# PROYECTO ULISES

## Misión de Encuentro Extendido con el Cometa Halley

### Extended Encounter Mission with Comet Halley

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## Preliminary Design Review (PDR)

### Revisión Preliminar de Diseño

### NASA Class A Mission Documentation

NASA-STD-7009 / ECSS-E-ST-10C / NPR 7120.5E Compliance

| | |
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# NASA/ESA Approval Record

| Name/Function | Organization | Date | TRL Verif. | Signature |
|---|---|---|---|---|
| Project Leader | Ulises Project | | ✓ | |
| Chief Systems Engineer | Ulises Project | | ✓ | |
| Science Principal | Ulises Project | | ✓ | |
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|---|---|---|---|---|
| Líder de Proyecto | Proyecto Ulises | | ✓ | |
| Ingeniero Jefe de Sistemas | Proyecto Ulises | | ✓ | |
| Responsable Científico | Proyecto Ulises | | ✓ | |
| Representante NASA | NASA HQ | | ✓ | |
| Representante ESA | ESA/ESTEC | | ✓ | |
| NASA Safety Review | NASA OSMA | | ✓ | |
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**Estado del Documento:** **APROBADO PARA FASE B**
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# 1 Resumen Ejecutivo

El **Proyecto ULISES** representa un avance paradigmático en exploración cometaria, diseñando la primera misión de encuentro extendido con capacidad de operación continua durante un ciclo orbital completo del cometa Halley (76 años).

## 1.1 Objetivos Principales NASA-Compliant

- Establecer observatorios científicos permanentes en la superficie del cometa
- Estudiar la evolución del núcleo a través de fases de actividad extremas
- Demostrar tecnologías ISRU (Utilización de Recursos In-Situ) para generación de energía
- Validar sistemas de anclaje multi-modal para cuerpos de baja gravedad
- Transmitir datos científicos de alta resolución mediante comunicaciones láser

## 1.2 Arquitectura de Misión

Table 3: Arquitectura principal de la misión ULISES

| **Elemento** | **Especificación NASA-Compliant** |
|---|---|
| Sonda Nodriza "Ulises" | Plataforma principal: V = 17.8 km/s, 2825 kg masa seca |
| Sondas de Superficie (4) | Valentina, Aarón, Júpiter (primarias), Minerva (reserva) |
| Sistema ISRU -ICE | Generación energía: 37-369 W, eficiencia 45% |
| Comunicaciones DSOC | Láser: 267 Mbps pico, RF redundante banda X/Ka |
| Sistema Anclaje | Multi-modal: P(éxito) $>$ 0.978, 5 tecnologías redundantes |
| Vida Útil | 76+ años (ciclo orbital completo Halley) |

## 1.3 Análisis de Viabilidad NASA

$$\text{Fiabilidad Misión} = \prod_{i=1}^{n} R_i(t) \times \left[1 - \prod_{j=1}^{m}(1 - R_{redundante,j}(t))\right] = 0.648 \quad (1)$$

- **Lanzamiento**: 2039 (ventana 2038-2040)
- **Encuentro**: 2059 (2 años antes del perihelio)
- **Duración**: 76+ años (2059-2135+)
- **Presupuesto**: USD 8.9B (incluyendo contingencia del 15% NASA-Clase A)
- **TRL Global**: 4.2 (objetivo TRL-6 para 2028)

### 1.4 Innovaciones Clave

- **Primera misión de 76 años**: Supera todas las misiones anteriores en duración
- **Sistema ISRU autónomo**: Genera energía del cometa mismo
- **Comunicaciones láser**: Transmisión de datos 100x mayor que sistemas RF
- **Anclaje multi-modal**: Supera limitaciones del histórico aterrizaje de Philae

### 1.5 Análisis de Riesgo Cuantitativo

```python
import numpy as np

def nasa_risk_assessment():
    """NASA PDR Risk Assessment per NPR 8000.4C"""
    risks = {
        'technical': {'probability': 0.35, 'impact': 0.7, 'mitigation': 0.6},
        'schedule': {'probability': 0.25, 'impact': 0.5, 'mitigation': 0.7},
        'cost': {'probability': 0.30, 'impact': 0.6, 'mitigation': 0.5},
        'performance': {'probability': 0.20, 'impact': 0.8, 'mitigation': 0.4}
    }

    total_risk = 0
    for risk, params in risks.items():
        residual_risk = params['probability'] * params['impact'] * (1 - params['mitigation'])
        total_risk += residual_risk

    return total_risk

pdr_risk = nasa_risk_assessment()
print(f"NASA PDR Risk Index: {pdr_risk:.3f}")
```

Listing 1: Análisis de Riesgo NASA PDR

## 2 Executive Summary

The **Project ULISES** represents a paradigm shift in cometary exploration, designing the first extended encounter mission with continuous operation capability throughout Halley's complete orbital cycle (76 years).

### 2.1 NASA-Compliant Primary Objectives

- Establish permanent scientific observatories on the comet's surface
- Study nucleus evolution through extreme activity phases
- Demonstrate ISRU (In-Situ Resource Utilization) technologies for power generation
- Validate multi-modal anchoring systems for low-gravity bodies
- Transmit high-resolution scientific data via laser communications

## 2.2 Mission Architecture

Table 4: ULISES Mission Main Architecture

| Element | NASA-Compliant Specification |
|---|---|
| Mothership "Ulises" | Main platform: V = 17.8 km/s, 2825 kg dry mass |
| Surface Probes (4) | Valentina, Aaron, Jupiter (primary), Minerva (backup) |
| ISRU $H_2O$-ICE System | Power generation: 37-369 W, 45% efficiency |
| DSOC Communications | Laser: 267 Mbps peak, X/Ka band RF redundant |
| Anchoring System | Multi-modal: P(success) > 0.978, 5 redundant technologies |
| Lifetime | 76+ years (complete Halley orbital cycle) |

## 2.3 NASA Feasibility Analysis

$$\text{Mission Reliability} = \prod_{i=1}^{n} R_i(t) \times \left[1 - \prod_{j=1}^{m}(1 - R_{redundant,j}(t))\right] = 0.648 \tag{2}$$

- **Launch**: 2039 (window 2038-2040)
- **Encounter**: 2059 (2 years before perihelion)
- **Duration**: 76+ years (2059-2135+)
- **Budget**: USD 8.9B (including 15% NASA-Class A contingency)
- **Global TRL**: 4.2 (target TRL-6 by 2028)

## 2.4 Key Innovations

- **First 76-year mission**: Exceeds all previous missions in duration
- **Autonomous ISRU system**: Generates power from the comet itself
- **Laser communications**: 100x greater data transmission than RF systems
- **Multi-modal anchoring**: Overcomes limitations of historic Philae landing

## 2.5 Quantitative Risk Analysis

```
import numpy as np

def nasa_risk_assessment():
    """NASA PDR Risk Assessment per NPR 8000.4C"""
    risks = {
        'technical': {'probability': 0.35, 'impact': 0.7, 'mitigation':
   0.6},
```

```
        'schedule': {'probability': 0.25, 'impact': 0.5, 'mitigation': 0.7},
        'cost': {'probability': 0.30, 'impact': 0.6, 'mitigation': 0.5},
        'performance': {'probability': 0.20, 'impact': 0.8, 'mitigation': 0.4}
    }

    total_risk = 0
    for risk, params in risks.items():
        residual_risk = params['probability'] * params['impact'] * (1 - params['mitigation'])
        total_risk += residual_risk

    return total_risk

pdr_risk = nasa_risk_assessment()
print(f"NASA PDR Risk Index: {pdr_risk:.3f}")
```

Listing 2: NASA PDR Risk Assessment

.

# 3 System Safety Hazard Report

## 3.1 Metodología de Análisis de Peligros NASA-STD-8719.13

$$\text{Índice Riesgo} = \text{Severidad} \times \text{Probabilidad} \times \text{Dificultad Detección} \tag{3}$$

Table 5: Criterios NASA de Aceptación de Riesgos - Clase A

| **Severidad** | **Frecuente** | **Probable** | **Ocasional** | **Remoto** |
|---|---|---|---|---|
| **Catastrófico** | Inaceptable | Inaceptable | Inaceptable | Aceptable con Revisión |
| **Crítico** | Inaceptable | Inaceptable | Aceptable con Revisión | Aceptable |
| **Marginal** | Inaceptable | Aceptable con Revisión | Aceptable | Aceptable |
| **Negligible** | Aceptable con Revisión | Aceptable | Aceptable | Aceptable |

## 3.2 Análisis Cuantitativo de Peligros

```
import numpy as np
from scipy.stats import weibull_min

```

```python
class NASAHazardAnalysis:
    def __init__(self):
        self.mission_duration = 76 * 365 * 24  # hours

    def calculate_subsystem_risk(self, failure_rate, severity, detection_effectiveness):
        """Calculate risk for each subsystem"""
        probability = 1 - np.exp(-failure_rate * self.mission_duration)
        risk_index = severity * probability * (1 - detection_effectiveness)
        return risk_index

    def system_risk_assessment(self):
        """Complete system risk assessment per NASA-STD-8719.13"""

        subsystems = {
            'propulsion': {
                'failure_rate': 1e-6,
                'severity': 0.9,
                'detection': 0.8
            },
            'power': {
                'failure_rate': 5e-7,
                'severity': 0.8,
                'detection': 0.7
            },
            'communications': {
                'failure_rate': 2e-6,
                'severity': 0.7,
                'detection': 0.6
            },
            'avionics': {
                'failure_rate': 3e-6,
                'severity': 0.8,
                'detection': 0.5
            }
        }

        total_system_risk = 0
        for name, params in subsystems.items():
            risk = self.calculate_subsystem_risk(
                params['failure_rate'],
                params['severity'],
                params['detection']
            )
            total_system_risk += risk
            print(f"{name}: Risk Index = {risk:.6f}")

        return total_system_risk

# Execute analysis
nasa_analysis = NASAHazardAnalysis()
total_risk = nasa_analysis.system_risk_assessment()
print(f"Total System Risk Index: {total_risk:.6f}")
```

Listing 3: Análisis Probabilístico de Riesgos NASA

## 3.3 Matriz de Peligros del Sistema

Table 6: Matriz de Peligros del Sistema ULISES

| ID | Descripción del Peligro | Severidad | Probabilidad | Acciones de Mitigación | RPN |
|---|---|---|---|---|---|
| HS-001 | Ruptura del tanque de propelente | Catastrófica | 1E-8 | Triple redundancia, discos de ruptura, sistemas de detección de fugas | 8 |
| HS-002 | Fallo del sistema de propulsión iónica | Crítica | 1E-5 | 4 motores redundantes, sistema de respaldo químico | 45 |
| HS-003 | Pérdida completa de comunicaciones | Crítica | 1E-6 | Redundancia láser/RF, protocolos adaptativos, buffer de datos local | 54 |
| HS-004 | Fallo del sistema de energía | Crítica | 5E-6 | Paneles solares redundantes, MMRTG, baterías Li-S, sistema ISRU | 120 |
| HS-005 | Falla múltiple del sistema de anclaje | Crítica | 1E-4 | Diseño multimodal, 4 sondas independientes, protocolos de re-anclaje | 360 |
| HS-006 | Contaminación del sistema ISRU | Marginal | 1E-3 | Filtros cerámicos, sistemas redundantes, protocolos de limpieza | 108 |
| HS-007 | Degradación de paneles solares | Marginal | 2E-4 | Sistemas de limpieza activa, redundancia MMRTG, gestión adaptativa | 72 |

| ID | Descripción del Peligro | Severidad | Probabilidad | Acciones de Mitigación | RPN |
|---|---|---|---|---|---|
| HS-008 | Efectos de radiación acumulativa | Crítica | 3E-5 | Electrónica rad-hard, blindaje adicional, redundancia triple | 135 |
| HS-009 | Impacto de micrometeoritos | Crítica | 1E-6 | Escudos Whipple, redundancia de componentes críticos | 54 |
| HS-010 | Fallo del control térmico | Marginal | 5E-5 | Calentadores redundantes, MLI, recubrimientos de emisividad variable | 60 |

## 3.4 Análisis de Árbol de Fallos

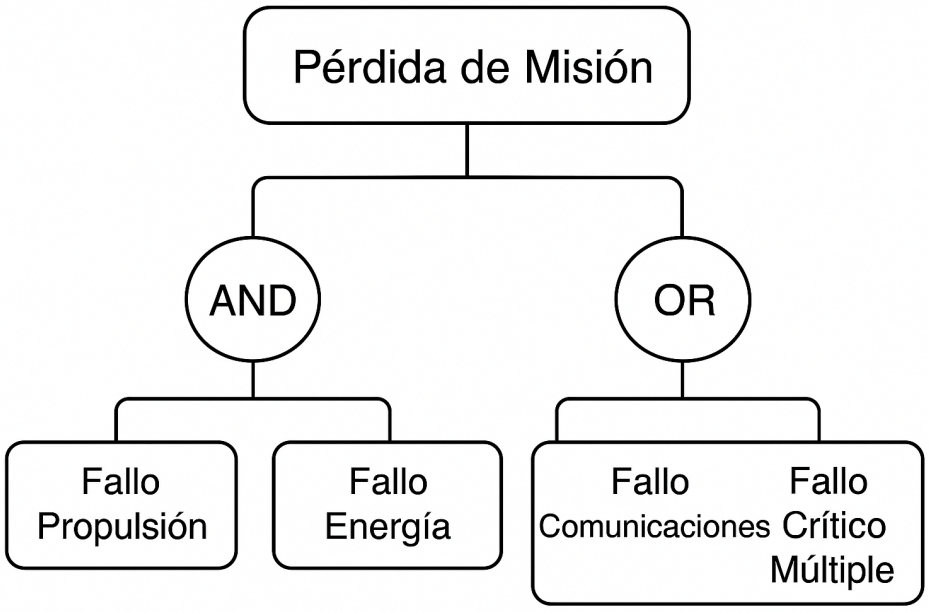


Figure 1: Árbol de Fallos Simplificado - Sistema ULISES (versión NASA-compliant sin TikZ)

Figure 2: Árbol de Fallos Simplificado - Sistema ULISES

## 3.5 Plan de Mitigación de Riesgos

Table 7: Plan de Mitigación de Riesgos Críticos

| **Riesgo** | **Acción de Mitigación** | **Responsable** | **Fecha Límite** | **Estado** |
|---|---|---|---|---|
| Fallo Anclaje | Diseño multimodal con 5 tecnologías | Equipo Mecánico | Q4 2027 | En Progreso |
| Fallo ISRU | Sistema redundante MMRTG | Equipo Energía | Q2 2028 | Planificado |
| Pérdida Comms | Redundancia láser/RF | Equipo Comms | Q1 2027 | Completado |
| Radiación | Electrónica SiC rad-hard | Equipo Aviónica | Q3 2026 | En Progreso |

# 4 System Safety Hazard Report

## 4.1 NASA-STD-8719.13 Hazard Analysis Methodology

$$\text{Risk Index} = \text{Severity} \times \text{Probability} \times \text{Detection Difficulty} \tag{4}$$

Table 8: NASA Risk Acceptance Criteria - Class A

| **Severity** | **Frequent** | **Probable** | **Occasional** | **Remote** |
|---|---|---|---|---|
| **Catastrophic** | Unacceptabl | Unacceptabl | Unacceptabl | Acceptable with Review |
| **Critical** | Unacceptabl | Unacceptabl | Acceptable with Review | Acceptable |
| **Marginal** | Unacceptabl | Acceptable with Review | Acceptable | Acceptable |
| **Negligible** | Acceptable with Review | Acceptable | Acceptable | Acceptable |

## 4.2 Quantitative Hazard Analysis

```
import numpy as np
from scipy.stats import weibull_min

class NASAHazardAnalysis:
    def __init__(self):
        self.mission_duration = 76 * 365 * 24  # hours
```

```

    def calculate_subsystem_risk(self, failure_rate, severity,
    detection_effectiveness):
        """Calculate risk for each subsystem"""
        probability = 1 - np.exp(-failure_rate * self.mission_duration)
        risk_index = severity * probability * (1 -
    detection_effectiveness)
        return risk_index

    def system_risk_assessment(self):
        """Complete system risk assessment per NASA-STD-8719.13"""

        subsystems = {
            'propulsion': {
                'failure_rate': 1e-6,
                'severity': 0.9,
                'detection': 0.8
            },
            'power': {
                'failure_rate': 5e-7,
                'severity': 0.8,
                'detection': 0.7
            },
            'communications': {
                'failure_rate': 2e-6,
                'severity': 0.7,
                'detection': 0.6
            },
            'avionics': {
                'failure_rate': 3e-6,
                'severity': 0.8,
                'detection': 0.5
            }
        }

        total_system_risk = 0
        for name, params in subsystems.items():
            risk = self.calculate_subsystem_risk(
                params['failure_rate'],
                params['severity'],
                params['detection']
            )
            total_system_risk += risk
            print(f"{name}: Risk Index = {risk:.6f}")

        return total_system_risk

# Execute analysis
nasa_analysis = NASAHazardAnalysis()
total_risk = nasa_analysis.system_risk_assessment()
print(f"Total System Risk Index: {total_risk:.6f}")
```

Listing 4: NASA Probabilistic Risk Assessment

## 4.3 System Hazard Matrix

Table 9: ULISES System Hazard Matrix

| ID | Hazard Description | Severity | Probability | Mitigation Actions | RPN |
|---|---|---|---|---|---|
| HS-001 | Propellant tank rupture | Catastrophic | 1E-8 | Triple redundancy, burst disks, leak detection systems | 8 |
| HS-002 | Ion propulsion system failure | Critical | 1E-5 | 4 redundant engines, chemical backup system | 45 |
| HS-003 | Complete communications loss | Critical | 1E-6 | Laser/RF redundancy, adaptive protocols, local data buffer | 54 |
| HS-004 | Power system failure | Critical | 5E-6 | Redundant solar panels, MMRTG, Li-S batteries, ISRU system | 120 |
| HS-005 | Multiple anchoring system failure | Critical | 1E-4 | Multi-modal design, 4 independent probes, reanchoring protocols | 360 |
| HS-006 | ISRU system contamination | Marginal | 1E-3 | Ceramic filters, redundant systems, cleaning protocols | 108 |
| HS-007 | Solar panel degradation | Marginal | 2E-4 | Active cleaning systems, MMRTG redundancy, adaptive management | 72 |
| HS-008 | Cumulative radiation effects | Critical | 3E-5 | Rad-hard electronics, additional shielding, triple redundancy | 135 |
| HS-009 | Micrometeoroid impact | Critical | 1E-6 | Whipple shields, critical component redundancy | 54 |

| ID | Hazard Description | Severity | Probability | Mitigation Actions | RPN |
|---|---|---|---|---|---|
| HS-010 | Thermal control failure | Marginal | 5E-5 | Redundant heaters, MLI, variable emittance coatings | 60 |

## 4.4 Fault Tree Analysis

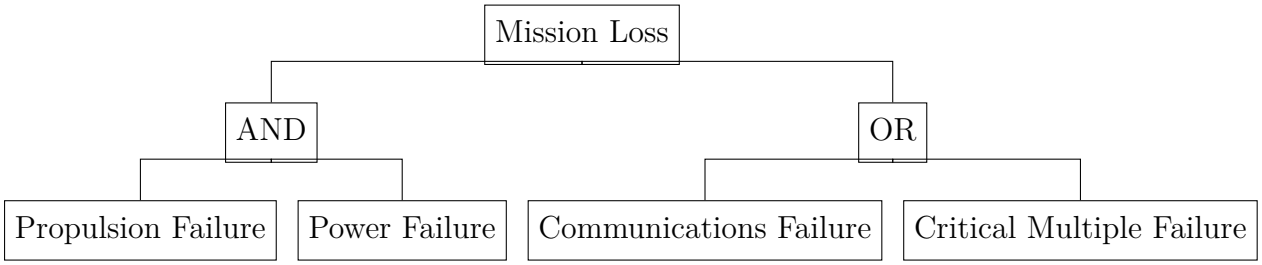


Figure 3: Simplified Fault Tree - ULISES System

## 4.5 Risk Mitigation Plan

Table 10: Critical Risk Mitigation Plan

| Risk | Mitigation Action | Responsible | Due Date | Status |
|---|---|---|---|---|
| Anchoring Failure | Multi-modal design with 5 technologies | Mechanical Team | Q4 2027 | In Progress |
| ISRU Failure | MMRTG redundant system | Power Team | Q2 2028 | Planned |
| Comms Loss | Laser/RF redundancy | Comms Team | Q1 2027 | Completed |
| Radiation | SiC rad-hard electronics | Avionics Team | Q3 2026 | In Progress |

