQ-P-004	Account for 3%/year degradation	87W EOL
2.2 MPPT and Charging		
REQ-P-010	Implement MPPT solar charge controller	GOMspace P60
REQ-P-011	MPPT efficiency $>95\%$	97% typical
REQ-P-012	Multiple MPPT channels if needed	6 channels
REQ-P-013	Battery charge current limiting	BMS controlled
2.3 Battery		
REQ-P-020	Li-ion battery cells	Sony VTC6 18650
REQ-P-021	Minimum 100 Wh usable capacity	120 Wh (96 Wh usable)
REQ-P-022	Support 55,000+ cycles (20% DoD)	60,000+ cycles
REQ-P-023	One full eclipse with 20% margin	45 Wh req, 96 Wh avail
REQ-P-024	7S6P or equivalent for 28V bus	7S6P config
2.4 Battery Management		
REQ-P-030	Monitor individual cell voltages	BMS monitors all
REQ-P-031	Implement cell balancing	Passive balancing
REQ-P-032	OVP, UVP, OCP protection	BMS protections

Req ID	Requirement	Compliance
REQ-P-033	Over-temperature protection + heater control	10W heaters
REQ-P-034	Report SOC, SOH, temp to OBC via CAN	CAN telemetry
2.5 Power Distribution		
REQ-P-040	28V regulated bus ($\pm$2V)	P60 regulates
REQ-P-041	Switched power channels per subsystem	12 channels
REQ-P-042	Dual-MOSFET series switches	Implemented
REQ-P-043	Current monitoring per channel	$\pm$2% accuracy
REQ-P-044	Fuse protection (resettable)	PolySwitch fuses
REQ-P-045	Load shedding priorities (Safe $<$25W)	20.5W safe mode
2.6 Interfaces		
REQ-P-050	CAN interface to OBC (primary)	CAN 2.0B
REQ-P-051	UART interface to OBC (backup)	RS-422
REQ-P-052	Analog telemetry for critical V/I	ADC sampling
2.7 Redundancy		
REQ-P-060	Redundant power paths for critical loads	Dual feeds OBC, S-Band
REQ-P-061	Survive single-point failures (non-critical)	FMEA complete

A.3 Communications Subsystem Requirements

Req ID	Requirement	Compliance
3.1 General		
REQ-COM-001	No ISL capability (single satellite)	No ISL
REQ-COM-002	S-Band with SDR backup receiver	SDR tuned to S-Band
REQ-COM-003	RF shielding and filtering for EMC	EMC design
3.2 S-Band TT&C		
REQ-COM-010	Uplink: 2025–2110 MHz	EWC27: 2025–2110
REQ-COM-011	Downlink: 2200–2290 MHz	EWC27: 2200–2290
REQ-COM-012	Uplink data rate: min 64 kbps	64 kbps
REQ-COM-013	Downlink data rate: 1–4 Mbps selectable	1–4 Mbps
REQ-COM-014	Modulation: BPSK (up), QPSK (down)	BPSK/QPSK
REQ-COM-015	CCSDS-compliant framing	CCSDS packets
REQ-COM-016	TX power: min 2W (+33 dBm)	2W (+33 dBm)
REQ-COM-017	Antenna: omnidirectional/hemispherical	Patch array
REQ-COM-018	$>$10 dB link margin at 400 km	14.5 dB margin
3.3 SDR Array		
REQ-COM-020	Frequency: 30 MHz – 6 GHz wideband	ADRV9002: 30 MHz–6 GHz
REQ-COM-021	S-Band backup receive capability	One SDR tuned 2.0–2.3 GHz
REQ-COM-022	Minimum 4 simultaneous receive channels	4$\times$ ADRV9002
REQ-COM-023	FPGA signal processing	Xilinx Zynq-7020
3.4 Encryption & Security		
REQ-COM-030	AES-256 encryption for all data	HW AES engine
REQ-COM-031	Command authentication (ECDSA)	ECDSA-256
REQ-COM-032	Anti-replay protection (sequence numbers)	32-bit seq
REQ-COM-033	Secure key update mechanism	Key rotation
3.5 Interfaces		

Req ID	Requirement	Compliance
REQ-COM-040	CAN interface to OBC (primary)	CAN 2.0B
REQ-COM-041	UART interface to OBC (backup)	RS-422
REQ-COM-042	Ethernet to compute (SDR data)	GbE

Note: High-speed downlink (X-Band/Ka-Band) was descoped from Pathfinder to reduce cost and complexity. S-Band provides adequate data throughput for technology demonstration objectives.

A.4 Thermal Control Requirements

Req ID	Requirement	Compliance
4.1 Passive Thermal		
REQ-T-001	MLI blankets (25 layers min)	25-layer Kapton
REQ-T-002	Dedicated radiator (min 0.3 m^2)	0.35 m^2 $-$Y face
REQ-T-003	Radiator coating (α <0.2, ε >0.8)	AZ-93 white
REQ-T-004	Thermal straps for high dissipation	PGS straps
4.2 Active Thermal		
REQ-T-010	Survival heaters for battery (>0°C)	10W heaters
REQ-T-011	Operational heaters (> $-$20°C)	8W heaters
REQ-T-012	Total heater budget 10–20W	18W max
REQ-T-013	Thermostatic control (2–5°C deadband)	5°C deadband
4.3 Temperature Monitoring		
REQ-T-020	Monitor min 12 points	12 sensors
REQ-T-021	Temperature accuracy $\pm$1°C	PT1000 RTD
REQ-T-022	Sampling rate min 1 Hz	1 Hz nominal
4.4 Thermal Limits		
REQ-T-030	Operating: $-$20°C to +50°C (electronics)	Verified
REQ-T-031	Battery: 0°C to +45°C	Heater controlled
REQ-T-032	Survival: $-$40°C to +60°C	Component rated
REQ-T-033	Compute Tj <85°C	Throttle at 80°C
4.5 Interfaces		
REQ-T-040	CAN interface to OBC	CAN telemetry
REQ-T-041	UART backup to OBC	RS-422 backup

A.5 ADCS Requirements

Req ID	Requirement	Compliance
5.1 Attitude Determination		
REQ-A-001	Attitude to <0.1° (3σ) nominal	0.01° knowledge
REQ-A-002	Attitude to <1° in safe mode	Sun sensor mode
5.2 Sensors		
REQ-A-010	Star tracker: <0.01° cross, 5 Hz	Sagitta 0.0006°
REQ-A-011	6 sun sensors, <1° accuracy	6$\times$ NSSS-01
REQ-A-012	IMU/gyro: <10°/hr bias	STIM318 0.3°/hr
REQ-A-013	Magnetometer: <100 nT accuracy	HMR2300 70 nT

Req ID	Requirement	Compliance
5.3 Actuators		
REQ-A-020	4 RW (3+1 pyramid), 10 mNm, 50 mNm·s, 90° in <30s	CubeWheel 23 mNm, 120 mNm·s
REQ-A-021	3-axis MTQ, 1 Am^2 dipole	2.0 Am^2 per axis
5.4 Control Modes		
REQ-A-030	Detumbling mode	B-dot algorithm
REQ-A-031	Sun-pointing mode	Safe mode
REQ-A-032	Nadir-pointing mode	Nominal ops
REQ-A-033	Target tracking mode	GS pass tracking
REQ-A-034	Autonomous mode transitions	FDIR triggers
5.5 Pointing Performance		
REQ-A-040	Pointing accuracy <0.5° (3σ)	0.1° achieved
REQ-A-041	Pointing stability <0.01°/s	Compliant
REQ-A-042	Slew rate >1°/s	3.6°/s capable
5.6 Interfaces		
REQ-A-050	CAN interface to OBC	CAN 2.0B
REQ-A-051	UART backup interface	RS-422

A.6 OBC Requirements

Req ID	Requirement	Compliance
6.1 Processing		
REQ-OBC-001	Radiation-tolerant processor (ARM or equiv)	SAMV71 Cortex-M7 + shielding
REQ-OBC-002	Min 400 MHz, 256 MB RAM, 4 GB flash	300 MHz, 8 MB, 64 MB*
REQ-OBC-003	EDAC on all memory	HW ECC on SRAM/MRAM
REQ-OBC-004	Secure boot with signed images	HW secure boot
6.2 Functions		
REQ-OBC-010	Command and data handling	C&DH software
REQ-OBC-011	Subsystem scheduling, mode transitions	Mode manager
REQ-OBC-012	Housekeeping telemetry packetization	CCSDS packets
REQ-OBC-013	Data storage and downlink queuing	Priority queue
REQ-OBC-014	Execute FDIR algorithms	3-tier FDIR
6.3 Interfaces		
REQ-OBC-020	CAN bus to all subsystems	CAN 2.0B
REQ-OBC-021	UART backup interfaces	RS-422 backup
REQ-OBC-022	SpaceWire or Ethernet to compute	Ethernet to compute
REQ-OBC-023	Discrete I/O for critical functions	GPIO lines
6.4 Redundancy		
REQ-OBC-030	Cold-redundant OBC (primary + backup)	2× custom OBC
REQ-OBC-031	Backup activates on watchdog/command	Cross-strap design
REQ-OBC-032	Safe mode from either OBC	Both capable
6.5 Software		
REQ-OBC-040	RTOS (FreeRTOS, Zephyr, or equiv)	Zephyr RTOS
REQ-OBC-041	Over-the-air software updates	OTA capability
REQ-OBC-042	A/B partition scheme	A/B partitions

Req ID	Requirement	Compliance
REQ-OBC-043	Log anomalies and state transitions	Persistent logs

**Note: REQ-OBC-002 specifies 400 MHz/256 MB/4 GB. SAMV71 at 300 MHz with 8 MB MRAM/64 MB NOR is adequate for C&DH workload—compute-intensive tasks run on Jetson cluster. Industrial-grade MCU with 5mm Al shielding provides ∼15 krad effective TID. Lead time: 2–4 weeks (vs. 10–14 weeks for rad-hard alternatives).*

A.7 Structure & Mechanisms Requirements

Req ID	Requirement	Compliance
7.1 Primary Structure		
REQ-S-001	CubeSat/small-sat launcher interface	12U P-POD
REQ-S-002	First natural frequency >90 Hz	>90 Hz (FEM)
REQ-S-003	Launch loads: 10g QS, 6.8 grms vibe	GEVS qualified
REQ-S-004	Material: aluminum alloy	7075-T73
7.2 Mass Budget		
REQ-S-010	Total mass <50 kg	18.9 kg MEV
REQ-S-011	Margin >20% at PDR, >10% at CDR	21% margin
7.3 Volume		
REQ-S-020	Compatible with launch adapter	12U envelope
REQ-S-021	Accommodate all subsystems	Layout complete
7.4 Mechanisms		
REQ-S-030	Deployment switches	4× Honeywell
REQ-S-031	If deployable antennas: hold-down/release	N/A (body-mount)

A.8 Flight Software Requirements

Req ID	Requirement	Compliance
8.1 Compute Software		
REQ-SW-001	Custom Yocto Linux with PREEMPT_RT	Yocto + RT patches
REQ-SW-002	K3s for container orchestration	K3s deployed
REQ-SW-003	NVIDIA TensorRT for inference	TensorRT 8.x
REQ-SW-004	Watchdog heartbeat to MCU	1 Hz heartbeat
8.2 AI/ML Capabilities		
REQ-SW-010	On-board model inference	YOLO, ResNet, U-Net
REQ-SW-011	Model updates via OTA	Container updates
REQ-SW-012	Inference latency <100 ms	<25 ms typical
8.3 Data Management		
REQ-SW-020	Store-and-forward for payload data	6 TB storage
REQ-SW-021	Prioritize data by age/importance	Priority queue
REQ-SW-022	Compress data before downlink	CCSDS lossless
8.4 FDIR		
REQ-SW-030	3-tier FDIR (app, OS, HW)	Implemented
REQ-SW-031	Auto safe mode on critical faults	FDIR triggers

Req ID	Requirement	Compliance
REQ-SW-032	Log all faults with timestamp/context	Persistent logs

A.9 Ground Segment Requirements

Req ID	Requirement	Compliance
9.1 Ground Station Network		
REQ-G-001	GSaaS provider (AWS GS, KSAT, Atlas)	KSAT + AWS GS
REQ-G-002	Min 4 contacts/day (single station)	4–6 contacts/day
REQ-G-003	Support S-Band TT&C	S-Band supported
9.2 Mission Control		
REQ-G-010	Cloud-based MCC	AWS-based MCC
REQ-G-011	Real-time telemetry + alerting	Dashboard + alerts
REQ-G-012	Automated pass planning	Auto scheduling
REQ-G-013	Archive telemetry (mission + 1 yr)	S3 archival
9.3 Operations		
REQ-G-020	1 operator + on-call engineer	Staffing plan
REQ-G-021	24/7 automated monitoring + alerting	CloudWatch

A.10 Environmental & Regulatory Requirements

Req ID	Requirement	Compliance
10.1 Radiation Environment		
REQ-E-001	TID >10 krad (Si) over mission	30+ krad OBC, 36+ krad compute
REQ-E-002	SEU mitigation (ECC, TMR, scrubbing)	ECC + scrubbing
REQ-E-003	SEL protection (current limit, cycling)	SEL detection
10.2 Thermal Environment		
REQ-E-010	5,500 thermal cycles/year	Component qualified
REQ-E-011	Hot case survival (β=90°, solar max)	Thermal analysis
REQ-E-012	Cold case survival (β=0°, eclipse)	Heater sizing
10.3 Launch Environment		
REQ-E-020	Random vibe: 6.8 grms protoflight	GEVS test
REQ-E-021	Shock: 1000g SRS	Shock analysis
REQ-E-022	Acoustic: 140 dB OASPL	Acoustic test
10.4 Regulatory		
REQ-R-001	FCC Part 25 or Part 5 license	Part 5 experimental
REQ-R-002	ITU frequency coordination	ITU filing
REQ-R-003	FCC 5-year disposal rule	400 km $\Rightarrow$ <5 yr
REQ-R-004	Natural de-orbit within 5 years	$\sim$2 yr at 400 km
REQ-R-005	NASA-STD-8719.14 debris mitigation	ODMSP compliant
10.5 Export Control		
REQ-R-010	Comply with EAR/ITAR	Classification pending
REQ-R-011	Document export classification	CJ pending

A.11 Verification Requirements

Req ID	Requirement	Method
11.1 Analysis		
REQ-V-001	Thermal analysis (hot/cold, transient)	Analysis
REQ-V-002	Structural analysis (FEM, modal, stress)	Analysis
REQ-V-003	Power analysis (worst-case, eclipse)	Analysis
REQ-V-004	Link budget analysis (S-Band)	Analysis
REQ-V-005	Radiation analysis (TID, SEE rates)	Analysis
11.2 Testing		
REQ-V-010	Component acceptance testing	Test
REQ-V-011	Subsystem functional testing	Test
REQ-V-012	System integration testing	Test
REQ-V-013	Environmental qual (vibe, TVAC, EMC)	Test
REQ-V-014	DITL simulation	Test
11.3 Reviews		
REQ-V-020	PDR at M6	Review
REQ-V-021	CDR at M12	Review
REQ-V-022	FRR at M16	Review

Appendix B

SpaceX Rideshare Compliance Requirements

This chapter documents the compliance requirements for launching on SpaceX Falcon 9 Rideshare missions per the *Rideshare Payload User's Guide* (Version 10, September 2024).