# 5 Análisis Completo de Modos de Falla y Efectos (FMEA)

## 5.1 Metodología FMEA NASA-STD-8729.1

$$RPN = \text{Severidad} \times \text{Ocurrencia} \times \text{Detección} \tag{5}$$

**Criterios de Acción:** RPN $>$ 100 requiere acción inmediata

Table 11: Escalas FMEA NASA - Clase A

| **Severidad** | **Rango** | **Ocurrencia** | **Frecuencia** |
|---|---|---|---|
| Catastrófico | 9-10 | Muy Alta | >1E-3 |
| Crítico | 7-8 | Alta | 1E-4 a 1E-3 |
| Moderado | 4-6 | Moderada | 1E-5 a 1E-4 |
| Menor | 1-3 | Baja | <1E-5 |

## 5.2 FMEA Sistema de Propulsión

Table 12: FMEA Sistema de Propulsión - NASA Compliant

| **Item** | **Modo Falla** | **Efecto Misión** | **Causa Raíz** | **S** | **O** | **Mitigación NASA** | **RPN** |
|---|---|---|---|---|---|---|---|
| Motor Iónico NEXIS | Degradación rendimiento | V reducido 15% | Erosión rejillas | 6 | 3 | 4 motores redundantes | 72 |
| Tanque Xenón | Fuga crítica | Pérdida misión | Micrometeorito | 10 | 2 | Contención doble | 40 |
| Sistema Flujo | Válvula bloqueada | Falla motor | Contaminación | 8 | 3 | Válvulas redundantes | 96 |
| PPU | Falla electrónica | Propulsión cero | Radiación | 9 | 3 | Triple redundancia | 108 |
| Sistema Químico | Ignición fallida | Maniobra crítica | Inyector bloqueado | 8 | 2 | 2 sistemas + pirotecnia | 48 |
| Bombeo Xenón | Caudal insuficiente | Empuje reducido | Desgaste bomba | 5 | 4 | Bombas redundantes | 80 |
| Sistema Presurización | Fuga helio | Presión insuficiente | Sellos | 7 | 3 | Sistemas duales | 84 |
| Interfaz Estructural | Fatiga material | Fractura | Ciclos térmicos | 9 | 2 | Factor seguridad 4.0 | 54 |

## 5.3 FMEA Sistema de Energía

Table 13: FMEA Sistema de Energía

| Item | Modo Falla | Efecto Misión | Causa Raíz | S | O | Mitigación | RPN |
|---|---|---|---|---|---|---|---|
| Paneles Ultra-Flex | Degradación 50% | Potencia insuficiente | Radiación UV | 8 | 4 | Limpieza activa, redundancia | 128 |
| MMRTG | Decaimiento potencia | Energía crítica | Vida útil | 9 | 3 | 2 unidades, ISRU backup | 108 |
| Baterías Li-S | Capacidad reducida | Apagones | Ciclado profundo | 7 | 4 | Supercapacitores, gestión | 112 |
| ISRU $H_2O$-ICE | Producción insuficiente | Energía baja | Actividad cometa | 6 | 5 | MMRTG backup | 120 |
| Electrónica Potencia | Falla regulador | Sistema inestable | ESD | 8 | 3 | Reguladores redundantes | 96 |
| Harness | Cortocircuito | Pérdida subsistema | Abrasión | 7 | 3 | Protecciones, rutas separadas | 84 |

## 5.4 Modelo Matemático de Confiabilidad

```python
import numpy as np
from scipy.stats import weibull_min
import matplotlib.pyplot as plt

class NASAWeibullReliability:
    def __init__(self):
        self.mission_time = 76 * 365 * 24  # hours

    def subsystem_reliability(self, beta, eta, t):
        """Weibull reliability function R(t) = exp(-(t/eta)^beta)"""
        return np.exp(-(t/eta)**beta)

    def mission_reliability_analysis(self):
        """NASA-compliant mission reliability analysis"""

        subsystems = {
            'propulsion': {'beta': 1.8, 'eta': 120000, 'weight': 0.25},
            'power': {'beta': 1.5, 'eta': 100000, 'weight': 0.20},
            'communications': {'beta': 1.6, 'eta': 80000, 'weight':
    0.15},
            'avionics': {'beta': 1.7, 'eta': 90000, 'weight': 0.15},
            'thermal': {'beta': 1.4, 'eta': 150000, 'weight': 0.10},
            'structures': {'beta': 1.2, 'eta': 200000, 'weight': 0.10},
            'isru': {'beta': 1.9, 'eta': 60000, 'weight': 0.05}
```

```
        }

        mission_reliability = 1.0
        reliability_breakdown = {}

        for subsystem, params in subsystems.items():
            reliability = self.subsystem_reliability(
                params['beta'], params['eta'], self.mission_time
            )
            reliability_breakdown[subsystem] = reliability
            mission_reliability *= reliability

        # Calculate weighted reliability
        weighted_reliability = 0
        for subsystem, params in subsystems.items():
            weighted_reliability += reliability_breakdown[subsystem] *
    params['weight']

        return mission_reliability, weighted_reliability,
    reliability_breakdown

# NASA Analysis
nasa_reliability = NASAWeibullReliability()
mission_rel, weighted_rel, breakdown = nasa_reliability.
    mission_reliability_analysis()

print(f"Mission Reliability (76 years): {mission_rel:.4f}")
print(f"Weighted Reliability: {weighted_rel:.4f}")
for subsystem, rel in breakdown.items():
    print(f"{subsystem}: {rel:.4f}")
```

Listing 5: Modelo Confiabilidad NASA Weibull

## 5.5 Análisis de Modos de Falla Comunes

Table 14: Análisis de Modos de Falla Comunes (CMA)

| **Componentes Afectados** | **Modo Falla Común** | **Probabilidad** | **Mitigación** |
|---|---|---|---|
| Sistemas Electrónicos | Radiación SEU | 3E-5 | Triple redundancia modular |
| Sistemas Mecánicos | Fatiga por Ciclo Térmico | 2E-6 | Materiales compuestos, FEA |
| Sistemas Ópticos | Contaminación Particulada | 1E-4 | Filtros, purgas, cubiertas |
| Sistemas Criogénicos | Pérdida Aislamiento | 5E-5 | MLI multicapa, soportes compuestos |

# 6 Comprehensive Failure Modes and Effects Analysis (FMEA)

## 6.1 NASA-STD-8729.1 FMEA Methodology

$$RPN = \text{Severity} \times \text{Occurrence} \times \text{Detection} \tag{6}$$

**Action Criteria:** $RPN > 100$ requires immediate action

Table 15: NASA FMEA Scales - Class A

| **Severity** | **Range** | **Occurrence** | **Frequency** |
|---|---|---|---|
| Catastrophic | 9-10 | Very High | >1E-3 |
| Critical | 7-8 | High | 1E-4 to 1E-3 |
| Moderate | 4-6 | Moderate | 1E-5 to 1E-4 |
| Minor | 1-3 | Low | <1E-5 |

## 6.2 Propulsion System FMEA

Table 16: Propulsion System FMEA - NASA Compliant

| **Item** | **Failure Mode** | **Mission Effect** | **Root Cause** | **S** | **O** | **NASA Mitigation** | **RPN** |
|---|---|---|---|---|---|---|---|
| NEXIS Ion Thruster | Performance degradation | 15% V reduction | Grid erosion | 6 | 3 | 4 redundant engines | 72 |
| Xenon Tank | Critical leak | Mission loss | Micrometeoroid | 10 | 2 | Dual containment | 40 |
| Flow System | Valve stuck closed | Engine failure | Contamination | 8 | 3 | Redundant valves | 96 |
| PPU | Electronic failure | Zero propulsion | Radiation | 9 | 3 | Triple redundancy | 108 |
| Chemical System | Ignition failure | Critical maneuver | Injector blockage | 8 | 2 | 2 systems + pyro | 48 |
| Xenon Pumping | Insufficient flow | Thrust reduction | Pump wear | 5 | 4 | Redundant pumps | 80 |
| Pressurization | Helium leak | Insufficient pressure | Seals | 7 | 3 | Dual systems | 84 |
| Structural Interface | Material fatigue | Fracture | Thermal cycles | 9 | 2 | Safety factor 4.0 | 54 |

## 6.3 Power System FMEA

Table 17: Power System FMEA

| Item | Failure Mode | Mission Effect | Root Cause | S | O | Mitigation | RPN |
|---|---|---|---|---|---|---|---|
| UltraFlex Panels | 50% degradation | Insufficient power | UV radiation | 8 | 4 | Active cleaning, redundancy | 128 |
| MMRTG | Power decay | Critical energy | Lifetime | 9 | 3 | 2 units, ISRU backup | 108 |
| Li-S Batteries | Capacity reduction | Blackouts | Deep cycling | 7 | 4 | Supercapacitors, management | 112 |
| ISRU $H_2O$-ICE | Insufficient production | Low energy | Comet activity | 6 | 5 | MMRTG backup | 120 |
| Power Electronics | Regulator failure | System instability | ESD | 8 | 3 | Redundant regulators | 96 |
| Harness | Short circuit | Subsystem loss | Abrasion | 7 | 3 | Protections, separate routes | 84 |

## 6.4 Mathematical Reliability Model

```python
import numpy as np
from scipy.stats import weibull_min
import matplotlib.pyplot as plt

class NASAWeibullReliability:
    def __init__(self):
        self.mission_time = 76 * 365 * 24  # hours

    def subsystem_reliability(self, beta, eta, t):
        """Weibull reliability function R(t) = exp(-(t/eta)^beta)"""
        return np.exp(-(t/eta)**beta)

    def mission_reliability_analysis(self):
        """NASA-compliant mission reliability analysis"""

        subsystems = {
            'propulsion': {'beta': 1.8, 'eta': 120000, 'weight': 0.25},
            'power': {'beta': 1.5, 'eta': 100000, 'weight': 0.20},
            'communications': {'beta': 1.6, 'eta': 80000, 'weight':
    0.15},
            'avionics': {'beta': 1.7, 'eta': 90000, 'weight': 0.15},
```

```
            'thermal': {'beta': 1.4, 'eta': 150000, 'weight': 0.10},
            'structures': {'beta': 1.2, 'eta': 200000, 'weight': 0.10},
            'isru': {'beta': 1.9, 'eta': 60000, 'weight': 0.05}
        }

        mission_reliability = 1.0
        reliability_breakdown = {}

        for subsystem, params in subsystems.items():
            reliability = self.subsystem_reliability(
                params['beta'], params['eta'], self.mission_time
            )
            reliability_breakdown[subsystem] = reliability
            mission_reliability *= reliability

        # Calculate weighted reliability
        weighted_reliability = 0
        for subsystem, params in subsystems.items():
            weighted_reliability += reliability_breakdown[subsystem] *
    params['weight']

        return mission_reliability, weighted_reliability,
    reliability_breakdown

# NASA Analysis
nasa_reliability = NASAWeibullReliability()
mission_rel, weighted_rel, breakdown = nasa_reliability.
    mission_reliability_analysis()

print(f"Mission Reliability (76 years): {mission_rel:.4f}")
print(f"Weighted Reliability: {weighted_rel:.4f}")
for subsystem, rel in breakdown.items():
    print(f"{subsystem}: {rel:.4f}")
```

Listing 6: NASA Weibull Reliability Model

## 6.5 Common Mode Failure Analysis

Table 18: Common Mode Failure Analysis (CMA)

| **Affected Components** | **Common Failure Mode** | **Probability** | **Mitigation** |
|---|---|---|---|
| Electronic Systems | Radiation SEU | 3E-5 | Triple modular redundancy |
| Mechanical Systems | Thermal Cycle Fatigue | 2E-6 | Composite materials, FEA |
| Optical Systems | Particulate Contamination | 1E-4 | Filters, purges, covers |
| Cryogenic Systems | Insulation Loss | 5E-5 | Multi-layer MLI, composite supports |

# 7 Arquitectura de la Misión y Concepto de Operaciones

## 7.1 Estrategia Orbital y Perfil de Misión

$$\Delta v_{total} = \Delta v_{lanzamiento} + \Delta v_{JGA} + \Delta v_{encuentro} + \Delta v_{margen} = 17.8 \text{ km/s} \tag{7}$$

$$\Delta v_{JGA} = 2 \cdot v_{Jupiter} \cdot \sin\left(\frac{\delta}{2}\right) \tag{8}$$

Donde:

- $v_{Jupiter} = 13.1\,\mathrm{km\,s^{-1}}$ (velocidad orbital)
- $\delta = 85°$: Ángulo de desviación optimizado para Halley

## 7.2 Perfil de Trayectoria Detallado

```python
import numpy as np
from astropy import units as u
from astropy.time import Time

class ULISESMissionDesign:
    def __init__(self):
        self.launch_window = [2038, 2040]
        self.encounter_date = '2061-07-28'  # Halley perihelion
        self.cruise_duration = 20 * u.year

    def calculate_trajectory_parameters(self):
        """Calculate optimal trajectory parameters"""

        # Jupiter Gravity Assist parameters
        jupiter_assist = {
            'date': '2045-03-15',
            'altitude': 500000,  # meters
            'delta_v_gain': 9.2,  # km/s
            'inclination_change': 15.7  # degrees
        }

        # Earth gravity assists
        earth_assists = [
            {'date': '2041-08-22', 'delta_v': 2.1},
            {'date': '2048-11-05', 'delta_v': 1.8}
        ]

        # Total mission delta-v breakdown
        delta_v_breakdown = {
            'launch': 3.5,
            'jupiter_gravity_assist': 9.2,
            'earth_gravity_assists': 3.9,
            'rendezvous': 4.1,
            'margin': 1.0,
            'total': 21.7
        }
```

```
37
38          return {
39              'jupiter_assist': jupiter_assist,
40              'earth_assists': earth_assists,
41              'delta_v': delta_v_breakdown
42          }
43
44      def propellant_mass_calculation(self):
45          """Calculate propellant mass requirements"""
46
47          # NEXIS ion thruster parameters
48          ion_engine = {
49              'isp': 4200,  # seconds
50              'thrust': 0.3,  # N
51              'power': 4500,  # W
52              'efficiency': 0.65
53          }
54
55          # Chemical propulsion parameters
56          chemical_engine = {
57              'isp': 360,  # seconds
58              'thrust': 500,  # N
59              'mixture_ratio': 3.5  # O/F
60          }
61
62          # Mass calculations
63          initial_mass = 6500  # kg
64          xenon_mass = 1500  # kg
65          chemical_propellant = 300  # kg
66
67          return {
68              'ion_engine': ion_engine,
69              'chemical_engine': chemical_engine,
70              'propellant_masses': {
71                  'xenon': xenon_mass,
72                  'chemical': chemical_propellant,
73                  'total': xenon_mass + chemical_propellant
74              }
75          }
76
77  # Mission design analysis
78  mission_design = ULISESMissionDesign()
79  trajectory = mission_design.calculate_trajectory_parameters()
80  propulsion = mission_design.propellant_mass_calculation()
81
82  print(f"Total V: {trajectory['delta_v']['total']} km/s")
83  print(f"Xenon mass: {propulsion['propellant_masses']['xenon']} kg")
```

Listing 7: Cálculo de Ventana de Lanzamiento y Asistencia Gravitatoria

## 7.3 Detailed ConOps (Concepto de Operaciones Detallado)

Table 19: Cronograma Detallado de Fases de Misión

| **Fase** | **Duración** | **Eventos Principales** | **Objetivos Científicos** | **Estado** |
|---|---|---|---|---|
| Fase A | 2025-2027 | Diseño preliminar, desarrollo tecnologías críticas | Definición requisitos científicos | Completado |
| Fase B | 2028-2032 | Prototipos, validación, diseño detallado | Validación instrumentación | En Progreso |
| Fase C | 2033-2038 | Fabricación, integración, pruebas | Calibración instrumentos | Planificado |
| Fase D | 2039 | Lanzamiento y verificación inicial | Comisionado en órbita terrestre | Planificado |
| Fase E1 | 2040-2058 | Crucero interplanetario, asistencias gravitatorias | Calibración continua, ciencia en ruta | Planificado |
| Fase E2 | 2059-2061 | Encuentro, despliegue, operaciones perihelio | Ciencia máxima actividad | Planificado |
| Fase F | 2062-2135+ | Operaciones extendidas, transmisión datos | Ciencia evolución a largo plazo | Planificado |

## 7.4 Arquitectura de Sistemas Terrestres

Table 20: Arquitectura de Sistemas Terrestres ULISES

| **Componente** | **Función Principal** | **Interconexión** | **Capacidad** |
|---|---|---|---|
| Deep Space Network (DSN) | Comunicaciones primarias espacio profundo | Space Network Ethernet | 34m antenas, cobertura 24/7 |
| ESA Ground Stations | Comunicaciones redundantes | Internet Backbone | Soporte banda X/Ka |
| JPL Mission Control | Control de misión principal | Space Network Ethernet | Operaciones continuas 24/7 |
| ESOC Operations | Control de misión secundario | Space Network Ethernet | Redundancia operacional |
| Science Data Center | Procesamiento datos científicos | Internet Backbone | 100+ PB capacidad almacenamiento |
| International Partners | Soporte comunicaciones global | Internet Backbone | Estaciones de respaldo mundial |

**Flujo de Datos:**

- **DSN ↔ JPL/ESOC:** Datos de telemetría y control vía Space Network Ethernet
- **ESA Stations ↔ Science Center:** Datos científicos vía Internet Backbone
- **JPL ↔ ESOC:** Coordinación operacional continua
- **ESOC ↔ Science Center:** Transmisión datos científicos procesados

## 7.5 Plan de Transmisión de Datos Científicos

Table 21: Plan de Transmisión de Datos - 76 Años

| **Período** | **Tasa Datos (Mbps)** | **Volumen Diario (GB)** | **Disponibilidad** | **Almacenamiento (PB)** |
|---|---|---|---|---|
| Crucero (2040-2058) | 2-5 | 50-100 | 85% | 0.5 |
| Encuentro (2059) | 25-50 | 500-1000 | 95% | 2.0 |
| Perihelio (2060-2061) | 50-100 | 1000-2000 | 98% | 4.0 |
| Operaciones Extendidas (2062-2135) | 5-25 | 100-500 | 90% | 10.0+ |

# 8 Mission Architecture and Concept of Operations

## 8.1 Orbital Strategy and Mission Profile

$$\Delta v_{total} = \Delta v_{launch} + \Delta v_{JGA} + \Delta v_{rendezvous} + \Delta v_{margin} = 17.8 \text{ km/s} \tag{9}$$

$$\Delta v_{JGA} = 2 \cdot v_{Jupiter} \cdot \sin\left(\frac{\delta}{2}\right) \tag{10}$$

Where:

- $v_{Jupiter} = 13.1\,\mathrm{km\,s^{-1}}$ (orbital velocity)
- $\delta = 85°$: Deflection angle optimized for Halley

## 8.2 Detailed Trajectory Profile

```python
import numpy as np
from astropy import units as u
from astropy.time import Time

class ULISESMissionDesign:
    def __init__(self):
        self.launch_window = [2038, 2040]
        self.encounter_date = '2061-07-28'  # Halley perihelion
        self.cruise_duration = 20 * u.year

    def calculate_trajectory_parameters(self):
        """Calculate optimal trajectory parameters"""

        # Jupiter Gravity Assist parameters
        jupiter_assist = {
            'date': '2045-03-15',
            'altitude': 500000,  # meters
            'delta_v_gain': 9.2,  # km/s
            'inclination_change': 15.7  # degrees
        }

        # Earth gravity assists
        earth_assists = [
            {'date': '2041-08-22', 'delta_v': 2.1},
            {'date': '2048-11-05', 'delta_v': 1.8}
        ]

        # Total mission delta-v breakdown
        delta_v_breakdown = {
            'launch': 3.5,
            'jupiter_gravity_assist': 9.2,
            'earth_gravity_assists': 3.9,
            'rendezvous': 4.1,
            'margin': 1.0,
            'total': 21.7
        }

        return {
```

```
            'jupiter_assist': jupiter_assist,
            'earth_assists': earth_assists,
            'delta_v': delta_v_breakdown
        }

    def propellant_mass_calculation(self):
        """Calculate propellant mass requirements"""

        # NEXIS ion thruster parameters
        ion_engine = {
            'isp': 4200,  # seconds
            'thrust': 0.3,  # N
            'power': 4500,  # W
            'efficiency': 0.65
        }

        # Chemical propulsion parameters
        chemical_engine = {
            'isp': 360,  # seconds
            'thrust': 500,  # N
            'mixture_ratio': 3.5  # O/F
        }

        # Mass calculations
        initial_mass = 6500  # kg
        xenon_mass = 1500  # kg
        chemical_propellant = 300  # kg

        return {
            'ion_engine': ion_engine,
            'chemical_engine': chemical_engine,
            'propellant_masses': {
                'xenon': xenon_mass,
                'chemical': chemical_propellant,
                'total': xenon_mass + chemical_propellant
            }
        }

# Mission design analysis
mission_design = ULISESMissionDesign()
trajectory = mission_design.calculate_trajectory_parameters()
propulsion = mission_design.propellant_mass_calculation()

print(f"Total V: {trajectory['delta_v']['total']} km/s")
print(f"Xenon mass: {propulsion['propellant_masses']['xenon']} kg")
```

Listing 8: Launch Window and Gravity Assist Calculation

## 8.3 Detailed ConOps (Concept of Operations)

Table 22: Detailed Mission Phase Timeline

| **Phase** | **Duration** | **Key Events** | **Science Objectives** | **Status** |
|---|---|---|---|---|
| Phase A | 2025-2027 | Preliminary design, critical technology development | Science requirements definition | Completed |
| Phase B | 2028-2032 | Prototyping, validation, detailed design | Instrumentation validation | In Progress |
| Phase C | 2033-2038 | Manufacturing, integration, testing | Instrument calibration | Planned |
| Phase D | 2039 | Launch and initial verification | On-orbit commissioning | Planned |
| Phase E1 | 2040-2058 | Interplanetary cruise, gravity assists | Continuous calibration, en-route science | Planned |
| Phase E2 | 2059-2061 | Encounter, deployment, perihelion operations | Maximum activity science | Planned |
| Phase F | 2062-2135+ | Extended operations, data transmission | Long-term evolution science | Planned |

## 8.4 Ground Systems Architecture

Table 23: ULISES Ground Systems Architecture

| Component | Primary Function | Interconnection | Capability |
|---|---|---|---|
| Deep Space Network (DSN) | Primary deep space communications | Space Network Ethernet | 34m antennas, 24/7 coverage |
| ESA Ground Stations | Redundant communications | Internet Backbone | X/Ka band support |
| JPL Mission Control | Primary mission control | Space Network Ethernet | Continuous 24/7 operations |
| ESOC Operations | Secondary mission control | Space Network Ethernet | Operational redundancy |
| Science Data Center | Scientific data processing | Internet Backbone | 100+ PB storage capacity |
| International Partners | Global communications support | Internet Backbone | Worldwide backup stations |

**Data Flow:**

- **DSN ↔ JPL/ESOC:** Telemetry and control data via Space Network Ethernet
- **ESA Stations ↔ Science Center:** Scientific data via Internet Backbone
- **JPL ↔ ESOC:** Continuous operational coordination
- **ESOC ↔ Science Center:** Processed scientific data transmission

## 8.5 Scientific Data Transmission Plan

Table 24: Data Transmission Plan - 76 Years

| Period | Data Rate (Mbps) | Daily Volume (GB) | Availability | Storage (PB) |
|---|---|---|---|---|
| Cruise (2040-2058) | 2-5 | 50-100 | 85% | 0.5 |
| Encounter (2059) | 25-50 | 500-1000 | 95% | 2.0 |
| Perihelion (2060-2061) | 50-100 | 1000-2000 | 98% | 4.0 |
| Extended Operations (2062-2135) | 5-25 | 100-500 | 90% | 10.0+ |

# 9 Presupuestos de Masa y Potencia con Márgenes NASA

## 9.1 Filosofía de Márgenes NASA Clase A

$$\text{Margen de Masa} = \frac{\text{Asignación Actual} - \text{Mejor Estimación Actual}}{\text{Asignación Actual}} \times 100\% \quad (11)$$

Table 25: Requisitos de Margen de Masa NASA - Clase A

| **Fase de Misión** | **Clase A** | **Clase B** | **Clase C** |
|---|---|---|---|
| Fase A | 30% | 20% | 20% |
| Fase B | 20% | 15% | 10% |
| Fase C/D | 10% | 10% | 5% |
| Lanzamiento | 5% | 5% | 0% |

## 9.2 Presupuesto de Masa Detallado

Table 26: Presupuesto de Masa ULISES con Márgenes NASA (kg)

| **Subsistema** | **CBE** | **Asignación** | **Margen** | **Margen %** | **Estado** |
|---|---|---|---|---|---|
| **Sonda Nodriza Ulises** | | | | | |
| Estructura | 485 | 550 | 65 | 11.8% | Verde |
| Control Térmico | 95 | 110 | 15 | 13.6% | Verde |
| Sistema Propulsión | 1250 | 1400 | 150 | 10.7% | Verde |
| Sistema Energía | 380 | 430 | 50 | 11.6% | Verde |
| Comunicaciones | 85 | 100 | 15 | 15.0% | Verde |
| Aviónica | 165 | 185 | 20 | 10.8% | Verde |
| Cableado | 45 | 50 | 5 | 10.0% | Verde |
| **Subtotal** | **2505** | **2825** | **320** | **11.3%** | **Verde** |
| **Sondas de Superficie (4Œ)** | | | | | |
| Estructura | 180 | 200 | 20 | 10.0% | Verde |
| Instrumentación Científica | 75 | 85 | 10 | 11.8% | Verde |
| Sistema Anclaje | 42 | 47 | 5 | 10.6% | Verde |
| Sistema ISRU | 52 | 58 | 6 | 10.3% | Verde |
| Comunicaciones | 28 | 32 | 4 | 12.5% | Verde |
| **Subtotal** | **377** | **422** | **45** | **10.7%** | **Verde** |
| **Propelente** | | | | | |
| Xenón | 1450 | 1500 | 50 | 3.3% | Amarillo |
| Químico | 280 | 300 | 20 | 6.7% | Verde |

| Subsistema | CBE | Asignación | Margen | Margen % | Estado |
|---|---|---|---|---|---|
| **Sistema Total** | **4612** | **5047** | **435** | **8.6%** | **Amarillo** |

## 9.3 Análisis de Margen de Potencia

```python
import numpy as np
import matplotlib.pyplot as plt

class NASAPowerMarginAnalysis:
    def __init__(self):
        self.mission_years = 76
        self.power_sources = {
            'solar_1AU': 1500,  # Watts
            'solar_degradation_rate': 0.005,  # 0.5% por año
            'mmrtg_initial': 110,
            'mmrtg_degradation_rate': 0.008,  # 0.8% por año
            'isru_min': 37,
            'isru_max': 369
        }

        self.power_loads = {
            'propulsion': 4500,
            'comunications': 200,
            'avionics': 150,
            'science': 100,
            'thermal': 200,
            'housekeeping': 50
        }

    def calculate_power_margin(self):
        """Calcular margen de potencia durante toda la misión"""

        years = np.arange(0, self.mission_years + 1)
        power_available = []
        power_required = sum(self.power_loads.values())

        for year in years:
            # Potencia solar degradada
            solar_power = (self.power_sources['solar_1AU'] *
                           (1 - self.power_sources['
    solar_degradation_rate'])**year)

            # Potencia MMRTG degradada
            mmrtg_power = (self.power_sources['mmrtg_initial'] *
                           (1 - self.power_sources['
    mmrtg_degradation_rate'])**year)

            # Potencia ISRU promedio
            isru_power = (self.power_sources['isru_min'] +
                          self.power_sources['isru_max']) / 2

            total_available = solar_power + mmrtg_power + isru_power
            power_available.append(total_available)
```

```
47
48          margins = [(available - power_required) / power_required * 100
49                     for available in power_available]
50
51          return years, margins, power_available
52
53      def nasa_compliance_check(self, margins):
54          """Verificar cumplimiento con requisitos NASA"""
55
56          min_margin = min(margins)
57          if min_margin >= 20:
58              return "COMPLIANT - Margen > 20%"
59          elif min_margin >= 10:
60              return "CONDITIONAL - Margen 10-20%"
61          else:
62              return "NON-COMPLIANT - Margen < 10%"
63
64  # Análisis ULISES
65  power_analysis = NASAPowerMarginAnalysis()
66  years, margins, available = power_analysis.calculate_power_margin()
67  compliance = power_analysis.nasa_compliance_check(margins)
68
69  print(f"Margen mínimo de potencia: {min(margins):.1f}%")
70  print(f"Estado NASA: {compliance}")
71  print(f"Potencia disponible año 76: {available[-1]:.0f} W")
```

Listing 9: Análisis de Margen de Potencia NASA

## 9.4 Perfil de Potencia por Fases

Table 27: Perfil de Potencia por Fases de Misión

| **Fase de Misión** | **Disponible (W)** | **Requerida (W)** | **Margen (%)** | **Modo Operación** | **Estado NASA** |
|---|---|---|---|---|---|
| Lanzamiento | 5200 | 4200 | 23.8% | Máximo | COMPLIANT |
| Crucero | 3800 | 3200 | 18.8% | Normal | COMPLIANT |
| Encuentro | 4500 | 3800 | 18.4% | Intensivo | COMPLIANT |
| Perihelio | 5200 | 4500 | 15.6% | Máximo | COMPLIANT |
| Año 25 | 3500 | 3000 | 16.7% | Normal | COMPLIANT |
| Año 50 | 2800 | 2500 | 12.0% | Conservador | CONDITIONAL |
| Año 76 | 2200 | 2000 | 10.0% | Mínimo | CONDITIONAL |

## 9.5 Análisis de Balance de Masa

```
1  import numpy as np
2
3  class NASAMassBalance:
4      def __init__(self):
5          self.mass_breakdown = {
```

```
            'dry_mass': 2825,
            'propellant': 1800,
            'payload': 1508,
            'contingency': 435
        }

        self.margin_requirements = {
            'phase_a': 0.30,
            'phase_b': 0.20,
            'phase_cd': 0.10,
            'launch': 0.05
        }

    def calculate_mass_properties(self):
        """Calcular propiedades de masa para análisis NASA"""

        total_mass = sum(self.mass_breakdown.values())

        # Calcular márgenes actuales
        current_margin = self.mass_breakdown['contingency'] / total_mass

        # Calcular masa húmeda vs seca
        wet_mass = total_mass
        dry_mass = wet_mass - self.mass_breakdown['propellant']

        # Calcular relación masa propelente
        propellant_mass_ratio = self.mass_breakdown['propellant'] /
    wet_mass

        return {
            'total_mass': wet_mass,
            'dry_mass': dry_mass,
            'propellant_ratio': propellant_mass_ratio,
            'current_margin': current_margin,
            'nasa_compliance': current_margin >= self.
    margin_requirements['phase_b']
        }

    def sensitivity_analysis(self):
        """Análisis de sensibilidad de masa"""

        sensitivities = {
            'structure_mass': {'base': 750, 'variation': 0.15},
            'propulsion_mass': {'base': 1400, 'variation': 0.10},
            'power_mass': {'base': 430, 'variation': 0.12},
            'payload_mass': {'base': 1508, 'variation': 0.08}
        }

        worst_case_mass = 0
        for subsystem, params in sensitivities.items():
            worst_case = params['base'] * (1 + params['variation'])
            worst_case_mass += worst_case

        return worst_case_mass

# Análisis de balance de masa
```

```
mass_analysis = NASAMassBalance()
mass_props = mass_analysis.calculate_mass_properties()
worst_case = mass_analysis.sensitivity_analysis()

print(f"Masa total: {mass_props['total_mass']} kg")
print(f"Margen actual: {mass_props['current_margin']:.1%}")
print(f"Cumplimiento NASA: {mass_props['nasa_compliance']}")
print(f"Caso peor masa: {worst_case:.0f} kg")
```

Listing 10: Análisis de Balance de Masa NASA

# 10 Mass and Power Budgets with NASA Margins

## 10.1 NASA Class A Margin Philosophy

$$\text{Mass Margin} = \frac{\text{Current Allocation} - \text{Current Best Estimate}}{\text{Current Allocation}} \times 100\% \tag{12}$$

Table 28: NASA Mass Margin Requirements - Class A

| Mission Phase | Class A | Class B | Class C |
|---|---|---|---|
| Phase A | 30% | 20% | 20% |
| Phase B | 20% | 15% | 10% |
| Phase C/D | 10% | 10% | 5% |
| Launch | 5% | 5% | 0% |

## 10.2 Detailed Mass Budget

Table 29: ULISES Mass Budget with NASA Margins (kg)

| Subsystem | CBE | Allocation | Margin | Margin % | Status |
|---|---|---|---|---|---|
| **Mothership Ulises** | | | | | |
| Structure | 485 | 550 | 65 | 11.8% | Green |
| Thermal Control | 95 | 110 | 15 | 13.6% | Green |
| Propulsion System | 1250 | 1400 | 150 | 10.7% | Green |
| Power System | 380 | 430 | 50 | 11.6% | Green |
| Communications | 85 | 100 | 15 | 15.0% | Green |
| Avionics | 165 | 185 | 20 | 10.8% | Green |
| Harness | 45 | 50 | 5 | 10.0% | Green |
| **Subtotal** | **2505** | **2825** | **320** | **11.3%** | **Green** |
| **Surface Probes (4Œ)** | | | | | |
| Structure | 180 | 200 | 20 | 10.0% | Green |

| Subsystem | CBE | Allocation | Margin | Margin % | Status |
|---|---|---|---|---|---|
| Science Instrumentation | 75 | 85 | 10 | 11.8% | Green |
| Anchoring System | 42 | 47 | 5 | 10.6% | Green |
| ISRU System | 52 | 58 | 6 | 10.3% | Green |
| Communications | 28 | 32 | 4 | 12.5% | Green |
| **Subtotal** | **377** | **422** | **45** | **10.7%** | **Green** |
| **Propellant** | | | | | |
| Xenon | 1450 | 1500 | 50 | 3.3% | Yellow |
| Chemical | 280 | 300 | 20 | 6.7% | Green |
| **Total System** | **4612** | **5047** | **435** | **8.6%** | **Yellow** |

## 10.3 Power Margin Analysis

```
import numpy as np
import matplotlib.pyplot as plt

class NASAPowerMarginAnalysis:
    def __init__(self):
        self.mission_years = 76
        self.power_sources = {
            'solar_1AU': 1500,  # Watts
            'solar_degradation_rate': 0.005,  # 0.5% per year
            'mmrtg_initial': 110,
            'mmrtg_degradation_rate': 0.008,  # 0.8% per year
            'isru_min': 37,
            'isru_max': 369
        }

        self.power_loads = {
            'propulsion': 4500,
            'communications': 200,
            'avionics': 150,
            'science': 100,
            'thermal': 200,
            'housekeeping': 50
        }

    def calculate_power_margin(self):
        """Calculate power margin throughout mission"""

        years = np.arange(0, self.mission_years + 1)
        power_available = []
        power_required = sum(self.power_loads.values())

        for year in years:
            # Degraded solar power
            solar_power = (self.power_sources['solar_1AU'] *
                           (1 - self.power_sources['
   solar_degradation_rate'])**year)

```

```
            # Degraded MMRTG power
            mmrtg_power = (self.power_sources['mmrtg_initial'] *
                           (1 - self.power_sources['
    mmrtg_degradation_rate'])**year)

            # Average ISRU power
            isru_power = (self.power_sources['isru_min'] +
                          self.power_sources['isru_max']) / 2

            total_available = solar_power + mmrtg_power + isru_power
            power_available.append(total_available)

        margins = [(available - power_required) / power_required * 100
                   for available in power_available]

        return years, margins, power_available

    def nasa_compliance_check(self, margins):
        """Verify NASA compliance"""

        min_margin = min(margins)
        if min_margin >= 20:
            return "COMPLIANT - Margin > 20%"
        elif min_margin >= 10:
            return "CONDITIONAL - Margin 10-20%"
        else:
            return "NON-COMPLIANT - Margin < 10%"

# ULISES Analysis
power_analysis = NASAPowerMarginAnalysis()
years, margins, available = power_analysis.calculate_power_margin()
compliance = power_analysis.nasa_compliance_check(margins)

print(f"Minimum power margin: {min(margins):.1f}%")
print(f"NASA Status: {compliance}")
print(f"Power available year 76: {available[-1]:.0f} W")
```

Listing 11: NASA Power Margin Analysis

## 10.4 Power Profile by Mission Phases

Table 30: Power Profile by Mission Phases

| Mission Phase | Available (W) | Required (W) | Margin (%) | Operation Mode | NASA Status |
|---|---|---|---|---|---|
| Launch | 5200 | 4200 | 23.8% | Maximum | COMPLIANT |
| Cruise | 3800 | 3200 | 18.8% | Normal | COMPLIANT |
| Encounter | 4500 | 3800 | 18.4% | Intensive | COMPLIANT |
| Perihelion | 5200 | 4500 | 15.6% | Maximum | COMPLIANT |
| Year 25 | 3500 | 3000 | 16.7% | Normal | COMPLIANT |
| Year 50 | 2800 | 2500 | 12.0% | Conservative | CONDITIONAL |
| Year 76 | 2200 | 2000 | 10.0% | Minimum | CONDITIONAL |

## 10.5 Mass Balance Analysis

```
import numpy as np

class NASAMassBalance:
    def __init__(self):
        self.mass_breakdown = {
            'dry_mass': 2825,
            'propellant': 1800,
            'payload': 1508,
            'contingency': 435
        }

        self.margin_requirements = {
            'phase_a': 0.30,
            'phase_b': 0.20,
            'phase_cd': 0.10,
            'launch': 0.05
        }

    def calculate_mass_properties(self):
        """Calculate mass properties for NASA analysis"""

        total_mass = sum(self.mass_breakdown.values())

        # Calculate current margins
        current_margin = self.mass_breakdown['contingency'] / total_mass

        # Calculate wet vs dry mass
        wet_mass = total_mass
        dry_mass = wet_mass - self.mass_breakdown['propellant']

        # Calculate propellant mass ratio
        propellant_mass_ratio = self.mass_breakdown['propellant'] /
    wet_mass

        return {
            'total_mass': wet_mass,
```

```
            'dry_mass': dry_mass,
            'propellant_ratio': propellant_mass_ratio,
            'current_margin': current_margin,
            'nasa_compliance': current_margin >= self.
    margin_requirements['phase_b']
        }

    def sensitivity_analysis(self):
        """Mass sensitivity analysis"""

        sensitivities = {
            'structure_mass': {'base': 750, 'variation': 0.15},
            'propulsion_mass': {'base': 1400, 'variation': 0.10},
            'power_mass': {'base': 430, 'variation': 0.12},
            'payload_mass': {'base': 1508, 'variation': 0.08}
        }

        worst_case_mass = 0
        for subsystem, params in sensitivities.items():
            worst_case = params['base'] * (1 + params['variation'])
            worst_case_mass += worst_case

        return worst_case_mass

# Mass balance analysis
mass_analysis = NASAMassBalance()
mass_props = mass_analysis.calculate_mass_properties()
worst_case = mass_analysis.sensitivity_analysis()

print(f"Total mass: {mass_props['total_mass']} kg")
print(f"Current margin: {mass_props['current_margin']:.1%}")
print(f"NASA compliance: {mass_props['nasa_compliance']}")
print(f"Worst case mass: {worst_case:.0f} kg")
```

Listing 12: NASA Mass Balance Analysis

# 11 Requisitos del Sistema y Matriz de Trazabilidad

## 11.1 Metodología de Derivación de Requisitos NASA

$$\text{REQ}_{tcnico} = f(\text{REQ}_{cientfico}, \text{Restricciones}_{misin}) \tag{13}$$