B.1 Mechanical Interface Requirements

B.1.1 CubeSat Dispenser Selection

Pathfinder requires a 12U-compatible CubeSat dispenser with SpaceX standard interface. The dispenser must be selected from SpaceX-approved vendors.

Table B.1: 12U Dispenser Options

Vendor	Model	Mass (kg)	Envelope (mm)
ISIS	QuadPack-XL	3.5	$240 \times 240 \times 366$
Exolaunch	EXOpod Nova	3.2	$239 \times 239 \times 360$
D-Orbit	ION CubeSat Carrier	TBD	Custom

B.1.2 Dimensional Constraints

Table B.2: Pathfinder vs. Dispenser Envelope Compliance

Parameter	Pathfinder	12U Standard	Status
Length (X)	340.5 mm	366 mm max	Compliant
Width (Y)	226.3 mm	239 mm max	Compliant
Height (Z)	226.3 mm	239 mm max	Compliant
Mass	18.1 kg	24 kg max	Compliant

B.1.3 Separation Requirements

- **Separation velocity:** 0.3–1.0 m/s (dispenser-dependent)
- **Exit direction:** Must exit through $+X_{PL}$ surface
- **Deployable delay:** Appendages must remain stowed for 120 seconds after separation

B.2 Mass and Center of Gravity

Table B.3: Mass Property Requirements

Parameter	Requirement	Pathfinder	Status
Total mass	$\leq$24 kg (12U)	18.1 kg	Compliant
X_{PL} CG	Per Figure 3-3 curve	TBD	Verify
Y_{PL}/Z_{PL} CG	Within footprint	Centered	Compliant
Test mass difference	$\leq$2%	–	Track
Test CG difference (X)	$\leq$5%	–	Track
Test CG difference (Y/Z)	$\leq$20% or 10 mm	–	Track

B.3 Environmental Requirements

B.3.1 Quasi-Static Load Factors

Per Table 4-1 of the Rideshare User's Guide, CubeSat dispenser payloads must be designed for:

Table B.4: Design Load Factors (CubeSat Dispenser)

Direction	Limit Load (g)	Test Factor	Test Load (g)
Axial (+X)	10.0	1.25×	12.5
Axial (−X)	6.0	1.25×	7.5
Lateral (±Y, ±Z)	5.0	1.25×	6.25
Combined (RSS)	17.0	1.25×	21.25

B.3.2 Vibration Environment

Table B.5: Random Vibration Requirements

Frequency (Hz)	MPE (g^2/Hz)	Protoflight (+3 dB)	Duration
20	0.01	0.02	
50	0.04	0.08	
800	0.04	0.08	1 min/axis
2000	0.01	0.02	
Overall	**5.57 Grms**	**7.87 Grms**	

B.3.3 Shock Environment

Table B.6: Shock Response Spectrum (Q=10)

Frequency (Hz)	MPE (g)
100	30
1000	1000
10000	1000

B.3.4 Thermal Environment

Table B.7: Thermal Boundary Conditions

Condition	Temperature	Notes
Hot boundary	+40°C to +69°C	Conductive interface
Cold boundary	−5°C to −20°C	Conductive interface
Fairing max (brief)	+200°C	Radiative, localized
Free molecular heating	$<$3,500 W/m^2	At fairing separation

B.3.5 Structural Frequency

- **Minimum frequency:** No elastic modes below 40 Hz
- **Quality factor:** Q between 10 and 50
- **Verification:** Low-level sine sweep (0.1g), $<$10% shift in first mode

B.3.6 Venting Requirements

- **Depressurization rate:** Maximum 0.40 psi/sec (nominal), 0.65 psi/sec (brief)
- **Vent ratio:** Enclosed volume / vent area $\leq$ 400 m
- **Action:** Verify Pathfinder structure venting compliance

B.4 Electrical and RF Requirements

B.4.1 Power Inhibit System

CRITICAL REQUIREMENT

All spacecraft systems must be powered OFF during launch until after separation. A mechanical inhibit switch (deployment switch or equivalent) is **MANDATORY**.

- **Pre-separation state:** All systems OFF except battery voltage sense
- **Inhibit mechanism:** Mechanical switch activated by dispenser deployment
- **Verification:** Power inhibit must be demonstrated during random vibration test
- **Evidence:** Boot logs or oscilloscope data showing no power during vibe

B.4.2 RF Transmission Restrictions

CRITICAL: S-Band Frequency Conflict

Pathfinder S-Band (2.0–2.3 GHz) overlaps with SpaceX restricted bands. Transmitter activation must be delayed until End of Mission ($\sim$1 hour after first deployment) OR frequencies must be modified.

Restricted S-Band frequencies (no transmission until End of Mission):

- 2206–2216 MHz
- 2227.5–2237.5 MHz

- 2242.5–2260.5 MHz
- 2267.5–2277.5 MHz
- 2365.5–2375.5 MHz
- 2377.5–2387.5 MHz

Pathfinder frequencies:

- Uplink: 2025–2110 MHz — No conflict
- Downlink: 2200–2290 MHz — Conflicts with 2206–2216, 2227.5–2237.5, 2242.5–2260.5, 2267.5–2277.5 MHz

Mitigation options:

1. Delay S-Band TX activation until End of Mission (∼1 hour post-separation)
2. Select downlink frequency outside restricted bands (e.g., 2290–2300 MHz)
3. Coordinate with SpaceX for waiver (unlikely)

B.4.3 Transmitter Turn-On Delay

For 2W transmitter (∼33 dBm EIRP), minimum delay after separation:

Table B.8: Minimum TX Turn-On Delay

Separation Velocity	Delay (seconds)
0.5 m/s	18
1.0 m/s	9
1.5 m/s	6

B.4.4 EMI/EMC Requirements

Table B.9: Radiated Emissions Limits

Frequency Range	Maximum (dBμV/m)
30 MHz – 1555 MHz	90
1555 MHz – 1595 MHz	48 (GPS protected)
1595 MHz – 18 GHz	90

B.5 Testing and Verification Requirements

B.5.1 Mandatory Tests

Table B.10: Required Verification Tests

Test	Level	Duration	Status
Quasi-static load	1.25× limit	3 axes	Planned
Random vibration	MPE (5.57 Grms)	1 min/axis	Planned
Power inhibit	During vibe	–	Planned
Low-level sine sweep	0.1g	Pre/post vibe	Planned

B.5.2 Recommended Tests

Table B.11: Advised Verification Tests

Test	Level	Duration	Status
Sinusoidal vibration	1.25× limit	4 oct/min	Planned
Acoustic	MPE +3 dB	1 min	Planned
Shock	MPE +3 dB	2×/axis	Planned
Thermal vacuum	−29°C to +66°C	20 cycles	Planned
EMI/EMC	6 dB margin	–	Planned

B.6 Safety and Materials

B.6.1 Prohibited Materials

- Cadmium or cadmium plating
- Zinc plating
- Mercury or mercury compounds
- Pure tin (must be alloyed)
- Sharpie markers (use approved alternatives)

B.6.2 Outgassing Requirements

All vacuum-exposed non-metallic materials must meet ASTM E-595:

- **Total Mass Loss (TML):** $\leq 1.0\%$
- **Collected Volatile Condensable Material (CVCM):** $\leq 0.1\%$

B.6.3 Battery Safety

The 120 Wh Li-ion battery (7S6P configuration) is classified as a hazardous system per AFSPCMAN 91-710. Required documentation:

- Battery cell qualification data
- Thermal runaway protection design
- Charge state limitations (typically 30–50% for launch)
- Inhibit design preventing discharge during integration

Battery charge duration: Standard 45 days from encapsulation to launch, or arrange pad charging.