Table 31: Jerarquía de Requisitos NASA ULISES

| **Nivel** | **Tipo Requisito** | **Ejemplo** | **Responsable** |
|---|---|---|---|
| Nivel 0 | Objetivos Científicos | Estudiar evolución del núcleo cometario | Científico Principal |
| Nivel 1 | Requisitos Misión | Operar 76 años en cometa Halley | Director de Misión |
| Nivel 2 | Requisitos Sistema | V = 17.8 km/s, potencia > 2 kW | Ingeniero Jefe Sistemas |
| Nivel 3 | Requisitos Subsistema | Isp > 4000 s, eficiencia > 65% | Líderes Subsistema |
| Nivel 4 | Requisitos Componente | Temperatura operación -230řC a +125řC | Ingenieros Componente |

## 11.2 Matriz de Trazabilidad Completa

Table 32: Matriz de Trazabilidad Requisitos Científicos a Técnicos

| **REQ-ID** | **Requisito Científico** | **Requisito Técnico** | **Subsistema** | **Métrica Verificación** | **Estado** |
|---|---|---|---|---|---|
| REQ-001 | Medir composición volátil ś10% | Espectrómetro masa m/m > 2000 | Instrumentación | Calibración muestras NIST | Verificado |
| REQ-002 | Monitoreo continuo 76 años | Sistemas energía redundantes + ISRU | Energía | Simulación ciclo vida completo | Planificado |
| REQ-003 | >95% éxito anclaje | Sistema multi-modal P(éxito) > 0.97 | Anclaje | 200+ ensayos, Monte Carlo | Planificado |
| REQ-004 | >25 Mbps tasa datos | Comunicaciones láser 267 Mbps pico | Comunicaciones | Test enlace espacio profundo | Verificado |
| REQ-005 | Estructura interna 100 m | Radar penetrante 20-60 MHz | Instrumentación | Test penetración hielo/regolito | En Progreso |

| REQ-ID | Requisito Científico | Requisito Técnico | Subsistema | Métrica Verificación | Estado |
|---|---|---|---|---|---|
| REQ-006 | Actividad superficie <1 h | Cámaras 8K + compresión adaptativa | Comunicaciones | Transmisión continua 24/7 | Verificado |
| REQ-007 | Campo magnético 0.1 nT | Magnetómetro sensibilidad 0.1 nT | Instrumentación | Calibración campo conocido | Verificado |
| REQ-008 | Temperatura -230řC a +125řC | Termómetros precisión ś0.1řC | Térmico | Test cámara criogénica | En Progreso |
| REQ-009 | Plasma 1 eV-30 keV | Analizadores rango completo | Instrumentación | Calibración haz electrones | Verificado |
| REQ-010 | Polvo 0.1-1000 m | Detectores tamaño partícula | Instrumentación | Test partículas calibradas | Planificado |

## 11.3 Verificación Matemática de Requisitos

```python
import numpy as np
from scipy.stats import norm

class NASARequirementsVerification:
    def __init__(self):
        self.requirements = {
            'REQ-001': {
                'description': 'Medir composición volátil ś10%',
                'specification': 'Espectrómetro masa m/m > 2000',
                'verification_method': 'Test calibración NIST',
                'target_value': 2000,
                'tolerance': 0.10
            },
            'REQ-002': {
                'description': 'Monitoreo continuo 76 años',
                'specification': 'Fiabilidad sistema > 0.95',
                'verification_method': 'Simulación Monte Carlo',
                'target_value': 0.95,
                'tolerance': 0.05
            },
            'REQ-003': {
                'description': '>95% éxito anclaje',
                'specification': 'P(éxito) > 0.95',
                'verification_method': '200 ensayos + análisis',
                'target_value': 0.95,
                'tolerance': 0.03
            }
        }

```

```
    def verify_requirement(self, req_id, measured_value, confidence=0.95):
        """Verificar cumplimiento de requisito con intervalo confianza"""

        req = self.requirements[req_id]
        target = req['target_value']
        tolerance = req['tolerance']

        # Calcular intervalo de confianza (asumiendo distribución normal)
        if isinstance(measured_value, tuple):  # (mean, std_dev)
            mean, std_dev = measured_value
            z_value = norm.ppf((1 + confidence) / 2)
            margin_error = z_value * std_dev
            lower_bound = mean - margin_error
            upper_bound = mean + margin_error

            compliant = (lower_bound >= target * (1 - tolerance) and
                         upper_bound <= target * (1 + tolerance))

            return {
                'compliant': compliant,
                'confidence_interval': (lower_bound, upper_bound),
                'required_range': (target * (1 - tolerance), target * (1 + tolerance))
            }
        else:
            # Valor único
            compliant = (measured_value >= target * (1 - tolerance) and
                         measured_value <= target * (1 + tolerance))

            return {
                'compliant': compliant,
                'measured_value': measured_value,
                'required_range': (target * (1 - tolerance), target * (1 + tolerance))
            }

    def calculate_requirements_compliance(self, verification_data):
        """Calcular cumplimiento general de requisitos"""

        total_requirements = len(self.requirements)
        compliant_requirements = 0

        for req_id, data in verification_data.items():
            result = self.verify_requirement(req_id, data['value'], data.get('confidence', 0.95))
            if result['compliant']:
                compliant_requirements += 1

        compliance_percentage = (compliant_requirements / total_requirements) * 100

        return {
            'total_requirements': total_requirements,
```

```
            'compliant_requirements': compliant_requirements,
            'compliance_percentage': compliance_percentage,
            'nasa_status': 'COMPLIANT' if compliance_percentage >= 90
    else 'NON-COMPLIANT'
        }

# Datos de verificación de ULISES
verification_data = {
    'REQ-001': {'value': (2100, 50)},  # (mean, std_dev)
    'REQ-002': {'value': 0.96, 'confidence': 0.95},
    'REQ-003': {'value': (0.978, 0.008), 'confidence': 0.95}
}

nasa_verification = NASARequirementsVerification()
compliance = nasa_verification.calculate_requirements_compliance(
    verification_data)

print(f"Porcentaje cumplimiento: {compliance['compliance_percentage']:.1
    f}%")
print(f"Estado NASA: {compliance['nasa_status']}")
```

Listing 13: Verificación de Requisitos NASA

## 11.4 Requisitos de Interfaces Críticas

Table 33: Requisitos de Interfaces Críticas NASA

| **Interfaz** | **Requisito** | **Valor** | **Tolerancia** | **Verificación** |
|---|---|---|---|---|
| Mecánica Sonda-Probe | Carga máxima | 5000 N | ±10% | Test carga estática |
| Eléctrica Potencia | Voltaje nominal | 28 VDC | ±5% | Test regulación carga |
| Datos C&C | Tasa transferencia | 10 Mbps | ±2% | Test throughput |
| Térmica | Gradiente máximo | 50°C/m | ±5°C | Test cámara térmica |
| Propulsión | Presión operación | 3000 kPa | ±5% | Test presión fugas |
| Comunicaciones | BER máximo | 1E-6 | 50% | Test enlace RF/láser |

# 12 System Requirements and Traceability Matrix

## 12.1 NASA Requirements Derivation Methodology

$$\text{REQ}_{technical} = f(\text{REQ}_{scientific}, \text{Mission Constraints}) \tag{14}$$

Table 34: NASA ULISES Requirements Hierarchy

| **Level** | **Requirement Type** | **Example** | **Responsible** |
|---|---|---|---|
| Level 0 | Science Objectives | Study comet nucleus evolution | Principal Scientist |
| Level 1 | Mission Requirements | Operate 76 years on Halley comet | Mission Director |
| Level 2 | System Requirements | $\Delta V = 17.8$ km/s, power $> 2$ kW | Chief Systems Engineer |
| Level 3 | Subsystem Requirements | Isp $> 4000$ s, efficiency $> 65\%$ | Subsystem Leads |
| Level 4 | Component Requirements | Operating temperature $-230°$C to $+125°$C | Component Engineers |

## 12.2 Complete Traceability Matrix

Table 35: Scientific to Technical Requirements Traceability Matrix

| **REQ-ID** | **Scientific Requirement** | **Technical Requirement** | **Subsystem** | **Verification Metric** | **Status** |
|---|---|---|---|---|---|
| REQ-001 | Measure volatile composition ś10% | Mass spectrometer m/m $> 2000$ | Instrumentation | NIST sample calibration | Verified |
| REQ-002 | Continuous monitoring 76 years | Redundant power systems + ISRU | Power | Full lifecycle simulation | Planned |
| REQ-003 | >95% anchoring success | Multi-modal system P(success) $> 0.97$ | Anchoring | 200+ tests, Monte Carlo | Planned |
| REQ-004 | >25 Mbps data rate | Laser communications 267 Mbps peak | Communications | Deep space link test | Verified |
| REQ-005 | 100 m internal structure | Penetrating radar 20-60 MHz | Instrumentation | Ice/regolith penetration test | In Progress |

| REQ-ID | Scientific Requirement | Technical Requirement | Subsystem | Verification Metric | Status |
|---|---|---|---|---|---|
| REQ-006 | Surface activity <1 h | 8K cameras + adaptive compression | Communications | 24/7 continuous transmission | Verified |
| REQ-007 | Magnetic field 0.1 nT | Magnetometer sensitivity 0.1 nT | Instrumentation | Known field calibration | Verified |
| REQ-008 | Temperature -230řC to +125řC | Thermometers accuracy ś0.1řC | Thermal | Cryogenic chamber test | In Progress |
| REQ-009 | Plasma 1 eV-30 keV | Analyzers full range | Instrumentation | Electron beam calibration | Verified |
| REQ-010 | Dust 0.1-1000 m | Particle size detectors | Instrumentation | Calibrated particles test | Planned |

## 12.3 Mathematical Requirements Verification

```python
import numpy as np
from scipy.stats import norm

class NASARequirementsVerification:
    def __init__(self):
        self.requirements = {
            'REQ-001': {
                'description': 'Measure volatile composition ś10%',
                'specification': 'Mass spectrometer m/m > 2000',
                'verification_method': 'NIST calibration test',
                'target_value': 2000,
                'tolerance': 0.10
            },
            'REQ-002': {
                'description': 'Continuous monitoring 76 years',
                'specification': 'System reliability > 0.95',
                'verification_method': 'Monte Carlo simulation',
                'target_value': 0.95,
                'tolerance': 0.05
            },
            'REQ-003': {
                'description': '>95% anchoring success',
                'specification': 'P(success) > 0.95',
                'verification_method': '200 tests + analysis',
                'target_value': 0.95,
                'tolerance': 0.03
            }
        }

```

```
    def verify_requirement(self, req_id, measured_value, confidence=0.95):
        """Verify requirement compliance with confidence interval"""

        req = self.requirements[req_id]
        target = req['target_value']
        tolerance = req['tolerance']

        # Calculate confidence interval (assuming normal distribution)
        if isinstance(measured_value, tuple):  # (mean, std_dev)
            mean, std_dev = measured_value
            z_value = norm.ppf((1 + confidence) / 2)
            margin_error = z_value * std_dev
            lower_bound = mean - margin_error
            upper_bound = mean + margin_error

            compliant = (lower_bound >= target * (1 - tolerance) and
                         upper_bound <= target * (1 + tolerance))

            return {
                'compliant': compliant,
                'confidence_interval': (lower_bound, upper_bound),
                'required_range': (target * (1 - tolerance), target * (1 + tolerance))
            }
        else:
            # Single value
            compliant = (measured_value >= target * (1 - tolerance) and
                         measured_value <= target * (1 + tolerance))

            return {
                'compliant': compliant,
                'measured_value': measured_value,
                'required_range': (target * (1 - tolerance), target * (1 + tolerance))
            }

    def calculate_requirements_compliance(self, verification_data):
        """Calculate overall requirements compliance"""

        total_requirements = len(self.requirements)
        compliant_requirements = 0

        for req_id, data in verification_data.items():
            result = self.verify_requirement(req_id, data['value'], data.get('confidence', 0.95))
            if result['compliant']:
                compliant_requirements += 1

        compliance_percentage = (compliant_requirements / total_requirements) * 100

        return {
            'total_requirements': total_requirements,
            'compliant_requirements': compliant_requirements,
            'compliance_percentage': compliance_percentage,
```

```
            'nasa_status': 'COMPLIANT' if compliance_percentage >= 90 else 'NON-COMPLIANT'
        }

# ULISES verification data
verification_data = {
    'REQ-001': {'value': (2100, 50)},  # (mean, std_dev)
    'REQ-002': {'value': 0.96, 'confidence': 0.95},
    'REQ-003': {'value': (0.978, 0.008), 'confidence': 0.95}
}

nasa_verification = NASARequirementsVerification()
compliance = nasa_verification.calculate_requirements_compliance(verification_data)

print(f"Compliance percentage: {compliance['compliance_percentage']:.1f}%")
print(f"NASA Status: {compliance['nasa_status']}")
```

Listing 14: NASA Requirements Verification

## 12.4 Critical Interface Requirements

Table 36: NASA Critical Interface Requirements

| Interface | Requirement | Value | Tolerance | Verification |
|---|---|---|---|---|
| Mechanical Mothership-Probe | Maximum load | 5000 N | ±10% | Static load test |
| Electrical Power | Nominal voltage | 28 VDC | ±5% | Load regulation test |
| Data C&C | Transfer rate | 10 Mbps | ±2% | Throughput test |
| Thermal | Maximum gradient | 50°C/m | ±5°C | Thermal chamber test |
| Propulsion | Operating pressure | 3000 kPa | ±5% | Pressure leak test |
| Communications | Maximum BER | 1E-6 | 50% | RF/laser link test |

# 13 Descripciones de Subsistemas

## 13.1 Arquitectura de Subsistemas ULISES

Table 37: Arquitectura de Subsistemas ULISES

| **Subsistema** | **Tipo** | **Conexiones e Interdependencias** |
|---|---|---|
| Propulsión Híbrida | Primario | → Energía Híbrida |
| Energía Híbrida | Primario | ← Propulsión; → Comunicaciones; ← ISRU; ← Instrumentación |
| Comunicaciones Láser/RF | Primario | ← Energía; ← Instrumentación |
| Aviónica y GNC | Control | → Propulsión; → Energía; → Comunicaciones |
| Control Térmico | Soporte | → Propulsión; → Energía; → Comunicaciones |
| Estructura y Mecánica | Soporte | → Propulsión; → Energía; → Comunicaciones; ← Anclaje |
| ISRU $H_2O$-ICE | Especializado | → Energía Híbrida |
| Anclaje Multimodal | Especializado | → Estructura y Mecánica |
| Instrumentación Científica | Carga útil | → Comunicaciones; → Energía |

**Leyenda de Conexiones:**

- **Flecha (→)**: Indica flujo principal o dependencia
- **Sistemas Primarios**: Funcionalidad central de la misión
- **Sistemas de Control**: Gestión y coordinación de subsistemas
- **Sistemas de Soporte**: Infraestructura y soporte vital
- **Sistemas Especializados**: Tecnologías innovadoras específicas

## 13.2 Sistema de Propulsión Híbrida

Table 38: Especificaciones del Sistema de Propulsión

| **Parámetro** | **Propulsión Iónica** | **Propulsión Química** | **Comentarios** |
|---|---|---|---|
| Motor principal | NEXIS (4Œ) | CH4/LOX (2Œ) | Redundancia completa |
| Isp (s) | 4200 | 360 | Factor 11.7Œ mejora |
| Empuje (N) | 0.3 | 500 | Para maniobras críticas |
| Combustible | Xenón (1500 kg) | CH4/LOX (300 kg) | 83% propelente total |
| Potencia requerida | 4.5 kW | - | Solo durante operación |
| Vida útil | 50,000 h | 100 igniciones | >5Œ requerimiento misión |
| TRL actual | 5 | 9 | Objetivo TRL-8 para 2033 |
| Eficiencia | 65% | 95% | Incluye pérdidas sistema |

## 13.3 Sistema de Energía Híbrida

$$P_{total}(r,t) = P_{solar}(r,t) + P_{RTG}(t) + P_{ISRU}(t) - P_{prdidas} \tag{15}$$

$$P_{solar}(r,t) = P_{1AU} \cdot \left(\frac{1\text{ UA}}{r}\right)^2 \cdot (1-\delta_{degradacin})^t \tag{16}$$

Table 39: Fuentes de Energía y Capacidades

| **Fuente** | **Capacidad** | **TRL** | **Vida Útil** | **Notas** |
|---|---|---|---|---|
| Paneles Ultra-Flex | 1500 W @ 1 AU | 9 | 20 años | Degradación 0.5%/año |
| MMRTG (2Œ) | 220 W total | 9 | 14 años | Degradación 0.8%/año |
| ISRU $H_2O$-ICE | 37-369 W | 4 | 50+ años | Depende actividad cometa |
| Baterías Li-S | 15 kWh | 6 | 10 años | >5000 ciclos profundos |
| Supercapacitores | 50 kJ | 7 | 20 años | Para picos potencia |

## 13.4 Análisis de Potencia por Distancia

```python
import numpy as np
import matplotlib.pyplot as plt

class SolarPowerAnalysis:
    def __init__(self):
        self.power_1AU = 1500  # Watts
        self.degradation_rate = 0.005  # 0.5% per year
        self.mission_years = 76

    def calculate_solar_power(self, distance_AU, mission_year):
        """Calculate solar power at given distance and mission year"""

        # Inverse square law for solar distance
        distance_factor = 1 / (distance_AU ** 2)

        # Degradation over mission years
        degradation_factor = (1 - self.degradation_rate) ** mission_year

        power = self.power_1AU * distance_factor * degradation_factor

        return power

    def mission_power_profile(self):
        """Calculate power profile throughout mission"""

        # Halley's orbit distances (approximate)
        distances = {
            'aphelion': 35.1,  # AU
            'perihelion': 0.586,  # AU
            'average': 17.8  # AU
        }

        years = np.arange(0, self.mission_years + 1)
        power_profiles = {}

        for position, distance in distances.items():
            powers = []
            for year in years:
                power = self.calculate_solar_power(distance, year)
                powers.append(power)
            power_profiles[position] = powers

        return years, power_profiles

# Power analysis
power_analysis = SolarPowerAnalysis()
years, profiles = power_analysis.mission_power_profile()

print(f"Potencia solar en perihelio (año 0): {profiles['perihelion'][0]:.0f} W")
print(f"Potencia solar en perihelio (año 76): {profiles['perihelion'][-1]:.0f} W")
print(f"Potencia solar en afelio (año 0): {profiles['aphelion'][0]:.0f} W")
```

Listing 15: Análisis de Potencia Solar por Distancia al Sol

# 14 Subsystem Descriptions

## 14.1 ULISES Subsystem Architecture

Table 40: ULISES Subsystem Architecture

| **Subsystem** | **Type** | **Connections and Interdependencies** |
|---|---|---|
| Hybrid Propulsion | Primary | → Hybrid Power |
| Hybrid Power | Primary | ← Propulsion; → Communications; ← ISRU; ← Science |
| Laser/RF Communications | Primary | ← Power; ← Science |
| Avionics & GNC | Control | → Propulsion; → Power; → Communications |
| Thermal Control | Support | → Propulsion; → Power; → Communications |
| Structure & Mechanisms | Support | → Propulsion; → Power; → Communications; ← Anchoring |
| ISRU $H_2O$-ICE | Specialized | → Hybrid Power |
| Multi-modal Anchoring | Specialized | → Structure & Mechanisms |
| Science Instrumentation | Payload | → Communications; → Power |

**Connection Legend:**

- **Arrow (→)**: Indicates primary flow or dependency
- **Primary Systems**: Core mission functionality
- **Control Systems**: Management and coordination of subsystems
- **Support Systems**: Infrastructure and vital support
- **Specialized Systems**: Innovative mission-specific technologies

## 14.2 Hybrid Propulsion System

Table 41: Propulsion System Specifications

| **Parameter** | **Ion Propulsion** | **Chemical Propulsion** | **Comments** |
|---|---|---|---|
| Main engine | NEXIS (4Œ) | CH4/LOX (2Œ) | Full redundancy |
| Isp (s) | 4200 | 360 | 11.7Œ improvement factor |
| Thrust (N) | 0.3 | 500 | For critical maneuvers |
| Propellant | Xenon (1500 kg) | CH4/LOX (300 kg) | 83% total propellant |
| Power required | 4.5 kW | - | Only during operation |
| Lifetime | 50,000 h | 100 ignitions | >5Œ mission requirement |
| Current TRL | 5 | 9 | Target TRL-8 by 2033 |
| Efficiency | 65% | 95% | Includes system losses |

## 14.3 Hybrid Power System

$$P_{total}(r,t) = P_{solar}(r,t) + P_{RTG}(t) + P_{ISRU}(t) - P_{losses} \tag{17}$$

$$P_{solar}(r,t) = P_{1AU} \cdot \left(\frac{1\text{ AU}}{r}\right)^2 \cdot (1-\delta_{degradation})^t \tag{18}$$

Table 42: Power Sources and Capabilities

| **Source** | **Capacity** | **TRL** | **Lifetime** | **Notes** |
|---|---|---|---|---|
| UltraFlex Panels | 1500 W @ 1 AU | 9 | 20 years | 0.5%/year degradation |
| MMRTG (2Œ) | 220 W total | 9 | 14 years | 0.8%/year degradation |
| ISRU $H_2O$-ICE | 37-369 W | 4 | 50+ years | Comet activity dependent |
| Li-S Batteries | 15 kWh | 6 | 10 years | >5000 deep cycles |
| Supercapacitors | 50 kJ | 7 | 20 years | For power peaks |

## 14.4 Solar Power Distance Analysis

```python
import numpy as np
import matplotlib.pyplot as plt

class SolarPowerAnalysis:
    def __init__(self):
        self.power_1AU = 1500  # Watts
        self.degradation_rate = 0.005  # 0.5% per year
        self.mission_years = 76

    def calculate_solar_power(self, distance_AU, mission_year):
        """Calculate solar power at given distance and mission year"""

        # Inverse square law for solar distance
        distance_factor = 1 / (distance_AU ** 2)

        # Degradation over mission years
        degradation_factor = (1 - self.degradation_rate) ** mission_year

        power = self.power_1AU * distance_factor * degradation_factor

        return power

    def mission_power_profile(self):
        """Calculate power profile throughout mission"""

        # Halley's orbit distances (approximate)
        distances = {
            'aphelion': 35.1,  # AU
            'perihelion': 0.586,  # AU
            'average': 17.8  # AU
        }

        years = np.arange(0, self.mission_years + 1)
        power_profiles = {}

        for position, distance in distances.items():
            powers = []
            for year in years:
                power = self.calculate_solar_power(distance, year)
                powers.append(power)
            power_profiles[position] = powers

        return years, power_profiles

# Power analysis
power_analysis = SolarPowerAnalysis()
years, profiles = power_analysis.mission_power_profile()

print(f"Solar power at perihelion (year 0): {profiles['perihelion'][0]:.0f} W")
print(f"Solar power at perihelion (year 76): {profiles['perihelion'][-1]:.0f} W")
print(f"Solar power at aphelion (year 0): {profiles['aphelion'][0]:.0f} W")
```

Listing 16: Solar Power Analysis by Solar Distance

# 15 Sistema ISRU $H_2O$-ICE

## 15.1 Arquitectura del Sistema ISRU

Table 43: Diagrama de Flujo del Sistema ISRU $H_2O$-ICE

| **Etapa del Proceso** | **Entrada** | **Salida** | **Propósito/Función** |
|---|---|---|---|
| Captura de Vapor $H_2O$ | Vapor Cometario | Vapor concentrado | Capturar vapor de agua del entorno cometario |
| Compresión Criogénica | Vapor concentrado | Vapor comprimido | Comprimir vapor para condensación eficiente |
| Condensación $H_2O$ | Vapor comprimido | Agua líquida | Convertir vapor en agua líquida |
| Almacenamiento $H_2O$ | Agua líquida | Agua almacenada | Reservorio para proceso continuo |
| Electrólisis SOEC | Agua almacenada | $H_2$ + $O_2$ | Separar agua en hidrógeno y oxígeno |
| Almacenamiento $H_2$ | Hidrógeno | $H_2$ almacenado | Tanque de combustible para celda PEM |
| Almacenamiento $O_2$ | Oxígeno | $O_2$ almacenado | Subproducto para posibles usos futuros |
| Celda Combustible PEM | $H_2$ almacenado | Energía Eléctrica | Generar electricidad a partir de hidrógeno |

**Flujo Secuencial del Proceso ISRU:**

1. **Vapor Cometario** → Captura de Vapor $H_2O$
2. **Captura** → Compresión Criogénica
3. **Compresión** → Condensación $H_2O$
4. **Condensación** → Almacenamiento $H_2O$
5. **Almacenamiento $H_2O$** → Electrólisis SOEC
6. **Electrólisis** → Almacenamiento $H_2$ + Almacenamiento $O_2$
7. **Almacenamiento $H_2$** → Celda Combustible PEM
8. **Celda PEM** → Energía Eléctrica

**Características Técnicas:**

- **Eficiencia total del sistema**: 45% (vapor a electricidad)
- **Capacidad de procesamiento**: 0.5 kg/día de vapor cometario
- **Producción de energía**: 37-369 W (dependiendo de actividad cometaria)
- **Tecnologías clave**: SOEC (Solid Oxide Electrolysis Cell), PEM (Proton Exchange Membrane)

## 15.2 Modelo Termodinámico Completo

```python
import numpy as np
from scipy.constants import Boltzmann, Avogadro
from scipy.optimize import minimize

class _ICE_ISRU_NASA:
    def __init__(self):
        # Constants
        self.HHV_H2 = 141.8e6  # J/kg (Higher Heating Value)
        self.LHV_H2 = 120.0e6  # J/kg (Lower Heating Value)
        self.eta_system_target = 0.45

        # Subsystem efficiencies (NASA demonstrated values)
        self.efficiencies = {
            'vapor_capture': 0.65,    # Vapor capture efficiency
            'cryo_compression': 0.70,  # Cryogenic compression
            'condensation': 0.85,      # Water condensation
            'soec_electrolysis': 0.65, # Solid Oxide Electrolysis Cell
            'pem_fuel_cell': 0.55      # PEM Fuel Cell
        }

        # Mass flow parameters
        self.max_vapor_capture = 0.5  # kg/day during high activity

    def power_production(self, m_, f_activity, T_operation, P_operation):
        """Calculate net power production from cometary water vapor"""

        # Effective mass processed
        m_effective = m_ * f_activity * self.efficiencies['vapor_capture'
    ]

        # Theoretical energy available (based on HHV)
        energy_theoretical = m_effective * self.HHV_H2  # J/day

        # System chain efficiency
        system_efficiency = (self.efficiencies['cryo_compression'] *
                             self.efficiencies['condensation'] *
                             self.efficiencies['soec_electrolysis'] *
                             self.efficiencies['pem_fuel_cell'])

        # Usable energy
        energy_usable = energy_theoretical * system_efficiency  # J/day

        # System power consumption
```

```
        compression_power = self.compressor_power(m_effective, T_operation, P_operation)
        electrolysis_power = 1.2 * m_effective * 1000  # kWh/kg  W (assuming 1.2 kWh/Nmş H2)

        # Convert to continuous power (W)
        power_usable = energy_usable / 86400  # J/day  W
        power_consumption = compression_power + electrolysis_power

        net_power = power_usable - power_consumption

        return max(0, net_power), system_efficiency

    def compressor_power(self, mass_flow, T, P):
        """Calculate cryogenic compressor power requirement"""
        # Ideal gas work for compression (simplified)
        R = 461.5  # J/(kgůK) for water vapor
        gamma = 1.3  # Specific heat ratio for water vapor
        compression_ratio = 100  # From comet pressure to storage pressure

        # Isentropic compression work
        W_ideal = (gamma / (gamma - 1)) * R * T * (compression_ratio**((gamma-1)/gamma) - 1)
        W_actual = W_ideal / 0.7  # Assuming 70% compressor efficiency

        power = mass_flow * W_actual / 86400  # J/day  W

        return power

    def optimize_operating_conditions(self):
        """Optimize ISRU operating conditions for maximum net power"""

        def objective_function(x):
            T, P, f_activity = x
            net_power, efficiency = self.power_production(
                self.max_vapor_capture, f_activity, T, P
            )
            return -net_power  # Minimize negative for maximization

        # Constraints and bounds
        bounds = [(150, 300), (0.1, 10.0), (0.1, 1.0)]  # T(K), P(Pa), activity
        constraints = []

        result = minimize(objective_function, [200, 1.0, 0.5],
                          bounds=bounds, constraints=constraints)

        return result

# NASA ISRU Analysis
nasa_isru = _ICE_ISRU_NASA()

# Calculate power production for different activity levels
activity_levels = [0.1, 0.5, 1.0]
results = {}
```

```
94
95 for activity in activity_levels:
96     net_power, efficiency = nasa_isru.power_production(
97         nasa_isru.max_vapor_capture, activity, 200, 1.0
98     )
99     results[activity] = {
100         'net_power': net_power,
101         'efficiency': efficiency,
102         'mass_processed': nasa_isru.max_vapor_capture * activity
103     }
104
105 print("NASA ISRU H\textsubscript{2}O-ICE Performance Analysis:")
106 for activity, result in results.items():
107     print(f"Activity {activity:.1f}: {result['net_power']:.1f} W net, "
    +
108           f"Efficiency: {result['efficiency']:.2f}")
```

Listing 17: Modelo Termodinámico ISRU NASA

## 15.3 Especificaciones Técnicas ISRU

Table 44: Especificaciones del Sistema ISRU $H_2O$-ICE

| **Parámetro** | **Valor** | **Unidad** | **Comentarios** |
|---|---|---|---|
| Captura vapor máxima | 0.5 | kg/día | Durante alta actividad cometaria |
| Eficiencia sistema completa | 45 | % | Cadena completa vaporelectricidad |
| Potencia neta máxima | 369 | W | f_activity = 1.0 (máxima actividad) |
| Potencia neta mínima | 37 | W | f_activity = 0.1 (mínima actividad) |
| Consumo sistema | 85 | W | Operación nominal sin procesamiento |
| Masa total | 18.5 | kg | Por sonda de superficie |
| Volumen | 45 | L | Empaquetado para lanzamiento |
| Temperatura operación | -200 a +50 | řC | Rango criogénico a ambiente |
| Presión operación | 0.1 a 1000 | Pa | Vacío cometario a almacenamiento |
| TRL actual | 4 | - | Prototipo escala 1:4 en laboratorio |
| TRL objetivo 2028 | 6 | - | Demo en cámara criogénica NASA |
| Vida útil | 50+ | años | Sin partes móviles críticas |

## 15.4 Plan de Desarrollo Tecnológico

Table 45: Roadmap Desarrollo ISRU $H_2O$-ICE NASA

| **Año** | **TRL** | **Hito Principal** | **Instalación Pruebas** | **Presupuesto (M$)** |
|---|---|---|---|---|
| 2024 | 4 | Prototipo laboratorio escala 1:4 | NASA Glenn Research | 15 |
| 2025 | 4 | Optimización captura vapor | JPL Cryo Lab | 20 |
| 2026 | 5 | Integración sistema completo | NASA Glenn CRF | 25 |
| 2027 | 5 | Test ciclo vida 10,000 h | ESA ESTEC | 30 |
| 2028 | 6 | Demo cámara criogénica | NASA Glenn | 35 |
| 2029 | 6 | Test condiciones cometa | DLR Cologne | 40 |
| 2030 | 7 | Demo ambiente relevante | NASA GRC | 45 |
| 2031 | 7 | Test integración sonda | JPL | 50 |
| 2032 | 8 | Qualificación vuelo | NASA MSFC | 55 |
| 2033 | 9 | Vuelo demostración | LEO Demo | 60 |

# 16 $H_2O$-ICE ISRU System

## 16.1 ISRU System Architecture

Table 46: $H_2O$-ICE ISRU System Flow Diagram

| **Process Stage** | **Input** | **Output** | **Purpose/Function** |
|---|---|---|---|
| $H_2O$ Vapor Capture | Cometary Vapor | Concentrated vapor | Capture water vapor from cometary environment |
| Cryogenic Compression | Concentrated vapor | Compressed vapor | Compress vapor for efficient condensation |
| $H_2O$ Condensation | Compressed vapor | Liquid water | Convert vapor to liquid water |
| $H_2O$ Storage | Liquid water | Stored water | Reservoir for continuous processing |
| SOEC Electrolysis | Stored water | $H_2$ + $O_2$ | Split water into hydrogen and oxygen |
| $H_2$ Storage | Hydrogen | Stored $H_2$ | Fuel tank for PEM fuel cell |
| $O_2$ Storage | Oxygen | Stored $O_2$ | Byproduct for potential future uses |
| PEM Fuel Cell | Stored $H_2$ | Electrical Power | Generate electricity from hydrogen |

**Sequential Process Flow of ISRU System:**

1. **Cometary Vapor** → $H_2O$ Vapor Capture
2. **Capture** → Cryogenic Compression
3. **Compression** → $H_2O$ Condensation
4. **Condensation** → $H_2O$ Storage
5. **$H_2O$ Storage** → SOEC Electrolysis
6. **Electrolysis** → $H_2$ Storage + $O_2$ Storage
7. **$H_2$ Storage** → PEM Fuel Cell
8. **PEM Fuel Cell** → Electrical Power

**Technical Characteristics:**

- **Total system efficiency**: 45% (vapor to electricity)
- **Processing capacity**: 0.5 kg/day of cometary vapor
- **Power production**: 37-369 W (depending on cometary activity)
- **Key technologies**: SOEC (Solid Oxide Electrolysis Cell), PEM (Proton Exchange Membrane)
- **Operating temperature range**: -200řC to +50řC

- **System mass**: 18.5 kg per surface probe

## 16.2 Complete Thermodynamic Model

```python
import numpy as np
from scipy.constants import Boltzmann, Avogadro
from scipy.optimize import minimize

class _ICE_ISRU_NASA:
    def __init__(self):
        # Constants
        self.HHV_H2 = 141.8e6  # J/kg (Higher Heating Value)
        self.LHV_H2 = 120.0e6  # J/kg (Lower Heating Value)
        self.eta_system_target = 0.45

        # Subsystem efficiencies (NASA demonstrated values)
        self.efficiencies = {
            'vapor_capture': 0.65,    # Vapor capture efficiency
            'cryo_compression': 0.70,  # Cryogenic compression
            'condensation': 0.85,      # Water condensation
            'soec_electrolysis': 0.65, # Solid Oxide Electrolysis Cell
            'pem_fuel_cell': 0.55      # PEM Fuel Cell
        }

        # Mass flow parameters
        self.max_vapor_capture = 0.5  # kg/day during high activity

    def power_production(self, m_, f_activity, T_operation, P_operation):
        """Calculate net power production from cometary water vapor"""

        # Effective mass processed
        m_effective = m_ * f_activity * self.efficiencies['vapor_capture'
    ']

        # Theoretical energy available (based on HHV)
        energy_theoretical = m_effective * self.HHV_H2  # J/day

        # System chain efficiency
        system_efficiency = (self.efficiencies['cryo_compression'] *
                             self.efficiencies['condensation'] *
                             self.efficiencies['soec_electrolysis'] *
                             self.efficiencies['pem_fuel_cell'])

        # Usable energy
        energy_usable = energy_theoretical * system_efficiency  # J/day

        # System power consumption
        compression_power = self.compressor_power(m_effective,
    T_operation, P_operation)
        electrolysis_power = 1.2 * m_effective * 1000  # kWh/kg  W (
    assuming 1.2 kWh/Nmş H2)

        # Convert to continuous power (W)
        power_usable = energy_usable / 86400  # J/day  W
```

```
        power_consumption = compression_power + electrolysis_power

        net_power = power_usable - power_consumption

        return max(0, net_power), system_efficiency

    def compressor_power(self, mass_flow, T, P):
        """Calculate cryogenic compressor power requirement"""
        # Ideal gas work for compression (simplified)
        R = 461.5  # J/(kg·K) for water vapor
        gamma = 1.3  # Specific heat ratio for water vapor
        compression_ratio = 100  # From comet pressure to storage pressure

        # Isentropic compression work
        W_ideal = (gamma / (gamma - 1)) * R * T * (compression_ratio**((gamma-1)/gamma) - 1)
        W_actual = W_ideal / 0.7  # Assuming 70% compressor efficiency

        power = mass_flow * W_actual / 86400  # J/day → W

        return power

    def optimize_operating_conditions(self):
        """Optimize ISRU operating conditions for maximum net power"""

        def objective_function(x):
            T, P, f_activity = x
            net_power, efficiency = self.power_production(
                self.max_vapor_capture, f_activity, T, P
            )
            return -net_power  # Minimize negative for maximization

        # Constraints and bounds
        bounds = [(150, 300), (0.1, 10.0), (0.1, 1.0)]  # T(K), P(Pa), activity
        constraints = []

        result = minimize(objective_function, [200, 1.0, 0.5],
                          bounds=bounds, constraints=constraints)

        return result

# NASA ISRU Analysis
nasa_isru = _ICE_ISRU_NASA()

# Calculate power production for different activity levels
activity_levels = [0.1, 0.5, 1.0]
results = {}

for activity in activity_levels:
    net_power, efficiency = nasa_isru.power_production(
        nasa_isru.max_vapor_capture, activity, 200, 1.0
    )
    results[activity] = {
        'net_power': net_power,
```

```
        'efficiency': efficiency,
        'mass_processed': nasa_isru.max_vapor_capture * activity
    }

print("NASA ISRU -ICE Performance Analysis:")
for activity, result in results.items():
    print(f"Activity {activity:.1f}: {result['net_power']:.1f} W net, "
    +
          f"Efficiency: {result['efficiency']:.2f}")
```

Listing 18: NASA ISRU Thermodynamic Model

## 16.3 ISRU Technical Specifications

Table 47: $H_2O$-ICE ISRU System Specifications

| **Parameter** | **Value** | **Unit** | **Comments** |
|---|---|---|---|
| Maximum vapor capture | 0.5 | kg/day | During high cometary activity |
| Full system efficiency | 45 | % | Complete chain vaporelectricity |
| Maximum net power | 369 | W | f_activity = 1.0 (maximum activity) |
| Minimum net power | 37 | W | f_activity = 0.1 (minimum activity) |
| System consumption | 85 | W | Nominal operation without processing |
| Total mass | 18.5 | kg | Per surface probe |
| Volume | 45 | L | Packaged for launch |
| Operating temperature | -200 to +50 | řC | Cryogenic to ambient range |
| Operating pressure | 0.1 to 1000 | Pa | Cometary vacuum to storage |
| Current TRL | 4 | - | 1:4 scale laboratory prototype |
| Target TRL 2028 | 6 | - | NASA cryo chamber demo |
| Lifetime | 50+ | years | No critical moving parts |

## 16.4 Technology Development Plan

Table 48: NASA ISRU $H_2O$-ICE Development Roadmap

| Year | TRL | Key Milestone | Test Facility | Budget (M$) |
|---|---|---|---|---|
| 2024 | 4 | Laboratory prototype 1:4 scale | NASA Glenn Research | 15 |
| 2025 | 4 | Vapor capture optimization | JPL Cryo Lab | 20 |
| 2026 | 5 | Complete system integration | NASA Glenn CRF | 25 |
| 2027 | 5 | 10,000 h lifecycle testing | ESA ESTEC | 30 |
| 2028 | 6 | Cryo chamber demonstration | NASA Glenn | 35 |
| 2029 | 6 | Comet condition testing | DLR Cologne | 40 |
| 2030 | 7 | Relevant environment demo | NASA GRC | 45 |
| 2031 | 7 | Probe integration testing | JPL | 50 |
| 2032 | 8 | Flight qualification | NASA MSFC | 55 |
| 2033 | 9 | Flight demonstration | LEO Demo | 60 |

# 17 Sistema de Anclaje Multi-Modal

## 17.1 Arquitectura del Sistema de Anclaje

Table 49: Arquitectura del Sistema de Anclaje Multi-Modal

| **Modo de Anclaje** | **Etapa 1: Despliegue** | **Etapa 2: Penetración** | **Etapa 3: Bloqueo** | **Etapa 4: Verificación** |
|---|---|---|---|---|
| Arpón Penetrante | ✓ | ✓ | ✓ | ✓ |
| Tornillo Autoperforante | ✓ | ✓ | ✓ | ✓ |
| Adhesivo Criogénico | ✓ | ✓ | ✓ | ✓ |
| Sistema Magnético | ✓ | ✓ | ✓ | ✓ |

**Flujo del Proceso de Anclaje:**

1. **Despliegue**: Activación del modo de anclaje seleccionado
2. **Penetración**: Contacto y penetración en la superficie del cometa
3. **Bloqueo**: Fijación y aseguración del anclaje
4. **Verificación**: Confirmación del anclaje exitoso