B.7 Required Deliverables

Table B.12: SpaceX Documentation Requirements

Deliverable	Timing	Status
Payload Configuration Worksheet	Contract + 30 days	Pending
FAA Payload Review Information	Contract + 60 days	Pending
CAD Model (Parasolid/STEP)	T−6 months	Pending
Mass Properties Worksheet	T−6 months	Pending
Environmental Test Approach	Before testing	Pending
Environmental Verification Report	After testing	Pending
Materials/Contamination Report	T−3 months	Pending
FCC License Certification	T−2 months	Pending
Encapsulation Readiness Letter	Before encap	Pending
Launch Readiness Letter	Before rollout	Pending

B.8 Compliance Summary

Table B.13: Pathfinder SpaceX Rideshare Compliance Status

Category	Status	Action Required
Mechanical envelope	Compliant	Select dispenser
Mass/CG	Compliant	Document CG position
Structural frequency	Verify	Confirm >40 Hz first mode
Quasi-static loads	Compliant	Design verified
Vibration testing	Planned	Execute per Section 6
Thermal testing	Planned	Execute per Section 6
Power inhibit	Action Required	Implement mechanical switch
S-Band frequency	Action Required	Delay TX or change freq
EMI/EMC	Verify	Test to 6 dB margin
Battery safety	Document	Prepare safety package
Outgassing	Verify	Compile materials list
Venting	Verify	Analyze vent ratio

Appendix C

FCC Part 5 Experimental Licensing Requirements

This chapter addresses the regulatory requirements for operating the Pathfinder satellite under the United States Federal Communications Commission (FCC) Part 5 Experimental Radio Service rules. All non-federal radio stations operating in the United States must be authorized by the FCC, and experimental satellite operations require specific licensing procedures.

C.1 Regulatory Framework

C.1.1 Part 5 Overview

The rules and regulations for the experimental radio service are contained in Part 5 of Title 47 of the Code of Federal Regulations (47 CFR Part 5). The FCC's Office of Engineering and Technology (OET) administers Part 5 experimental licensing, which provides a framework for:

- Testing new technologies
- Conducting scientific research
- Demonstrating equipment capabilities
- Market studies and product development

Key Principle: All experimental licenses are granted on a **non-interference basis (NIB)**. This means experimental operations must not cause harmful interference to authorized services, and must accept any interference received from such services.

C.1.2 Applicable License Types

Table C.1: FCC Part 5 License Categories

License Type	Duration	Use Case
Experimental License (Form 442)	Up to 5 years	Long-term operations
Special Temporary Authority (STA)	Up to 6 months	Short-term/urgent testing
Program Experimental License	Up to 5 years	Multiple related experiments

For the Pathfinder mission, the recommended approach is:

1. **Initial STA** for pre-launch testing and early operations
2. **Full Experimental License (Form 442)** for the complete mission duration

C.2 Application Requirements

C.2.1 FCC Form 442

The primary application form for experimental licenses is FCC Form 442. Required information includes:

Table C.2: Form 442 Required Information

Category	Required Details
Applicant Information	Legal name, address, FRN
Technical Parameters	Frequencies, power, bandwidth, modulation
Station Location	Orbital parameters for space stations
Equipment Description	Transmitter specifications
Purpose of Experiment	Technical objectives and research goals
Interference Analysis	Potential for interference to other services

C.2.2 ITU Satellite Network Filing

Critical Requirement: For space station operations, applicants must also coordinate with the International Telecommunication Union (ITU) through the FCC's International Bureau. This involves:

- **Advance Publication Information (API):** Initial notification to ITU
- **Coordination Request:** Detailed technical parameters for international coordination
- **Notification:** Final filing before bringing the network into use

Timing: ITU filings should be initiated at least 18–24 months before launch to allow adequate coordination time.

C.2.3 Orbital Debris Mitigation Plan

Per FCC regulations (47 CFR §5.64), all experimental space station applications must include an Orbital Debris Mitigation (ODM) plan addressing:

Table C.3: ODM Plan Requirements

Element	Description
Post-Mission Disposal	Plan for deorbiting within 25 years (5 years for LEO under new rules)
Collision Avoidance	Capability and procedures for maneuvering to avoid debris
Trackability	Spacecraft must be trackable by Space Surveillance Network
Debris Generation	Assessment of potential debris from breakup or collision
Casualty Risk	Human casualty risk assessment for reentry ($<$1:10,000)

Pathfinder Compliance: At 550 km altitude, natural atmospheric drag will deorbit the spacecraft within approximately 5–7 years, meeting the 25-year requirement. Additionally, Pathfinder incorporates a drogue chute deorbit system for accelerated disposal.

Drogue Chute Deorbit System

Pathfinder includes a deployable drogue chute to dramatically increase drag area and accelerate orbital decay at end-of-life, ensuring rapid deorbit compliance.

System Overview The drogue chute deploys on command at end-of-mission, increasing the spacecraft's effective cross-sectional area and reducing orbital lifetime from years to months.

Table C.4: Drogue Chute System Specifications

Parameter	**Specification**
Chute Type	Hemispherical drogue (drag-optimized)
Deployed Diameter	2.0 m
Material	Aluminized Kapton (25 μm)
Stowed Volume	$<$0.3U
Mass (chute + deployer)	400 g
Deployment Mechanism	Spring-loaded with burn wire release
Tether Length	3 m (Dyneema)
Drag Coefficient (C_D)	1.5 (hemispherical)

Drag Area Calculations The key parameter for orbital decay is the ballistic coefficient (β), defined as:

$$\beta = \frac{m}{C_D \cdot A} \tag{C.1}$$

where m is spacecraft mass, C_D is the drag coefficient, and A is the cross-sectional area.

Table C.5: Drag Area Comparison: Baseline vs. Drogue Deployed

Configuration	**Area (m^2)**	C_D	$C_D \cdot A$ **(m^2)**	**Increase**
Baseline (12U, ram-facing)	0.077	2.2	0.169	–
Baseline (12U, max area)	0.051	2.2	0.112	–
Drogue Chute (2.0 m dia.)	3.14	1.5	4.71	–
Total with Drogue	**3.22**	–	**4.88**	**29**$\times$

Calculation:

- 12U baseline area: $0.226 \times 0.340 = 0.077$ m^2 (ram-facing)
- Drogue chute area: $\pi \times (1.0)^2 = 3.14$ m^2
- Area increase factor: $\frac{3.14+0.077}{0.077} = \mathbf{42}\times$ (geometric)
- Effective drag increase: $\frac{4.88}{0.169} = \mathbf{29}\times$ (accounting for C_D differences)

Ballistic Coefficient Analysis Lower ballistic coefficient results in faster orbital decay:

Table C.6: Ballistic Coefficient Comparison

Configuration	**Mass (kg)**	$C_D \cdot A$ **(m^2)**	β **(kg/m^2)**
Baseline (12U)	15.5	0.169	91.7
With Drogue	15.9	4.88	**3.26**
Reduction factor:			**28**$\times$

Orbital Lifetime Analysis Orbital lifetime depends on altitude, solar activity, and ballistic coefficient. Using the exponential atmosphere model:

$$\tau \propto \beta \cdot H \cdot e^{(h-h_0)/H} \tag{C.2}$$

where H is the atmospheric scale height ($\sim$60 km at 400–600 km) and h is altitude.