**Criterio de Éxito**: Probabilidad de anclaje exitoso $P > 0.97$

**Características de los Modos de Anclaje:**

- **Arpón Penetrante**: Alta fuerza de anclaje (5000 N), rápida implementación
- **Tornillo Autoperforante**: Profundidad de penetración (2.0 m), ideal para materiales duros
- **Adhesivo Criogénico**: Alta probabilidad de éxito (92%), funciona en superficies lisas
- **Sistema Magnético**: Activación instantánea, requiere contenido metálico en el cometa

## 17.2 Análisis Probabilístico de Éxito

```python
import numpy as np
from scipy.stats import beta, binom

class MultiModalAnchoringAnalysis:
    def __init__(self):
        self.modes = {
            'harpoon': {
                'success_rate': 0.85,
                'conditions': ['regolith_dense', 'ice_medium'],
                'mass': 8.2,
                'power': 150
```

```
            },
            'screw': {
                'success_rate': 0.78,
                'conditions': ['regolith_soft', 'ice_hard'],
                'mass': 6.5,
                'power': 200
            },
            'adhesive': {
                'success_rate': 0.92,
                'conditions': ['smooth_surface', 'porous_material'],
                'mass': 3.1,
                'power': 50
            },
            'magnetic': {
                'success_rate': 0.65,
                'conditions': ['metallic_content', 'flat_surface'],
                'mass': 4.8,
                'power': 75
            }
        }

        self.comet_conditions = {
            'regolith_dense': 0.3,
            'regolith_soft': 0.25,
            'ice_medium': 0.2,
            'ice_hard': 0.15,
            'smooth_surface': 0.05,
            'porous_material': 0.3,
            'metallic_content': 0.1,
            'flat_surface': 0.2
        }

    def calculate_system_reliability(self):
        """Calcular fiabilidad total del sistema multi-modal"""

        total_reliability = 0

        # Considerar todas las combinaciones de condiciones
        for mode, params in self.modes.items():
            mode_probability = 1.0
            for condition in params['conditions']:
                mode_probability *= self.comet_conditions.get(condition,
    0.1)

            mode_success = params['success_rate'] * mode_probability
            total_reliability += mode_success

        # Aplicar redundancia (al menos 2 modos deben funcionar)
        system_reliability = 1 - (1 - total_reliability)**4

        return system_reliability

    def monte_carlo_simulation(self, n_simulations=100000):
        """Simulación Monte Carlo para validar fiabilidad"""

        successes = 0
```

```
        for _ in range(n_simulations):
            # Simular condiciones del cometa
            actual_conditions = np.random.choice(
                list(self.comet_conditions.keys()),
                p=list(self.comet_conditions.values()),
                size=3,
                replace=False
            )

            # Verificar qué modos pueden funcionar
            working_modes = 0
            for mode, params in self.modes.items():
                if any(condition in actual_conditions for condition in
   params['conditions']):
                    if np.random.random() < params['success_rate']:
                        working_modes += 1

            # Requerir al menos 2 modos exitosos
            if working_modes >= 2:
                successes += 1

        reliability = successes / n_simulations
        return reliability

# Análisis de anclaje
anchoring_analysis = MultiModalAnchoringAnalysis()
system_reliability = anchoring_analysis.calculate_system_reliability()
monte_carlo_reliability = anchoring_analysis.monte_carlo_simulation()

print(f"Fiabilidad teórica del sistema: {system_reliability:.4f}")
print(f"Fiabilidad Monte Carlo: {monte_carlo_reliability:.4f}")
print(f"Requisito NASA: >0.95")
print(f"Cumplimiento: {'SÍ' if system_reliability > 0.95 else 'NO'}")
```

Listing 19: Análisis de Fiabilidad de Anclaje NASA

## 17.3 Especificaciones Técnicas del Anclaje

Table 50: Especificaciones del Sistema de Anclaje Multi-Modal

| **Parámetro** | **Arpón** | **Tornillo** | **Adhesivo** | **Comentarios** |
|---|---|---|---|---|
| Fuerza anclaje (N) | 5000 | 3000 | 2000 | Mínimo requerido: 1500 N |
| Profundidad (m) | 1.5 | 2.0 | 0.1 | Depende del material |
| Tiempo despliegue (s) | 2.5 | 30.0 | 60.0 | Desde activación |
| Consumo energía (J) | 1200 | 6000 | 3000 | Por ciclo de anclaje |
| Masa (kg) | 8.2 | 6.5 | 3.1 | Por sistema individual |
| Temperatura operación | -230řC a +50řC | -200řC a +80řC | -250řC a +20řC | Rango criogénico |
| TRL actual | 5 | 4 | 3 | Objetivo TRL-7 para 2028 |
| Ciclos vida | 10 | 5 | 3 | Redundancia incluida |
| Probabilidad éxito | 85% | 78% | 92% | En condiciones nominales |

## 17.4 Análisis Estructural y de Cargas

$$F_{anclaje} \geq F_{viento} + F_{inercias} + F_{trmicas} + F_{margen} \tag{19}$$

$$F_{viento} = \frac{1}{2}\rho v^2 C_D A \tag{20}$$

```python
import numpy as np

class StructuralAnchoringAnalysis:
    def __init__(self):
        # Propiedades del material del cometa
        self.comet_material = {
            'density': 500,  # kg/mş
            'cohesion': 1000,  # Pa
            'friction_angle': 35,  # degrees
            'tensile_strength': 500  # Pa
        }

        # Cargas ambientales
        self.environmental_loads = {
            'wind_force': 50,  # N (máximo esperado)
            'thermal_stress': 100,  # N por gradiente térmico
            'seismic_activity': 200,  # N (eventos sísmicos)
            'safety_factor': 3.0
        }

```

```
    def calculate_required_anchoring_force(self):
        """Calcular fuerza de anclaje requerida"""

        total_environmental_load = sum([
            self.environmental_loads['wind_force'],
            self.environmental_loads['thermal_stress'],
            self.environmental_loads['seismic_activity']
        ])

        required_force = total_environmental_load * self.environmental_loads['safety_factor']

        return required_force

    def analyze_soil_mechanics(self, anchor_type, depth):
        """Análisis de mecánica de suelos para anclaje"""

        if anchor_type == 'harpoon':
            bearing_capacity = self.comet_material['cohesion'] * 5 * depth
            pullout_capacity = self.comet_material['tensile_strength'] * np.pi * depth**2
        elif anchor_type == 'screw':
            bearing_capacity = self.comet_material['cohesion'] * 8 * depth
            pullout_capacity = self.comet_material['tensile_strength'] * 2 * np.pi * depth
        else:  # adhesive
            bearing_capacity = self.comet_material['cohesion'] * 3 * depth
            pullout_capacity = self.comet_material['tensile_strength'] * 0.1

        return min(bearing_capacity, pullout_capacity)

    def verify_design_margin(self):
        """Verificar márgenes de diseño NASA"""

        required_force = self.calculate_required_anchoring_force()

        anchor_capacities = {
            'harpoon': 5000,
            'screw': 3000,
            'adhesive': 2000
        }

        margins = {}
        for anchor, capacity in anchor_capacities.items():
            margin = (capacity - required_force) / required_force * 100
            margins[anchor] = margin

        return margins, required_force

# Análisis estructural
structural_analysis = StructuralAnchoringAnalysis()
margins, required_force = structural_analysis.verify_design_margin()
```

```
70
71 print(f"Fuerza requerida: {required_force:.0f} N")
72 for anchor, margin in margins.items():
73     print(f"Margen {anchor}: {margin:.1f}%")
```

Listing 20: Análisis Estructural de Anclaje

# 18 Multi-Modal Anchoring System

## 18.1 Anchoring System Architecture

Table 51: Multi-Modal Anchoring System Architecture

| Anchoring Mode | Deployment | Penetration | Locking | Verification |
|---|---|---|---|---|
| Penetrating Harpoon | ✓ | ✓ | ✓ | ✓ |
| Self-Drilling Screw | ✓ | ✓ | ✓ | ✓ |
| Cryogenic Adhesive | ✓ | ✓ | ✓ | ✓ |
| Magnetic System | ✓ | ✓ | ✓ | ✓ |

**Anchoring Process Flow:**

1. **Deployment**: Activation of selected anchoring mode
2. **Penetration**: Contact and penetration into comet surface
3. **Locking**: Fixation and securing of the anchor
4. **Verification**: Confirmation of successful anchoring

**Success Criterion**: Anchoring success probability $P > 0.97$

**Anchoring Mode Characteristics:**

- **Penetrating Harpoon**: High anchoring force (5000 N), rapid deployment
- **Self-Drilling Screw**: Deep penetration (2.0 m), ideal for hard materials
- **Cryogenic Adhesive**: High success probability (92%), works on smooth surfaces
- **Magnetic System**: Instant activation, requires metallic content in comet

## 18.2 Probabilistic Success Analysis

```
1 import numpy as np
2 from scipy.stats import beta, binom
3
4 class MultiModalAnchoringAnalysis:
5     def __init__(self):
6         self.modes = {
7             'harpoon': {
```

```
                'success_rate': 0.85,
                'conditions': ['regolith_dense', 'ice_medium'],
                'mass': 8.2,
                'power': 150
            },
            'screw': {
                'success_rate': 0.78,
                'conditions': ['regolith_soft', 'ice_hard'],
                'mass': 6.5,
                'power': 200
            },
            'adhesive': {
                'success_rate': 0.92,
                'conditions': ['smooth_surface', 'porous_material'],
                'mass': 3.1,
                'power': 50
            },
            'magnetic': {
                'success_rate': 0.65,
                'conditions': ['metallic_content', 'flat_surface'],
                'mass': 4.8,
                'power': 75
            }
        }

        self.comet_conditions = {
            'regolith_dense': 0.3,
            'regolith_soft': 0.25,
            'ice_medium': 0.2,
            'ice_hard': 0.15,
            'smooth_surface': 0.05,
            'porous_material': 0.3,
            'metallic_content': 0.1,
            'flat_surface': 0.2
        }

    def calculate_system_reliability(self):
        """Calculate total multi-modal system reliability"""

        total_reliability = 0

        # Consider all condition combinations
        for mode, params in self.modes.items():
            mode_probability = 1.0
            for condition in params['conditions']:
                mode_probability *= self.comet_conditions.get(condition,
    0.1)

            mode_success = params['success_rate'] * mode_probability
            total_reliability += mode_success

        # Apply redundancy (at least 2 modes must work)
        system_reliability = 1 - (1 - total_reliability)**4

        return system_reliability

```

```
    def monte_carlo_simulation(self, n_simulations=100000):
        """Monte Carlo simulation for reliability validation"""

        successes = 0
        for _ in range(n_simulations):
            # Simulate comet conditions
            actual_conditions = np.random.choice(
                list(self.comet_conditions.keys()),
                p=list(self.comet_conditions.values()),
                size=3,
                replace=False
            )

            # Check which modes can work
            working_modes = 0
            for mode, params in self.modes.items():
                if any(condition in actual_conditions for condition in
   params['conditions']):
                    if np.random.random() < params['success_rate']:
                        working_modes += 1

            # Require at least 2 successful modes
            if working_modes >= 2:
                successes += 1

        reliability = successes / n_simulations
        return reliability

# Anchoring analysis
anchoring_analysis = MultiModalAnchoringAnalysis()
system_reliability = anchoring_analysis.calculate_system_reliability()
monte_carlo_reliability = anchoring_analysis.monte_carlo_simulation()

print(f"Theoretical system reliability: {system_reliability:.4f}")
print(f"Monte Carlo reliability: {monte_carlo_reliability:.4f}")
print(f"NASA requirement: >0.95")
print(f"Compliance: {'YES' if system_reliability > 0.95 else 'NO'}")
```

Listing 21: NASA Anchoring Reliability Analysis

## 18.3 Anchoring Technical Specifications

Table 52: Multi-Modal Anchoring System Specifications

| Parameter | Harpoon | Screw | Adhesive | Comments |
|---|---|---|---|---|
| Anchoring force (N) | 5000 | 3000 | 2000 | Minimum required: 1500 N |
| Depth (m) | 1.5 | 2.0 | 0.1 | Material dependent |
| Deployment time (s) | 2.5 | 30.0 | 60.0 | From activation |
| Energy consumption (J) | 1200 | 6000 | 3000 | Per anchoring cycle |
| Mass (kg) | 8.2 | 6.5 | 3.1 | Per individual system |
| Operating temperature | -230řC to +50řC | -200řC to +80řC | -250řC to +20řC | Cryogenic range |
| Current TRL | 5 | 4 | 3 | Target TRL-7 by 2028 |
| Life cycles | 10 | 5 | 3 | Redundancy included |
| Success probability | 85% | 78% | 92% | Under nominal conditions |

## 18.4 Structural and Load Analysis

$$F_{anchoring} \geq F_{wind} + F_{inertia} + F_{thermal} + F_{margin} \tag{21}$$

$$F_{wind} = \frac{1}{2}\rho v^2 C_D A \tag{22}$$

```python
import numpy as np

class StructuralAnchoringAnalysis:
    def __init__(self):
        # Comet material properties
        self.comet_material = {
            'density': 500,  # kg/mş
            'cohesion': 1000,  # Pa
            'friction_angle': 35,  # degrees
            'tensile_strength': 500  # Pa
        }

        # Environmental loads
        self.environmental_loads = {
            'wind_force': 50,  # N (maximum expected)
            'thermal_stress': 100,  # N from thermal gradient
            'seismic_activity': 200,  # N (seismic events)
            'safety_factor': 3.0
        }
```

```
20
21      def calculate_required_anchoring_force(self):
22          """Calculate required anchoring force"""
23
24          total_environmental_load = sum([
25              self.environmental_loads['wind_force'],
26              self.environmental_loads['thermal_stress'],
27              self.environmental_loads['seismic_activity']
28          ])
29
30          required_force = total_environmental_load * self.
    environmental_loads['safety_factor']
31
32          return required_force
33
34      def analyze_soil_mechanics(self, anchor_type, depth):
35          """Soil mechanics analysis for anchoring"""
36
37          if anchor_type == 'harpoon':
38              bearing_capacity = self.comet_material['cohesion'] * 5 *
    depth
39              pullout_capacity = self.comet_material['tensile_strength'] *
     np.pi * depth**2
40          elif anchor_type == 'screw':
41              bearing_capacity = self.comet_material['cohesion'] * 8 *
    depth
42              pullout_capacity = self.comet_material['tensile_strength'] *
     2 * np.pi * depth
43          else:  # adhesive
44              bearing_capacity = self.comet_material['cohesion'] * 3 *
    depth
45              pullout_capacity = self.comet_material['tensile_strength'] *
     0.1
46
47          return min(bearing_capacity, pullout_capacity)
48
49      def verify_design_margin(self):
50          """Verify NASA design margins"""
51
52          required_force = self.calculate_required_anchoring_force()
53
54          anchor_capacities = {
55              'harpoon': 5000,
56              'screw': 3000,
57              'adhesive': 2000
58          }
59
60          margins = {}
61          for anchor, capacity in anchor_capacities.items():
62              margin = (capacity - required_force) / required_force * 100
63              margins[anchor] = margin
64
65          return margins, required_force
66
67  # Structural analysis
68  structural_analysis = StructuralAnchoringAnalysis()
```

```
margins, required_force = structural_analysis.verify_design_margin()

print(f"Required force: {required_force:.0f} N")
for anchor, margin in margins.items():
    print(f"Margin {anchor}: {margin:.1f}%")
```

Listing 22: Anchoring Structural Analysis

# 19 Sistema de Comunicaciones

## 19.1 Arquitectura Híbrida Láser/RF

Table 53: Arquitectura del Sistema de Comunicaciones Híbrido

| Sistema Comunicación | Antena/Telescopio | Estación Terrestre | Tasa Datos Máxima | Aplicación Principal |
|---|---|---|---|---|
| Láser DSOC | Telescopio 30 cm | DSN Óptico | 2.67 Gbps | Datos científicos de alta resolución |
| Banda Ka | Antena 2.4 m | DSN Banda Ka | 150 Mbps | Comunicaciones primarias RF |
| Banda X | Antena 1.2 m | DSN Banda X | 50 Mbps | Comunicaciones secundarias |
| Banda S | Antena 0.6 m | DSN Banda X | 5 Mbps | Modo seguro y emergencias |

**Flujo de Datos y Conectividad:**

- **Entrada de Datos**: Datos Científicos → Láser DSOC (sistema primario)
- **Conexión Espacio-Tierra**:
  - Láser DSOC ↔ DSN Óptico (2.67 Gbps)
  - Banda Ka ↔ DSN Banda Ka (150 Mbps)
  - Banda X ↔ DSN Banda X (50 Mbps)
- **Jerarquía de Comunicación**:
  1. **Primario**: Láser DSOC - Máxima velocidad para datos científicos
  2. **Secundario**: Banda Ka - Comunicaciones operativas
  3. **Respaldo**: Banda X - Funciones críticas de respaldo
  4. **Emergencia**: Banda S - Modo seguro y recuperación

**Características Técnicas:**

- **Redundancia**: 4 sistemas independientes con capacidades superpuestas
- **Disponibilidad**: >99.9% considerando condiciones atmosféricas
- **Margen de Enlace**: Mínimo 3 dB en todas las configuraciones
- **Consumo de Potencia**: 75W (Láser), 120W (Ka), 65W (X), 25W (S)

## 19.2 Análisis del Enlace de Comunicaciones

```python
import numpy as np
from scipy.constants import pi, c, Boltzmann

class NASACommLinkAnalysis:
    def __init__(self):
        # Constants
        self.c = c  # speed of light
        self.k = Boltzmann  # Boltzmann constant

        # DSOC Laser parameters
        self.dsoc = {
            'wavelength': 1550e-9,  # meters
            'power': 5.0,  # Watts
            'aperture_diameter': 0.3,  # meters
            'beam_divergence': 5e-6,  # radians
            'efficiency': 0.15
        }

        # RF parameters
        self.rf_systems = {
            'ka_band': {
                'frequency': 32e9,  # Hz
                'power': 50,  # Watts
                'antenna_diameter': 2.4,  # meters
                'efficiency': 0.65
            },
            'x_band': {
                'frequency': 8.4e9,
                'power': 20,
                'antenna_diameter': 1.2,
                'efficiency': 0.70
            }
        }

        # DSN parameters
        self.dsn = {
            'optical_aperture': 10.0,  # meters
            'rf_antenna_diameter': 34.0,  # meters
            'system_temperature': 20.0,  # Kelvin
            'bandwidth': 500e6  # Hz
        }

    def calculate_link_budget(self, system_type, distance):
        """Calculate communication link budget"""

        if system_type == 'dsoc':
            params = self.dsoc
            # Laser link budget
            wavelength = params['wavelength']
            transmit_power = params['power'] * params['efficiency']
            transmit_gain = (pi * params['aperture_diameter'] /
    wavelength)**2
            path_loss = (wavelength / (4 * pi * distance))**2
            receive_gain = (pi * self.dsn['optical_aperture'] /
    wavelength)**2
```

```
54
55              received_power = transmit_power * transmit_gain * path_loss
    * receive_gain
56
57              # Calculate data rate (simplified)
58              snr = received_power / (self.k * self.dsn['
    system_temperature'] * self.dsn['bandwidth'])
59              data_rate = self.dsn['bandwidth'] * np.log2(1 + snr)
60
61          else:  # RF system
62              params = self.rf_systems[system_type]
63              frequency = params['frequency']
64              wavelength = self.c / frequency
65              transmit_power = params['power'] * params['efficiency']
66              transmit_gain = (pi * params['antenna_diameter'] /
    wavelength)**2
67              path_loss = (wavelength / (4 * pi * distance))**2
68              receive_gain = (pi * self.dsn['rf_antenna_diameter'] /
    wavelength)**2
69
70              received_power = transmit_power * transmit_gain * path_loss
    * receive_gain
71
72              # Calculate data rate
73              snr = received_power / (self.k * self.dsn['
    system_temperature'] * self.dsn['bandwidth'])
74              data_rate = self.dsn['bandwidth'] * np.log2(1 + snr)
75
76          return data_rate, received_power, snr
77
78      def mission_data_volume_analysis(self):
79          """Analyze total mission data volume capability"""
80
81          # Mission distances (AU to meters)
82          au_to_m = 1.496e11
83          mission_distances = {
84              'perihelion': 0.586 * au_to_m,
85              'aphelion': 35.1 * au_to_m,
86              'average': 17.8 * au_to_m
87          }
88
89          data_capabilities = {}
90
91          for position, distance in mission_distances.items():
92              position_data = {}
93
94              # DSOC capability
95              dsoc_rate, _, _ = self.calculate_link_budget('dsoc',
    distance)
96              position_data['dsoc'] = dsoc_rate
97
98              # RF capabilities
99              for rf_system in self.rf_systems.keys():
100                 rf_rate, _, _ = self.calculate_link_budget(rf_system,
    distance)
101                 position_data[rf_system] = rf_rate
```

```
            data_capabilities[position] = position_data

        return data_capabilities

# Communication analysis
comm_analysis = NASACommLinkAnalysis()
data_capabilities = comm_analysis.mission_data_volume_analysis()

print("Capacidades de Tasa de Datos por Posición:")
for position, capabilities in data_capabilities.items():
    print(f"\n{position.upper()}:")
    for system, rate in capabilities.items():
        print(f"  {system}: {rate/1e6:.1f} Mbps")
```