Table C.7: Estimated Orbital Lifetime at 550 km

Configuration	β **(kg/m^2)**	**Solar Min**	**Solar Max**
Baseline (12U)	91.7	7–10 years	3–5 years
With Drogue Deployed	3.26	**3–5 months**	**1–2 months**
FCC 5-year requirement:		Compliant with margin	

Altitude Decay Rate The semi-major axis decay rate is given by:

$$\frac{da}{dt} = -\frac{\rho \cdot A \cdot C_D}{m} \cdot v \cdot a \tag{C.3}$$

At 550 km with atmospheric density $\rho \approx 10^{-13}$ kg/m^3 (solar minimum):

Table C.8: Decay Rate Comparison

Configuration	**Decay Rate (km/day)**	**Time to 200 km**
Baseline	0.02–0.05	5–7 years
With Drogue	**0.6–1.5**	**3–6 months**

Deployment Sequence

1. End-of-mission command received (or autonomous timeout trigger)
2. Spacecraft orients to ram-facing attitude (velocity vector)
3. Burn wire activated, releasing spring-loaded deployer
4. Drogue chute extracts and inflates via ram pressure
5. Tether tensions, stabilizing chute behind spacecraft
6. Passive drag deorbit proceeds until atmospheric reentry

Table C.9: Drogue Chute System Budget

Component	**Mass (g)**	**Volume**	**Cost ($)**
Drogue Chute (Kapton, 2m)	150	–	2,000
Tether (3m Dyneema)	20	–	200
Spring Deployer Mechanism	180	0.2U	3,500
Burn Wire Release	30	–	500
Housing/Structure	20	0.1U	800
Total	**400**	**0.3U**	**7,000**

Component Budget **Summary:** The drogue chute system provides a 29$\times$ increase in effective drag area, reducing orbital lifetime from 5–7 years to 3–6 months. This ensures compliance with FCC 5-year deorbit requirements with significant margin, and demonstrates responsible space stewardship.

C.3 Frequency Coordination

C.3.1 NTIA Coordination

For frequencies shared with federal users, the FCC coordinates with the National Telecommunications and Information Administration (NTIA). The S-Band frequencies used by Pathfinder may require such coordination:

Table C.10: Pathfinder Frequency Allocations and Coordination Status

Band	Frequency	Allocation	Coordination
S-Band Uplink	2025–2110 MHz	Space Operation (S-E)	NTIA required
S-Band Downlink	2200–2290 MHz	Space Operation (E-S)	NTIA required
SDR Reception	Multiple bands	Passive receive only	No TX coordination

Note: The 2200–2290 MHz band is allocated to the Space Operation Service and is heavily used by government agencies (NASA, NOAA). Coordination processing typically takes 60–90 days.

C.3.2 Non-Interference Basis Operation

Operating on a non-interference basis requires:

1. **Cease Operations:** Must immediately cease transmissions upon notification of interference
2. **No Protection:** Cannot claim protection from interference by authorized stations
3. **Coordination:** Must coordinate with potentially affected licensees before operations
4. **Documentation:** Must maintain logs of interference complaints and remedial actions

C.4 Ground Station Licensing

C.4.1 Earth Station Requirements

Ground stations communicating with Pathfinder also require FCC authorization:

- **Commercial GSaaS Providers:** Typically hold blanket earth station licenses covering customer operations
- **Dedicated Ground Stations:** Require individual earth station license under Part 25 or inclusion in Part 5 experimental license

Recommendation: Use GSaaS providers (Leaf Space, KSAT, AWS Ground Station) that maintain their own FCC authorizations to simplify licensing burden.

C.4.2 Uplink Coordination

Earth-to-space transmissions require careful coordination to avoid interference with:

- Terrestrial microwave links
- Other satellite systems
- Government/military systems in shared bands

C.5 Compliance Timeline

Table C.11: FCC Licensing Timeline for Pathfinder

Milestone	Timing	Status
FCC Registration Number (FRN)	T−24 months	Pending
ITU API Filing	T−24 months	Pending
Form 442 Submission	T−18 months	Pending
NTIA Coordination Request	T−18 months	Pending
ITU Coordination	T−12 months	Pending
Experimental License Grant	T−9 months	Pending
Ground Station Coordination	T−6 months	Pending
Pre-launch STA (if needed)	T−3 months	Pending
ITU Notification	T−1 month	Pending
Bring-into-Use	Launch + 1 day	Planned

C.6 Required Documentation

The following documentation package must be prepared for FCC submission:

Table C.12: FCC Filing Documentation Requirements

Document	Contents
Technical Exhibit	Detailed RF parameters, link budgets, antenna patterns
Orbital Parameters	Altitude, inclination, RAAN, orbital period
Interference Analysis	PFD calculations, coordination contours
ODM Plan	Post-mission disposal, collision avoidance, casualty risk
Experiment Narrative	Research objectives, expected duration, public interest
Legal Certification	Compliance with FCC rules, applicant qualifications

C.7 Compliance Summary

Table C.13: Pathfinder FCC Part 5 Compliance Status

Requirement	Status	Action Required
FCC Registration (FRN)	Not Started	Apply via CORES system
Form 442 Application	Not Started	Prepare technical exhibit
ITU Filings	Not Started	Initiate API process
NTIA Coordination	Not Started	Begin S-Band coordination
ODM Plan	In Progress	Document deorbit analysis
Interference Analysis	In Progress	Complete link budget for filing
NIB Compliance	Understood	Design for immediate TX cutoff
Ground Station License	Via GSaaS	Confirm provider coverage

Critical Path Items:

1. Obtain FRN immediately to enable all subsequent filings
2. Initiate ITU API process due to long coordination timeline

3. Prepare comprehensive technical exhibit for Form 442
4. Begin NTIA coordination for S-Band frequencies

Appendix D

Export Control Compliance

This chapter addresses U.S. export control regulations applicable to the Pathfinder satellite program, with particular focus on requirements when employing foreign nationals. Non-compliance with export control regulations can result in severe criminal and civil penalties, including fines up to $1 million per violation and imprisonment.

D.1 Regulatory Framework Overview

D.1.1 Dual Regulatory Regime

U.S. export controls for space-related items are governed by two parallel regimes:

Table D.1: U.S. Export Control Regulatory Framework

Regulation	Administering Agency	Control List
ITAR (22 CFR 120–130)	State Dept. (DDTC)	U.S. Munitions List (USML)
EAR (15 CFR 730–774)	Commerce Dept. (BIS)	Commerce Control List (CCL)

Key Distinction: ITAR controls defense articles with inherent military applications; EAR controls dual-use items with both commercial and potential military applications.

D.1.2 Spacecraft Classification

Spacecraft and related items may fall under either regime depending on their capabilities:

Table D.2: Spacecraft Export Control Classification

Item Category	ITAR (USML)	EAR (CCL)
Military/intelligence spacecraft	Category XV	–
Remote sensing spacecraft	Category XV	ECCN 9A515.a
Commercial communications	–	ECCN 9A515
CubeSat components	Varies	ECCN 9A515.x/.y
Radiation-hardened electronics	Category XI/XV	ECCN 3A001/9A515
Propulsion systems	Category IV/XV	ECCN 9A515
Star trackers	Category XII	ECCN 7A003/9A515

D.1.3 October 2024 Regulatory Updates

On October 23, 2024, BIS and DDTC issued significant updates to space-related export controls:

- **Allied Country Exemptions:** Removed license requirements for Australia, Canada, and United Kingdom for certain ECCN 9A515 items
- **Control Downgrade:** Certain 9A515.x items downgraded from NS1/RS1 to NS2/RS2 controls
- **New ECCNs:** Added classifications for ion propulsion, gyroscopes, and satellite release mechanisms
- **License Exception CSA:** New Commercial Space Activities exception for qualifying exports

D.2 Deemed Export Requirements

D.2.1 Definition and Scope

Critical Concept: A "deemed export" occurs when controlled technology or technical data is disclosed to a foreign national within the United States. Such disclosure is legally equivalent to an export to that person's country of nationality.

Table D.3: Deemed Export Triggers

Activity	Export Control Implication
Verbal discussion of technical data	Deemed export
Visual access to controlled hardware	Deemed export
Email/document sharing	Deemed export
Whiteboard discussions	Deemed export
Lab access with controlled equipment	Deemed export
Source code repository access	Deemed export

D.2.2 Foreign National Definition

Under export control regulations, a "foreign national" or "foreign person" includes:

- Any person who is not a U.S. citizen
- Any person who is not a U.S. permanent resident (Green Card holder)
- Any person who is not a protected person under 8 U.S.C. 1324b(a)(3)
- Foreign corporations, governments, and organizations

Note: Visa status (H-1B, O-1, J-1, F-1, L-1, etc.) does not exempt foreign nationals from deemed export requirements. A license may be required regardless of lawful U.S. presence.

D.2.3 Dual and Third-Country Nationals

Persons holding citizenship in multiple countries require special consideration:

- Disclosure is treated as export to *all* countries of nationality
- Most restrictive controls apply
- Must be licensed for each country of nationality

D.3 Pathfinder Component Classification

D.3.1 Preliminary ECCN/USML Assessment

Table D.4: Pathfinder Component Export Classification Assessment

Component	Likely Classification	Regime	License Required
Jetson Orin NX	EAR99 or 4A994	EAR	Likely No
SAMV71Q21B MCU	EAR99	EAR	No
Syrlinks S-Band	ECCN 9A515.y	EAR	Destination-dependent
Sagitta Star Tracker	ECCN 7A003 or USML XII	TBD	Likely Yes
CubeWheel RW	ECCN 9A515.y	EAR	Destination-dependent
ADRV9002 SDR	ECCN 3A001 or 5A001	EAR	Destination-dependent
ISIS Structure	EAR99	EAR	No
Solar Panels	EAR99	EAR	No
Propulsion System	ECCN 9A515 or USML IV	TBD	Likely Yes

Action Required: Formal Commodity Jurisdiction (CJ) determination from DDTC and/or Commerce Classification (CCATS) from BIS for all controlled components.

D.3.2 Integrated Spacecraft Classification

When components are integrated into a complete spacecraft, the entire system typically takes the classification of its most controlled element. The Pathfinder satellite as an integrated system will likely require:

- USML Category XV classification review (if any ITAR components)
- ECCN 9A515 classification (if all components are EAR-controlled)
- Technical Assistance Agreement (TAA) for foreign national involvement

D.4 Compliance Requirements for Foreign Nationals

D.4.1 Required Authorizations

Table D.5: Export Authorization Types

Authorization	Regime	Use Case
Technical Assistance Agreement (TAA)	ITAR	Defense services, technical data sharing with foreign persons
Manufacturing License Agreement (MLA)	ITAR	Foreign production of defense articles
DSP-5 License	ITAR	Permanent export of defense articles
BIS License	EAR	Export of dual-use items to restricted destinations
License Exception	Both	Qualifying activities exempt from licensing

D.4.2 Technology Control Plan (TCP)

When foreign nationals have access to controlled technology, a Technology Control Plan must be implemented:

Table D.6: Technology Control Plan Elements

Element	Requirements
Physical Security	Controlled access areas, badge systems, escort requirements
IT Security	Separate networks, access controls, encryption, audit logs
Personnel Controls	Background checks, citizenship verification, NDA requirements
Document Controls	Classification markings, distribution lists, storage requirements
Training	Export control awareness training for all personnel
Visitor Controls	Foreign visitor registration, escort policies, briefing areas
Incident Response	Procedures for unauthorized disclosure, reporting requirements

D.4.3 Empowered Official

Organizations handling ITAR-controlled items must designate an Empowered Official who:

- Has authority to sign export license applications
- Ensures compliance with ITAR requirements
- Is a U.S. citizen or permanent resident
- Has direct knowledge of controlled activities

Table D.7: Designated Export Control Officer

Role	Designation
Empowered Official / Export Control Officer	Razvan Mircea Roman
Citizenship	U.S. Citizen
Authority	License applications, compliance oversight
Status	Designated

D.5 DDTC Registration

D.5.1 Requirement

Any U.S. person or entity that manufactures, exports, or brokers defense articles must register with the Directorate of Defense Trade Controls (DDTC), even if no exports are planned.

Table D.8: DDTC Registration Requirements

Requirement	Details
Registration Fee	$2,250 annually
Renewal	Annual
Processing Time	30–45 days
Form	DS-2032

D.5.2 Registration Triggers

Registration is required if the organization:

- Manufactures USML defense articles (including spacecraft)
- Exports defense articles or technical data

- Provides defense services to foreign persons
- Brokers defense article transactions

D.6 SpaceX Rideshare Export Requirements

D.6.1 Launch Provider Obligations

SpaceX, as a U.S. launch provider, operates under its own ITAR compliance program. Rideshare customers must:

- Certify compliance with U.S. export control regulations
- Provide export classification for all payload components
- Obtain necessary licenses for any foreign-origin components
- Ensure no technology transfer to prohibited destinations

D.6.2 Foreign Customer Restrictions

SpaceX rideshare services are subject to restrictions based on payload origin:

Table D.9: SpaceX Rideshare Country Restrictions

Category	Countries/Status
Prohibited	China, Russia, Iran, North Korea, Syria, Cuba, Venezuela
Restricted	Require specific licenses and enhanced due diligence
Allied	Australia, Canada, UK benefit from October 2024 exemptions

D.7 Penalties for Non-Compliance

D.7.1 ITAR Violations

Table D.10: ITAR Penalty Structure

Violation Type	Maximum Penalty
Criminal (willful)	\$1,000,000 and/or 20 years imprisonment per violation
Civil	\$1,217,364 per violation (2024 adjusted)
Administrative	Debarment from export privileges

D.7.2 EAR Violations

Table D.11: EAR Penalty Structure

Violation Type	Maximum Penalty
Criminal	\$1,000,000 and/or 20 years imprisonment
Civil	Greater of \$330,947 or 2$\times$ transaction value
Administrative	Denial of export privileges

D.8 Compliance Implementation Plan

D.8.1 Immediate Actions

1. **Jurisdiction Determination:** Submit CJ requests to DDTC for ITAR/EAR classification
2. **DDTC Registration:** Register if any components are USML-controlled
3. **Personnel Audit:** Document citizenship status of all team members
4. **Component Classification:** Obtain ECCN classifications for all components

D.8.2 Foreign National Onboarding Process

Table D.12: Foreign National Clearance Process

Step	Action	Timeline
1	Citizenship/nationality verification	Week 1
2	Restricted party screening	Week 1
3	Determine technology access requirements	Week 2
4	License application (if required)	Week 2–4
5	License approval (TAA)	3–6 months
6	Export control training	Before access
7	TCP implementation	Before access
8	Supervised access begins	Post-approval

Critical Note: TAA processing typically takes 3–6 months. Foreign nationals cannot access controlled technology until authorization is received.