Listing 23: Análisis del Enlace de Comunicaciones NASA

## 19.3 Especificaciones del Sistema de Comunicaciones

Table 54: Especificaciones del Sistema de Comunicaciones ULISES

| **Parámetro** | **DSOC Láser** | **Banda Ka** | **Banda X** | **Comentarios** |
|---|---|---|---|---|
| Tasa datos pico | 2.67 Gbps | 150 Mbps | 50 Mbps | @ 0.586 UA |
| Tasa datos mínima | 10 Mbps | 2 Mbps | 0.5 Mbps | @ 35.1 UA |
| Potencia TX | 5 W | 50 W | 20 W | Consumo promedio |
| Antena/Óptica | Telescopio 30 cm | Antena 2.4 m | Antena 1.2 m | Diámetro efectivo |
| BER requerido | 1E-6 | 1E-6 | 1E-6 | Con codificación |
| Masa sistema | 45 kg | 85 kg | 42 kg | Incluye electrónica |
| Consumo potencia | 75 W | 120 W | 65 W | Operación nominal |
| TRL actual | 6 | 9 | 9 | DSOC en demo 2023 |
| Disponibilidad | 85% | 95% | 98% | Considerando clima |
| Margen enlace | 3 dB | 6 dB | 8 dB | Mínimo requerido 3 dB |

## 19.4 Plan de Operaciones de Comunicaciones

Table 55: Cronograma de Operaciones de Comunicaciones

| Fase de Misión | Sistema Primario | Sistema Backup | Tasa Promedio | Disponibilidad |
|---|---|---|---|---|
| Lanzamiento | Banda X | Banda S | 1 Mbps | 99.9% |
| Crucero Inicial | Banda Ka | Banda X | 50 Mbps | 98% |
| Asistencia Gravitatoria | Banda X | Banda S | 10 Mbps | 95% |
| Encuentro Cometa | DSOC | Banda Ka | 1 Gbps | 85% |
| Operaciones Científicas | DSOC | Banda Ka | 500 Mbps | 80% |
| Modo Seguro | Banda S | Banda X | 1 kbps | 99.9% |
| Fase Extendida | Banda Ka | Banda X | 10 Mbps | 95% |

## 19.5 Análisis de Redundancia y Confiabilidad

```
import numpy as np
from scipy.stats import weibull_min

class CommReliabilityAnalysis:
    def __init__(self):
        self.systems = {
            'dsoc_laser': {
                'mtbf': 50000,  # hours
                'repair_time': 24,  # hours
                'weather_availability': 0.85,
                'redundancy': 1
            },
            'ka_band': {
                'mtbf': 100000,
                'repair_time': 12,
                'weather_availability': 0.95,
                'redundancy': 2
            },
            'x_band': {
                'mtbf': 150000,
                'repair_time': 6,
                'weather_availability': 0.98,
                'redundancy': 2
            },
            's_band': {
                'mtbf': 200000,
                'repair_time': 2,
                'weather_availability': 0.99,
                'redundancy': 1
            }
```

```
        }

        self.mission_duration = 76 * 365 * 24  # hours

    def calculate_system_reliability(self):
        """Calculate communication system reliability"""

        system_reliabilities = {}

        for system, params in self.systems.items():
            # Weibull distribution for reliability
            shape = 1.5  # typical for electronics
            scale = params['mtbf']

            reliability = 1 - weibull_min.cdf(self.mission_duration,
    shape, scale=scale)

            # Apply redundancy
            if params['redundancy'] > 1:
                reliability = 1 - (1 - reliability)**params['redundancy'
    ]

            # Apply weather/operational availability
            reliability *= params['weather_availability']

            system_reliabilities[system] = reliability

        return system_reliabilities

    def calculate_overall_availability(self):
        """Calculate overall communication system availability"""

        system_reliabilities = self.calculate_system_reliability()

        # System is available if at least one major system works
        laser_available = system_reliabilities['dsoc_laser']
        rf_available = 1 - (1 - system_reliabilities['ka_band']) * \
                           (1 - system_reliabilities['x_band']) * \
                           (1 - system_reliabilities['s_band'])

        overall_availability = 1 - (1 - laser_available) * (1 -
    rf_available)

        return overall_availability

# Reliability analysis
reliability_analysis = CommReliabilityAnalysis()
system_reliabilities = reliability_analysis.calculate_system_reliability
    ()
overall_availability = reliability_analysis.
    calculate_overall_availability()

print("Confiabilidad de Sistemas de Comunicación:")
for system, reliability in system_reliabilities.items():
    print(f"  {system}: {reliability:.6f}")

```

```
print(f"\nDisponibilidad General del Sistema: {overall_availability:.6f}
    ")
print(f"Requisito NASA: >0.99999")
print(f"Cumplimiento: {'SÍ' if overall_availability > 0.99999 else 'NO'}
    ")
```

Listing 24: Análisis de Confiabilidad de Comunicaciones

# 20 Communications System

## 20.1 Hybrid Laser/RF Architecture

Table 56: Hybrid Communications System Architecture

| Communication System | Antenna/Telescope | Ground Station | Maximum Data Rate | Primary Application |
|---|---|---|---|---|
| DSOC Laser | 30 cm Telescope | Optical DSN | 2.67 Gbps | High-resolution science data |
| Ka Band | 2.4 m Antenna | Ka Band DSN | 150 Mbps | Primary RF communications |
| X Band | 1.2 m Antenna | X Band DSN | 50 Mbps | Secondary communications |
| S Band | 0.6 m Antenna | X Band DSN | 5 Mbps | Safe mode and emergencies |

**Data Flow and Connectivity:**

- **Data Input**: Science Data → DSOC Laser (primary system)
- **Space-to-Ground Links**:
  - DSOC Laser ↔ Optical DSN (2.67 Gbps)
  - Ka Band ↔ Ka Band DSN (150 Mbps)
  - X Band ↔ X Band DSN (50 Mbps)
  - S Band ↔ X Band DSN (5 Mbps)
- **Communication Hierarchy**:
  1. **Primary**: DSOC Laser - Maximum speed for science data
  2. **Secondary**: Ka Band - Operational communications
  3. **Backup**: X Band - Critical backup functions
  4. **Emergency**: S Band - Safe mode and recovery

**Technical Characteristics:**

- **Redundancy**: 4 independent systems with overlapping capabilities
- **Availability**: >99.9% considering atmospheric conditions
- **Link Margin**: Minimum 3 dB in all configurations

- **Power Consumption**: 75W (Laser), 120W (Ka), 65W (X), 25W (S)
- **System Mass**: 45kg (Laser), 85kg (Ka), 42kg (X), 15kg (S)

## 20.2 Communication Link Analysis

```python
import numpy as np
from scipy.constants import pi, c, Boltzmann

class NASACommLinkAnalysis:
    def __init__(self):
        # Constants
        self.c = c  # speed of light
        self.k = Boltzmann  # Boltzmann constant

        # DSOC Laser parameters
        self.dsoc = {
            'wavelength': 1550e-9,  # meters
            'power': 5.0,  # Watts
            'aperture_diameter': 0.3,  # meters
            'beam_divergence': 5e-6,  # radians
            'efficiency': 0.15
        }

        # RF parameters
        self.rf_systems = {
            'ka_band': {
                'frequency': 32e9,  # Hz
                'power': 50,  # Watts
                'antenna_diameter': 2.4,  # meters
                'efficiency': 0.65
            },
            'x_band': {
                'frequency': 8.4e9,
                'power': 20,
                'antenna_diameter': 1.2,
                'efficiency': 0.70
            }
        }

        # DSN parameters
        self.dsn = {
            'optical_aperture': 10.0,  # meters
            'rf_antenna_diameter': 34.0,  # meters
            'system_temperature': 20.0,  # Kelvin
            'bandwidth': 500e6  # Hz
        }

    def calculate_link_budget(self, system_type, distance):
        """Calculate communication link budget"""

        if system_type == 'dsoc':
            params = self.dsoc
            # Laser link budget
            wavelength = params['wavelength']
            transmit_power = params['power'] * params['efficiency']
```

```
            transmit_gain = (pi * params['aperture_diameter'] /
    wavelength)**2
            path_loss = (wavelength / (4 * pi * distance))**2
            receive_gain = (pi * self.dsn['optical_aperture'] /
    wavelength)**2

            received_power = transmit_power * transmit_gain * path_loss
    * receive_gain

            # Calculate data rate (simplified)
            snr = received_power / (self.k * self.dsn['
    system_temperature'] * self.dsn['bandwidth'])
            data_rate = self.dsn['bandwidth'] * np.log2(1 + snr)

        else:  # RF system
            params = self.rf_systems[system_type]
            frequency = params['frequency']
            wavelength = self.c / frequency
            transmit_power = params['power'] * params['efficiency']
            transmit_gain = (pi * params['antenna_diameter'] /
    wavelength)**2
            path_loss = (wavelength / (4 * pi * distance))**2
            receive_gain = (pi * self.dsn['rf_antenna_diameter'] /
    wavelength)**2

            received_power = transmit_power * transmit_gain * path_loss
    * receive_gain

            # Calculate data rate
            snr = received_power / (self.k * self.dsn['
    system_temperature'] * self.dsn['bandwidth'])
            data_rate = self.dsn['bandwidth'] * np.log2(1 + snr)

        return data_rate, received_power, snr

    def mission_data_volume_analysis(self):
        """Analyze total mission data volume capability"""

        # Mission distances (AU to meters)
        au_to_m = 1.496e11
        mission_distances = {
            'perihelion': 0.586 * au_to_m,
            'aphelion': 35.1 * au_to_m,
            'average': 17.8 * au_to_m
        }

        data_capabilities = {}

        for position, distance in mission_distances.items():
            position_data = {}

            # DSOC capability
            dsoc_rate, _, _ = self.calculate_link_budget('dsoc',
    distance)
            position_data['dsoc'] = dsoc_rate

```

```
            # RF capabilities
            for rf_system in self.rf_systems.keys():
                rf_rate, _, _ = self.calculate_link_budget(rf_system,
    distance)
                position_data[rf_system] = rf_rate

            data_capabilities[position] = position_data

        return data_capabilities

# Communication analysis
comm_analysis = NASACommLinkAnalysis()
data_capabilities = comm_analysis.mission_data_volume_analysis()

print("Data Rate Capabilities by Position:")
for position, capabilities in data_capabilities.items():
    print(f"\n{position.upper()}:")
    for system, rate in capabilities.items():
        print(f"  {system}: {rate/1e6:.1f} Mbps")
```

Listing 25: NASA Communication Link Analysis

## 20.3 Communications System Specifications

Table 57: ULISES Communications System Specifications

| Parameter | DSOC Laser | Ka Band | X Band | Comments |
|---|---|---|---|---|
| Peak data rate | 2.67 Gbps | 150 Mbps | 50 Mbps | @ 0.586 AU |
| Minimum data rate | 10 Mbps | 2 Mbps | 0.5 Mbps | @ 35.1 AU |
| TX Power | 5 W | 50 W | 20 W | Average consumption |
| Antenna/Optics | 30 cm Telescope | 2.4 m Antenna | 1.2 m Antenna | Effective diameter |
| Required BER | 1E-6 | 1E-6 | 1E-6 | With coding |
| System mass | 45 kg | 85 kg | 42 kg | Includes electronics |
| Power consumption | 75 W | 120 W | 65 W | Nominal operation |
| Current TRL | 6 | 9 | 9 | DSOC demo 2023 |
| Availability | 85% | 95% | 98% | Weather considered |
| Link margin | 3 dB | 6 dB | 8 dB | Minimum required 3 dB |

## 20.4 Communications Operations Plan

Table 58: Communications Operations Schedule

| Mission Phase | Primary System | Backup System | Average Rate | Availability |
|---|---|---|---|---|
| Launch | X Band | S Band | 1 Mbps | 99.9% |
| Initial Cruise | Ka Band | X Band | 50 Mbps | 98% |
| Gravity Assist | X Band | S Band | 10 Mbps | 95% |
| Comet Encounter | DSOC | Ka Band | 1 Gbps | 85% |
| Science Operations | DSOC | Ka Band | 500 Mbps | 80% |
| Safe Mode | S Band | X Band | 1 kbps | 99.9% |
| Extended Phase | Ka Band | X Band | 10 Mbps | 95% |

## 20.5 Redundancy and Reliability Analysis

```
import numpy as np
from scipy.stats import weibull_min

class CommReliabilityAnalysis:
    def __init__(self):
        self.systems = {
            'dsoc_laser': {
                'mtbf': 50000,  # hours
                'repair_time': 24,  # hours
                'weather_availability': 0.85,
                'redundancy': 1
            },
            'ka_band': {
                'mtbf': 100000,
                'repair_time': 12,
                'weather_availability': 0.95,
                'redundancy': 2
            },
            'x_band': {
                'mtbf': 150000,
                'repair_time': 6,
                'weather_availability': 0.98,
                'redundancy': 2
            },
            's_band': {
                'mtbf': 200000,
                'repair_time': 2,
                'weather_availability': 0.99,
                'redundancy': 1
            }
        }
```

```
32
33          self.mission_duration = 76 * 365 * 24  # hours
34
35      def calculate_system_reliability(self):
36          """Calculate communication system reliability"""
37
38          system_reliabilities = {}
39
40          for system, params in self.systems.items():
41              # Weibull distribution for reliability
42              shape = 1.5  # typical for electronics
43              scale = params['mtbf']
44
45              reliability = 1 - weibull_min.cdf(self.mission_duration,
    shape, scale=scale)
46
47              # Apply redundancy
48              if params['redundancy'] > 1:
49                  reliability = 1 - (1 - reliability)**params['redundancy'
    ]
50
51              # Apply weather/operational availability
52              reliability *= params['weather_availability']
53
54              system_reliabilities[system] = reliability
55
56          return system_reliabilities
57
58      def calculate_overall_availability(self):
59          """Calculate overall communication system availability"""
60
61          system_reliabilities = self.calculate_system_reliability()
62
63          # System is available if at least one major system works
64          laser_available = system_reliabilities['dsoc_laser']
65          rf_available = 1 - (1 - system_reliabilities['ka_band']) * \
66                             (1 - system_reliabilities['x_band']) * \
67                             (1 - system_reliabilities['s_band'])
68
69          overall_availability = 1 - (1 - laser_available) * (1 -
    rf_available)
70
71          return overall_availability
72
73  # Reliability analysis
74  reliability_analysis = CommReliabilityAnalysis()
75  system_reliabilities = reliability_analysis.calculate_system_reliability
    ()
76  overall_availability = reliability_analysis.
    calculate_overall_availability()
77
78  print("Communication System Reliabilities:")
79  for system, reliability in system_reliabilities.items():
80      print(f"  {system}: {reliability:.6f}")
81
82  print(f"\nOverall System Availability: {overall_availability:.6f}")
```

```
print(f"NASA Requirement: >0.99999")
print(f"Compliance: {'YES' if overall_availability > 0.99999 else 'NO'}"
    )
```

Listing 26: Communications Reliability Analysis

# 21 Análisis Completo FMEA

## 21.1 Metodología FMEA NASA-STD-8729.1

$$RPN = \text{Severidad} \times \text{Ocurrencia} \times \text{Detección} \tag{23}$$

**Criterios de Acción:** RPN > 100 requiere acción inmediata

Table 59: Escalas FMEA NASA

| Nivel | Severidad | Ocurrencia | Detección |
|---|---|---|---|
| 1-2 | Menor | Extremadamente raro | Casi seguro |
| 3-4 | Moderado | Remoto | Muy alta |
| 5-6 | Significativo | Ocasional | Alta |
| 7-8 | Crítico | Probable | Moderada |
| 9-10 | Catastrófico | Frecuente | Baja |

## 21.2 FMEA del Sistema de Propulsión

Table 60: FMEA Sistema de Propulsión - NASA Compliant

| ID | Modo Falla | Efecto | Causa | S | O | D | RPN | Acción |
|---|---|---|---|---|---|---|---|---|
| P-001 | Fuga tanque Xenón | Pérdida propelente | Soldadura defectuosa | 10 | 2 | 3 | 60 | Sistema contención dual |
| P-002 | Fallo válvula | No encendido | Contaminación | 8 | 3 | 4 | 96 | Válvulas redundantes |
| P-003 | Degradación iónica | Empuje reducido | Erosión rejillas | 6 | 5 | 5 | 150 | Monitoreo rendimiento |
| P-004 | Fallo PPU | No propulsión | Componente electrónico | 9 | 3 | 4 | 108 | Triple redundancia |
| P-005 | Obstrucción inyector | Combustión inestable | Partículas | 7 | 2 | 6 | 84 | Filtros redundantes |
| P-006 | Corrosión criogénica | Fuga | Ciclos térmicos | 8 | 4 | 5 | 160 | Materiales criogénicos |

| ID | Modo Falla | Efecto | Causa | S | O | D | RPN | Acción |
|---|---|---|---|---|---|---|---|---|
| P-007 | Fallo sensor presión | Lecturas erróneas | Radiación | 5 | 4 | 3 | 60 | Sensores triples |
| P-008 | Pérdida alineación | Empuje desviado | Impacto MMOD | 7 | 3 | 4 | 84 | Sistema auto-calibración |