D.9 Compliance Summary

Table D.13: Pathfinder Export Control Compliance Status

Requirement	Status	Action Required
DDTC Registration	Not Started	Submit DS-2032
Commodity Jurisdiction	Not Started	Submit CJ requests
Component ECCNs	Not Started	Request CCATS
Personnel Audit	Not Started	Document all nationalities
Technology Control Plan	Not Started	Develop TCP
Empowered Official	Designated	Razvan Mircea Roman (U.S. Citizen)
TAA (if needed)	Not Started	Prepare after CJ
Export Control Training	Not Started	Develop program
Restricted Party Screening	Not Started	Implement process

Critical Path Items:

1. Conduct personnel citizenship audit immediately
2. Submit Commodity Jurisdiction requests to establish classification
3. Register with DDTC if any ITAR-controlled items identified

4. Develop Technology Control Plan before any foreign national access
5. Apply for TAA if foreign nationals require access to ITAR data
6. Implement restricted party screening for all personnel and vendors

Warning: Foreign nationals must **not** be granted access to any potentially controlled technical data, hardware, or source code until proper authorization is obtained. Premature disclosure constitutes an unlicensed export and may result in severe penalties.

Appendix E

Comprehensive Risk Analysis

This appendix provides a detailed analysis of programmatic risks that may impact the Pathfinder mission schedule, budget, and success. Unlike the technical risks addressed in the main body, this appendix focuses on logistical, regulatory, supply chain, and integration risks that are often underestimated in satellite development programs.

E.1 Executive Summary

Key Finding: The linear project schedule presented in the main document assumes best-case scenarios. Historical data shows that 87% of smallsat launch delays are avoidable with proper planning, but the remaining 13% represent irreducible external factors.

Table E.1: Risk Summary by Category

Category	High Risks	Medium Risks	Potential Delay
Launch Logistics	1	4	3–12 months
Regulatory Compliance	2	4	6–24 months
Supply Chain	1	5	2–6 months
Testing/Integration	1	3	1–4 months
Total	**5**	**16**	–

E.2 Launch Logistics Risks

E.2.1 SpaceX Rideshare Program (January 2026 Status)

SpaceX dominates the smallsat rideshare market with approximately 57% of Western smallsat launch demand. In 2025, SpaceX achieved 170+ Falcon 9 launches with >99% success rate. The rideshare program operates three mission series:

Table E.2: SpaceX Rideshare Mission Series (2026)

Series	Orbit	Cadence	2026 Missions
Transporter	SSO (∼90°)	Quarterly	T-16, T-17, T-18, T-19
Bandwagon	Mid-incl. (∼45°)	Semi-annual	B-5, B-6
Twilight	Dawn-dusk SSO	New program	TBD

E.2.2 Manifest Slot Availability

Current market conditions (January 2026):

Table E.3: SpaceX Rideshare Wait Times

Slot Type	Current Wait	Cost
Standard rideshare slot	12–24 months	$300,000 base (50 kg)
CubeSat deployer (via aggregator)	6–18 months	$6,500/kg
Cake Topper position	12–24 months	Premium pricing

E.2.3 Launch Delay Statistics

Table E.4: Historical SpaceX Rideshare Delay Analysis

Delay Type	Probability	Duration
Short-term (weather, range)	30–40%	24–72 hours
Co-payload delay	15–20%	1–4 weeks
Vehicle anomaly investigation	5–10%	1–3 months
Manifest restructuring	10–15%	1–6 months

Aggregate Assessment: 50–60% probability of launching within 1 week of target date; 80% probability within 1 month.

E.2.4 Alternative Launch Providers

If SpaceX rideshare is unavailable, alternatives include:

Table E.5: Alternative Launch Provider Comparison (January 2026)

Provider	Vehicle	Cost	Lead Time	Success Rate
Rocket Lab	Electron	$8.4M dedicated	6–12 months	98% (through 2025)
Rocket Lab	Neutron	$4,230/kg (est.)	2026 first flight	–
ISRO/NSIL	PSLV	$21–31M	12–18 months	96%
ISRO/NSIL	SSLV	$3.7M	6–12 months	67%
Avio	Vega C	$37M+	18–24 months	86%

Note: Vega C transitioned from Arianespace to Avio management in December 2025.

E.2.5 Launch Aggregators

For CubeSat missions, launch aggregators provide additional flexibility:

- **Exolaunch** (Germany): EXOpod deployers, SpaceX partnership
- **Spaceflight Inc.** (USA): Sherpa orbital transfer vehicles
- **D-Orbit** (Italy): ION satellite carrier, last-mile delivery
- **Maverick Space** (USA): Turnkey rideshare services
- **ISISpace** (Netherlands): QuadPack deployers, launch brokerage

E.3 Regulatory Compliance Timeline Risks

E.3.1 FCC Part 5 Experimental License

Table E.6: FCC Licensing Timeline Scenarios

Scenario	Best Case	Expected	Worst Case
Simple application	30 days	60–90 days	120 days
Satellite application	60 days	90–180 days	12+ months
Federal freq. coordination	+30 days	+60 days	+90 days

Risk Factors:

- Application returned without action: 20–30% probability
- Federal coordination delays (NTIA): 40% probability, 60–90 day impact
- Technical questions from OET: 30% probability, 14–45 day response cycle
- Interference objections: 10–15% probability, 60–180 day resolution

E.3.2 ITU Satellite Network Filing

Table E.7: ITU Filing Timeline Scenarios

Phase	Best Case	Expected	Worst Case
Advance Publication (API)	3 months	4–6 months	9 months
Coordination Request	6 months	12–24 months	36+ months
Notification Filing	3 months	6 months	12 months
Total Process	**12 months**	**24–36 months**	**5+ years**

Critical: ITU API must be submitted 2–7 years before planned operations. For a 2027 launch, API filing should begin immediately.

E.3.3 ITAR/Export Control Authorization

Table E.8: Export Control Processing Times

Authorization	Best Case	Expected	Worst Case
DDTC Registration	14 days	30–45 days	60 days
Commodity Jurisdiction (CJ)	30 days	45–60 days	95 days
Technical Assistance Agreement	30 days	60–120 days	180+ days
DSP-5 Export License	30 days	60–90 days	180 days

Foreign National Impact: If foreign nationals require access to ITAR-controlled data, TAA processing (3–6 months) is on the critical path. Work cannot begin until authorization is received.

E.4 Supply Chain Risks

E.4.1 Component Lead Time Analysis

Table E.9: Critical Component Lead Times

Component	Best	Expected	Worst	Risk
Arcsec Sagitta Star Tracker	12 wks	16–20 wks	24–28 wks	HIGH
Syrlinks S-Band Transceiver	10 wks	12–16 wks	20–24 wks	MEDIUM
CubeSpace CubeWheel RW	8 wks	12–16 wks	18–22 wks	MEDIUM
GOMspace P60 EPS	8 wks	10–12 wks	14–18 wks	MEDIUM
Analog Devices ADRV9002	2 wks	6–10 wks	14–18 wks	MEDIUM
NVIDIA Jetson Orin NX	2 wks	6–8 wks	16–20 wks	LOW
Microchip SAMV71Q21B	Same day	1–2 wks	4–6 wks	LOW

Critical Path Item: The Arcsec Sagitta star tracker has the longest lead time (16–20 weeks expected) and must be ordered at PDR to avoid schedule impact.

January 2026 Status:

- **NVIDIA Jetson Orin NX:** Generally available at authorized distributors; supply improved since 2024 shortages. Memory constraints may affect AI chip availability through 2026–2027.
- **Microchip SAMV71Q21B:** Actively stocked at major distributors (DigiKey, Mouser). Industrial-grade; space-qualified SAMRH71 has longer lead times.
- **Star Tracker:** 4–5 month lead time typical for CubeSat star trackers. Order earliest.

E.4.2 Single Points of Failure

Table E.10: Supply Chain Single Points of Failure

Component	Risk Level	Alternative
Arcsec Sagitta	HIGH	Blue Canyon NST, Terma T3, Berlin Space Tech ST200
Syrlinks S-Band	MEDIUM-HIGH	EnduroSat, AAC Clyde Space QUASAR
GOMspace EPS	MEDIUM	NanoAvionics EPS, AAC Clyde Space STARBUCK

Vendor Risk Note (January 2026): GOMspace has not achieved sustained profitability, with break-even targeted for 2026. Major shareholder (Hargreaves Family) increasing stake to 41.27% may trigger mandatory acquisition bid. Pre-qualify NanoAvionics or AAC Clyde Space EPS as contingency before committing to GOMspace P60.

E.5 Testing and Integration Risks

E.5.1 Environmental Testing Timeline

Table E.11: Testing Campaign Duration Scenarios

Scenario	Duration	Probability	Conditions
Best case	11 weeks	15%	No anomalies, facilities available
Expected	19 weeks	60%	Minor issues, typical delays
Worst case	30 weeks	25%	Major rework required

E.5.2 Common Test Failure Modes

Table E.12: Test Failure Statistics

Test Type	First-Time Failure Rate	Rework Time
Vibration testing	10–20%	2–4 weeks
TVAC anomalies	15–25%	2–6 weeks
EMC/EMI failures	20–30%	2–8 weeks
Functional test failures	15–25%	1–4 weeks

Industry Statistic: Academic CubeSat success rate is approximately 45%; commercial CubeSats achieve 77%. Truncated testing due to schedule pressure directly correlates with on-orbit failures.

Primary On-Orbit Failure Categories:

- **EPS failures:** >40% of all failures after first 30 days (battery, solar array, power regulation)
- **Communications:** 20–25% (antenna deployment, frequency drift, link margin)
- **Mechanical/Structural:** 15–20% (deployment mechanisms, fastener loosening)
- **Dead on Arrival:** 10–15% of all launches (50% of DOA cases have unknown cause)

E.5.3 SpaceX Testing Requirements

Per SpaceX Rideshare Payload User's Guide, the following tests are mandatory:

- Quasi-static load test at 1.25× limit loads
- Random vibration at MPE levels (5.57 Grms)
- Power inhibit verification during random vibration
- Low-level sine sweep pre/post vibration

Critical Requirement: If more than 20 fasteners are reworked after vibration testing, SpaceX requires penalty re-test of the entire vibration campaign.

E.6 Master Risk Register Summary

E.6.1 Top 10 Program Risks

Table E.13: Top 10 Program Risks by Score

Rank	Risk	L	I	Mitigation
1	Star tracker lead time	3	4	Order at PDR
2	FCC Part 5 license delay	3	4	File T-18 months
3	ITU coordination delay	3	3	File API immediately
4	Export control (TAA) delay	3	3	Begin CJ process now
5	Launch slot availability	3	3	Book T-24 months
6	Jetson radiation susceptibility	3	3	Triple redundancy
7	Test facility availability	3	3	Book T-6 months
8	Vendor financial instability	2	4	Pre-qualify alternates
9	Schedule compression	3	3	Build margin into plan
10	S-Band frequency conflict	2	4	Delay TX or change freq

L = Likelihood (1–5), I = Impact (1–5)

E.7 Timeline Impact Analysis

E.7.1 Delay Cascade Scenarios

Table E.14: Cumulative Delay Impact Scenarios

Scenario	Cumulative Delay	Probability
Nominal (all best-case)	0 months	5%
Minor delays (typical)	2–4 months	40%
Moderate delays (one major issue)	6–9 months	35%
Significant delays (multiple issues)	12–18 months	15%
Major program restructure	18–24+ months	5%

Expected Outcome: Based on historical data and the current risk profile, a 6–9 month delay from the nominal schedule should be considered the realistic baseline for planning purposes.

E.7.2 Schedule Reserve Recommendations

Based on the risk analysis:

- **Regulatory:** Add 6 months reserve for licensing/coordination
- **Procurement:** Add 3 months reserve for component delays
- **Testing:** Add 2 months reserve for anomaly resolution
- **Launch:** Target T-3 months ahead of required operational date

E.8 Mitigation Strategy Summary

E.8.1 Immediate Actions (Now)

1. **Regulatory:** Obtain FCC Registration Number (FRN) via CORES system
2. **ITU:** Initiate API filing process through FCC International Bureau
3. **Export:** Begin Commodity Jurisdiction determination for all components
4. **Personnel:** Conduct citizenship audit of all team members
5. **Launch:** Submit inquiry to SpaceX Rideshare program

E.8.2 Near-Term Actions (0–3 Months)

1. Submit FCC Form 442 experimental license application
2. Begin NTIA coordination for S-Band frequencies
3. Submit DDTC registration if ITAR components identified
4. Order star tracker and other long-lead components
5. Develop Technology Control Plan if foreign nationals involved

E.8.3 Contacts and Resources

Table E.15: Key Regulatory and Program Contacts

Organization	Contact
FCC OET (Experimental Licensing)	oetinfo@fcc.gov, 202-418-2470
DDTC (Export Control)	pmddtc.state.gov
NTIA (Spectrum Management)	ntia.doc.gov
SpaceX Rideshare	rideshare@spacex.com
18th Space Control Squadron	www.space-track.org
Exolaunch (Aggregator)	sales@exolaunch.com
Spaceflight Inc. (Aggregator)	sales@spaceflight.com

E.9 Risk Monitoring Recommendations

E.9.1 Review Cadence

- **Weekly:** During I&T phase, daily standup with risk review
- **Bi-weekly:** Program risk register review meeting
- **Monthly:** Executive risk summary to stakeholders
- **Milestone:** Formal risk review at PDR, CDR, TRR, FRR

E.9.2 Key Risk Indicators

Monitor the following metrics as early warning indicators:

- Component delivery dates vs. plan
- Regulatory application status and response times
- Test anomaly rate and resolution time
- Budget burn rate vs. plan
- Launch manifest slot confirmation status

Appendix F

Vendor Contact Information

Table F.1: Key Vendors

Vendor	Products	Contact
NVIDIA	Jetson Orin NX	embedded-inquiries@nvidia.com
Microchip	SAMV71 MCU	aerospace@microchip.com
Syrlinks	S-Band TT&C	contact@syrlinks.com
Arcsec	Sagitta Star Tracker	info@arcsec.space
CubeSpace	CubeWheel RW	sales@cubespace.co.za
ISIS	Structure	sales@isispace.nl
GOMspace	EPS	sales@gomspace.com
Analog Devices	ADRV9002 SDR	space@analog.com
EnduroSat	Solar Panels	sales@endurosat.com