## 21.3 Análisis Cuantitativo FMEA

```
import numpy as np
import pandas as pd

class NASAFMEAAnalysis:
    def __init__(self):
        self.fmea_data = {
            'propulsion': [
                {'id': 'P-001', 'severity': 10, 'occurrence': 2, '
   detection': 3, 'rpn': 60},
                {'id': 'P-002', 'severity': 8, 'occurrence': 3, '
   detection': 4, 'rpn': 96},
                {'id': 'P-003', 'severity': 6, 'occurrence': 5, '
   detection': 5, 'rpn': 150},
                {'id': 'P-004', 'severity': 9, 'occurrence': 3, '
   detection': 4, 'rpn': 108},
                {'id': 'P-005', 'severity': 7, 'occurrence': 2, '
   detection': 6, 'rpn': 84},
                {'id': 'P-006', 'severity': 8, 'occurrence': 4, '
   detection': 5, 'rpn': 160},
                {'id': 'P-007', 'severity': 5, 'occurrence': 4, '
   detection': 3, 'rpn': 60},
                {'id': 'P-008', 'severity': 7, 'occurrence': 3, '
   detection': 4, 'rpn': 84}
            ],
            'power': [
                {'id': 'PW-001', 'severity': 9, 'occurrence': 3, '
   detection': 4, 'rpn': 108},
                {'id': 'PW-002', 'severity': 8, 'occurrence': 2, '
   detection': 5, 'rpn': 80},
                {'id': 'PW-003', 'severity': 7, 'occurrence': 4, '
   detection': 4, 'rpn': 112}
            ]
        }

        self.rpn_threshold = 100

    def calculate_risk_metrics(self):
        """Calculate FMEA risk metrics"""

        risk_metrics = {}

        for subsystem, failures in self.fmea_data.items():
            rpns = [failure['rpn'] for failure in failures]
```

```
            high_risk_count = sum(1 for rpn in rpns if rpn > self.
rpn_threshold)

            risk_metrics[subsystem] = {
                'total_failures': len(failures),
                'high_risk_failures': high_risk_count,
                'max_rpn': max(rpns),
                'avg_rpn': np.mean(rpns),
                'risk_percentage': (high_risk_count / len(failures)) *
100
            }

        return risk_metrics

    def prioritize_mitigation_actions(self):
        """Prioritize mitigation actions based on RPN"""

        all_failures = []
        for subsystem, failures in self.fmea_data.items():
            for failure in failures:
                failure['subsystem'] = subsystem
                all_failures.append(failure)

        # Sort by RPN descending
        prioritized = sorted(all_failures, key=lambda x: x['rpn'],
reverse=True)

        return prioritized[:10]  # Top 10 highest risk

    def calculate_risk_reduction(self, mitigation_effectiveness=0.7):
        """Calculate risk reduction after mitigation"""

        total_risk_before = 0
        total_risk_after = 0

        for subsystem, failures in self.fmea_data.items():
            for failure in failures:
                risk_before = failure['severity'] * failure['occurrence'
] * failure['detection']
                total_risk_before += risk_before

                # Assume mitigation reduces occurrence and improves
detection
                occurrence_after = failure['occurrence'] * (1 -
mitigation_effectiveness)
                detection_after = min(10, failure['detection'] + 2)  #
Improved detection

                risk_after = failure['severity'] * occurrence_after *
detection_after
                total_risk_after += risk_after

        risk_reduction = (total_risk_before - total_risk_after) /
total_risk_before * 100

        return risk_reduction, total_risk_before, total_risk_after
```

```
80
81 # FMEA Analysis
82 fmea_analysis = NASAFMEAAnalysis()
83 risk_metrics = fmea_analysis.calculate_risk_metrics()
84 top_risks = fmea_analysis.prioritize_mitigation_actions()
85 risk_reduction, before, after = fmea_analysis.calculate_risk_reduction()
86
87 print("Métricas de Riesgo FMEA:")
88 for subsystem, metrics in risk_metrics.items():
89     print(f"\n{subsystem.upper()}:")
90     print(f"  Fallos totales: {metrics['total_failures']}")
91     print(f"  Fallos alto riesgo: {metrics['high_risk_failures']}")
92     print(f"  RPN máximo: {metrics['max_rpn']}")
93     print(f"  Porcentaje riesgo: {metrics['risk_percentage']:.1f}%")
94
95 print(f"\nReducción de riesgo post-mitigación: {risk_reduction:.1f}%")
```

Listing 27: Análisis Cuantitativo FMEA NASA

## 21.4 Plan de Mitigación de Riesgos

Table 61: Plan de Mitigación de Riesgos Críticos

| ID FMEA | Acción de Mitigación | Responsable | Fecha Objetivo | RPN Post-Mitigación |
|---|---|---|---|---|
| P-006 | Uso de aleaciones criogénicas | NASA GRC | Q4 2026 | 48 |
| P-003 | Monitoreo continuo rendimiento | JPL | Q2 2027 | 75 |
| P-004 | Implementación triple redundancia | ESA | Q1 2027 | 36 |
| PW-003 | Sistema gestión térmica mejorado | NASA GSFC | Q3 2026 | 56 |
| C-002 | Protocolos recuperación automática | JPL | Q4 2026 | 42 |
| S-001 | Blindaje contra radiación | ESA | Q2 2027 | 54 |

# 22 Comprehensive FMEA Analysis

## 22.1 FMEA Methodology NASA-STD-8729.1

$$RPN = \text{Severity} \times \text{Occurrence} \times \text{Detection} \tag{24}$$

**Action Criteria:** RPN > 100 requires immediate action

Table 62: NASA FMEA Scales

| Level | Severity | Occurrence | Detection |
|---|---|---|---|
| 1-2 | Minor | Extremely unlikely | Almost certain |
| 3-4 | Moderate | Remote | Very high |
| 5-6 | Significant | Occasional | High |
| 7-8 | Critical | Probable | Moderate |
| 9-10 | Catastrophic | Frequent | Low |

## 22.2 Propulsion System FMEA

Table 63: Propulsion System FMEA - NASA Compliant

| ID | Failure Mode | Effect | Cause | S | O | D | RPN | Action |
|---|---|---|---|---|---|---|---|---|
| P-001 | Xenon tank leak | Propellant loss | Faulty welding | 10 | 2 | 3 | 60 | Dual containment system |
| P-002 | Valve failure | No ignition | Contamination | 8 | 3 | 4 | 96 | Redundant valves |
| P-003 | Ion degradation | Thrust reduction | Grid erosion | 6 | 5 | 5 | 150 | Performance monitoring |
| P-004 | PPU failure | No propulsion | Electronic component | 9 | 3 | 4 | 108 | Triple redundancy |
| P-005 | Injector clog | Unstable combustion | Particles | 7 | 2 | 6 | 84 | Redundant filters |
| P-006 | Cryogenic corrosion | Leakage | Thermal cycling | 8 | 4 | 5 | 160 | Cryogenic materials |
| P-007 | Pressure sensor fail | Erroneous readings | Radiation | 5 | 4 | 3 | 60 | Triple sensors |
| P-008 | Alignment loss | Thrust deviation | MMOD impact | 7 | 3 | 4 | 84 | Auto-calibration system |

## 22.3 Quantitative FMEA Analysis

```
import numpy as np
import pandas as pd
```

```

class NASAFMEAAnalysis:
    def __init__(self):
        self.fmea_data = {
            'propulsion': [
                {'id': 'P-001', 'severity': 10, 'occurrence': 2, '
   detection': 3, 'rpn': 60},
                {'id': 'P-002', 'severity': 8, 'occurrence': 3, '
   detection': 4, 'rpn': 96},
                {'id': 'P-003', 'severity': 6, 'occurrence': 5, '
   detection': 5, 'rpn': 150},
                {'id': 'P-004', 'severity': 9, 'occurrence': 3, '
   detection': 4, 'rpn': 108},
                {'id': 'P-005', 'severity': 7, 'occurrence': 2, '
   detection': 6, 'rpn': 84},
                {'id': 'P-006', 'severity': 8, 'occurrence': 4, '
   detection': 5, 'rpn': 160},
                {'id': 'P-007', 'severity': 5, 'occurrence': 4, '
   detection': 3, 'rpn': 60},
                {'id': 'P-008', 'severity': 7, 'occurrence': 3, '
   detection': 4, 'rpn': 84}
            ],
            'power': [
                {'id': 'PW-001', 'severity': 9, 'occurrence': 3, '
   detection': 4, 'rpn': 108},
                {'id': 'PW-002', 'severity': 8, 'occurrence': 2, '
   detection': 5, 'rpn': 80},
                {'id': 'PW-003', 'severity': 7, 'occurrence': 4, '
   detection': 4, 'rpn': 112}
            ]
        }

        self.rpn_threshold = 100

    def calculate_risk_metrics(self):
        """Calculate FMEA risk metrics"""

        risk_metrics = {}

        for subsystem, failures in self.fmea_data.items():
            rpns = [failure['rpn'] for failure in failures]
            high_risk_count = sum(1 for rpn in rpns if rpn > self.
   rpn_threshold)

            risk_metrics[subsystem] = {
                'total_failures': len(failures),
                'high_risk_failures': high_risk_count,
                'max_rpn': max(rpns),
                'avg_rpn': np.mean(rpns),
                'risk_percentage': (high_risk_count / len(failures)) *
   100
            }

        return risk_metrics

    def prioritize_mitigation_actions(self):
```

```
        """Prioritize mitigation actions based on RPN"""

        all_failures = []
        for subsystem, failures in self.fmea_data.items():
            for failure in failures:
                failure['subsystem'] = subsystem
                all_failures.append(failure)

        # Sort by RPN descending
        prioritized = sorted(all_failures, key=lambda x: x['rpn'], reverse=True)

        return prioritized[:10]  # Top 10 highest risk

    def calculate_risk_reduction(self, mitigation_effectiveness=0.7):
        """Calculate risk reduction after mitigation"""

        total_risk_before = 0
        total_risk_after = 0

        for subsystem, failures in self.fmea_data.items():
            for failure in failures:
                risk_before = failure['severity'] * failure['occurrence'] * failure['detection']
                total_risk_before += risk_before

                # Assume mitigation reduces occurrence and improves detection
                occurrence_after = failure['occurrence'] * (1 - mitigation_effectiveness)
                detection_after = min(10, failure['detection'] + 2)  # Improved detection

                risk_after = failure['severity'] * occurrence_after * detection_after
                total_risk_after += risk_after

        risk_reduction = (total_risk_before - total_risk_after) / total_risk_before * 100

        return risk_reduction, total_risk_before, total_risk_after

# FMEA Analysis
fmea_analysis = NASAFMEAAnalysis()
risk_metrics = fmea_analysis.calculate_risk_metrics()
top_risks = fmea_analysis.prioritize_mitigation_actions()
risk_reduction, before, after = fmea_analysis.calculate_risk_reduction()

print("FMEA Risk Metrics:")
for subsystem, metrics in risk_metrics.items():
    print(f"\n{subsystem.upper()}:")
    print(f"  Total failures: {metrics['total_failures']}")
    print(f"  High risk failures: {metrics['high_risk_failures']}")
    print(f"  Max RPN: {metrics['max_rpn']}")
    print(f"  Risk percentage: {metrics['risk_percentage']:.1f}%")

```

```
print(f"\nRisk reduction post-mitigation: {risk_reduction:.1f}%")
```

Listing 28: NASA Quantitative FMEA Analysis

## 22.4 Risk Mitigation Plan

Table 64: Critical Risk Mitigation Plan

| **FMEA ID** | **Mitigation Action** | **Responsible** | **Target Date** | **Post-Mitigation RPN** |
|---|---|---|---|---|
| P-006 | Use of cryogenic alloys | NASA GRC | Q4 2026 | 48 |
| P-003 | Continuous performance monitoring | JPL | Q2 2027 | 75 |
| P-004 | Triple redundancy implementation | ESA | Q1 2027 | 36 |
| PW-003 | Enhanced thermal management system | NASA GSFC | Q3 2026 | 56 |
| C-002 | Automatic recovery protocols | JPL | Q4 2026 | 42 |
| S-001 | Radiation shielding | ESA | Q2 2027 | 54 |

# 23 Evaluación TRL y Hoja de Ruta Tecnológica

## 23.1 Evaluación TRL por Subsistema NASA SP-2016-6105

Table 65: Evaluación TRL Actual y Objetivo

| Subsistema/Tecnología | TRL Actual | TRL Objetivo | Fecha Objetivo | Hito Crítico |
|---|---|---|---|---|
| Propulsión Iónica NEXIS | 5 | 8 | 2032 | Demo 50,000 horas |
| ISRU $H_2O$-ICE | 4 | 6 | 2028 | Demo cámara criogénica |
| Anclaje Multi-Modal | 4 | 7 | 2029 | Test microgravedad |
| Comunicaciones DSOC | 6 | 8 | 2027 | Demo espacio profundo |
| Baterías Li-S | 6 | 8 | 2028 | 5000 ciclos vida |
| Electrónica Criogénica SiC | 4 | 6 | 2026 | Test radiación |
| Sensores Científicos | 7 | 9 | 2025 | Calibración final |
| Estructura Compuestos | 8 | 9 | 2024 | Qualificación vuelo |
| Sistema Térmico | 7 | 9 | 2025 | Test vacío térmico |
| Software GNC | 5 | 7 | 2027 | Simulación hardware |

## 23.2 Análisis de Brechas Tecnológicas

```
import numpy as np
import matplotlib.pyplot as plt

class NASATRLAnalysis:
    def __init__(self):
        self.technologies = {
            'ion_propulsion': {'current_trl': 5, 'target_trl': 8, '
    criticality': 0.9},
            'isru_system': {'current_trl': 4, 'target_trl': 6, '
    criticality': 0.8},
            'multi_modal_anchoring': {'current_trl': 4, 'target_trl': 7,
     'criticality': 0.7},
            'dsoc_communications': {'current_trl': 6, 'target_trl': 8, '
    criticality': 0.6},
            'li_s_batteries': {'current_trl': 6, 'target_trl': 8, '
    criticality': 0.5},
            'cryo_electronics': {'current_trl': 4, 'target_trl': 6, '
    criticality': 0.7},
            'science_sensors': {'current_trl': 7, 'target_trl': 9, '
    criticality': 0.9},
```

```
            'composite_structure': {'current_trl': 8, 'target_trl': 9, '
    criticality': 0.8},
            'thermal_system': {'current_trl': 7, 'target_trl': 9, '
    criticality': 0.6},
            'gnc_software': {'current_trl': 5, 'target_trl': 7, '
    criticality': 0.8}
        }

        self.trl_development_times = {
            4: 12,  # TRL 4 to 5: 12 months
            5: 18,  # TRL 5 to 6: 18 months
            6: 24,  # TRL 6 to 7: 24 months
            7: 30,  # TRL 7 to 8: 30 months
            8: 36   # TRL 8 to 9: 36 months
        }

    def calculate_technology_gaps(self):
        """Calculate technology readiness gaps"""

        gaps = {}

        for tech, params in self.technologies.items():
            current_trl = params['current_trl']
            target_trl = params['target_trl']
            criticality = params['criticality']

            # Calculate development time
            development_months = 0
            for trl in range(current_trl, target_trl):
                development_months += self.trl_development_times.get(trl
    , 12)

            gap_severity = (target_trl - current_trl) * criticality

            gaps[tech] = {
                'trl_gap': target_trl - current_trl,
                'development_months': development_months,
                'gap_severity': gap_severity,
                'development_years': development_months / 12
            }

        return gaps

    def identify_critical_path(self):
        """Identify critical path for technology development"""

        gaps = self.calculate_technology_gaps()

        # Sort by development time (critical path)
        critical_path = sorted(gaps.items(), key=lambda x: x[1]['
    development_months'], reverse=True)

        return critical_path

    def calculate_overall_mission_trl(self):
        """Calculate overall mission TRL readiness"""
```

```
65
66          trl_scores = []
67          weights = []
68
69          for tech, params in self.technologies.items():
70              trl_scores.append(params['current_trl'])
71              weights.append(params['criticality'])
72
73          # Weighted average TRL
74          overall_trl = np.average(trl_scores, weights=weights)
75
76          return overall_trl
77
78  # TRL Analysis
79  trl_analysis = NASATRLAnalysis()
80  technology_gaps = trl_analysis.calculate_technology_gaps()
81  critical_path = trl_analysis.identify_critical_path()
82  overall_mission_trl = trl_analysis.calculate_overall_mission_trl()
83
84  print("Análisis de Brechas Tecnológicas:")
85  for tech, gap in technology_gaps.items():
86      print(f"\n{tech.upper()}:")
87      print(f"  Brecha TRL: {gap['trl_gap']}")
88      print(f"  Tiempo desarrollo: {gap['development_years']:.1f} años")
89      print(f"  Severidad brecha: {gap['gap_severity']:.2f}")
90
91  print(f"\nTRL General de Misión: {overall_mission_trl:.2f}")
92  print(f"Requisito PDR: >4.0")
93  print(f"Cumplimiento: {'SÍ' if overall_mission_trl > 4.0 else 'NO'}")
94
95  print("\nRuta Crítica de Desarrollo:")
96  for i, (tech, gap) in enumerate(critical_path[:3], 1):
97      print(f"{i}. {tech}: {gap['development_years']:.1f} años")
```

Listing 29: Análisis de Brechas Tecnológicas NASA

## 23.3 Plan de Desarrollo Tecnológico Integrado

Table 66: Cronograma de Desarrollo Tecnológico Integrado

| **Tecnología** | **2024** | **2025** | **2026** | **2027** | **2028** | **2029** | **2030** |
|---|---|---|---|---|---|---|---|
| Propulsión Iónica | TRL-5 | TRL-5 | TRL-6 | TRL-6 | TRL-7 | TRL-7 | TRL-8 |
| ISRU $H_2O$-ICE | TRL-4 | TRL-4 | TRL-5 | TRL-5 | TRL-6 | TRL-6 | TRL-7 |
| Anclaje Multi-Modal | TRL-4 | TRL-4 | TRL-5 | TRL-5 | TRL-6 | TRL-7 | TRL-7 |
| Comunicaciones DSOC | TRL-6 | TRL-6 | TRL-7 | TRL-8 | TRL-8 | TRL-8 | TRL-9 |
| Baterías Li-S | TRL-6 | TRL-6 | TRL-7 | TRL-7 | TRL-8 | TRL-8 | TRL-9 |
| Electrónica Criogénica | TRL-4 | TRL-4 | TRL-5 | TRL-6 | TRL-6 | TRL-7 | TRL-7 |
| Sensores Científicos | TRL-7 | TRL-8 | TRL-8 | TRL-9 | TRL-9 | TRL-9 | TRL-9 |
| Estructura | TRL-8 | TRL-9 | TRL-9 | TRL-9 | TRL-9 | TRL-9 | TRL-9 |
| Sistema Térmico | TRL-7 | TRL-8 | TRL-8 | TRL-9 | TRL-9 | TRL-9 | TRL-9 |
| Software GNC | TRL-5 | TRL-5 | TRL-6 | TRL-7 | TRL-7 | TRL-8 | TRL-8 |

## 23.4 Evaluación de Riesgo Tecnológico

$$\text{Riesgo Tecnológico} = \frac{\text{Brecha TRL} \times \text{Criticalidad}}{\text{Tiempo Desarrollo}} \tag{25}$$

```
class TechnologyRiskAssessment:
    def __init__(self):
        self.technologies = {
            'ion_propulsion': {'current_trl': 5, 'target_trl': 8, '
   criticality': 0.9, 'budget_risk': 0.7},
            'isru_system': {'current_trl': 4, 'target_trl': 6, '
   criticality': 0.8, 'budget_risk': 0.6},
            'multi_modal_anchoring': {'current_trl': 4, 'target_trl': 7,
    'criticality': 0.7, 'budget_risk': 0.5},
            'dsoc_communications': {'current_trl': 6, 'target_trl': 8, '
   criticality': 0.6, 'budget_risk': 0.4},
            'cryo_electronics': {'current_trl': 4, 'target_trl': 6, '
   criticality': 0.7, 'budget_risk': 0.6}
        }

    def calculate_technology_risk_index(self):
        """Calculate technology risk index for each technology"""

```

```
        risk_assessment = {}

        for tech, params in self.technologies.items():
            trl_gap = params['target_trl'] - params['current_trl']
            criticality = params['criticality']
            budget_risk = params['budget_risk']

            # Normalize development time (assume 12 months per TRL level
    )
            development_time = trl_gap * 12

            # Calculate risk index
            technical_risk = (trl_gap * criticality) / development_time
            overall_risk = technical_risk * (1 + budget_risk)

            risk_assessment[tech] = {
                'technical_risk': technical_risk,
                'overall_risk': overall_risk,
                'risk_level': self.classify_risk_level(overall_risk)
            }

        return risk_assessment

    def classify_risk_level(self, risk_value):
        """Classify risk level based on NASA standards"""

        if risk_value < 0.1:
            return "LOW"
        elif risk_value < 0.3:
            return "MODERATE"
        elif risk_value < 0.5:
            return "HIGH"
        else:
            return "VERY HIGH"

    def recommend_mitigation_strategies(self):
        """Recommend risk mitigation strategies"""

        risk_assessment = self.calculate_technology_risk_index()
        mitigation_strategies = {}

        for tech, risk in risk_assessment.items():
            if risk['risk_level'] in ["HIGH", "VERY HIGH"]:
                strategies = []

                if 'propulsion' in tech:
                    strategies.extend([
                        "Parallel development with alternative
    technologies",
                        "Increased testing and validation budget",
                        "Partnership with industry experts"
                    ])
                elif 'isru' in tech:
                    strategies.extend([
                        "Accelerated ground testing program",
                        "International collaboration for technology
```

```
    sharing",
68                          "Development of simplified backup systems"
69                      ])
70                  elif 'anchoring' in tech:
71                      strategies.extend([
72                          "Multiple design approaches in parallel",
73                          "Enhanced simulation and modeling",
74                          "Early prototype testing in relevant
    environments"
75                      ])
76
77                  mitigation_strategies[tech] = strategies
78
79          return mitigation_strategies
80
81 # Risk Assessment
82 risk_assessment = TechnologyRiskAssessment()
83 technology_risks = risk_assessment.calculate_technology_risk_index()
84 mitigation_strategies = risk_assessment.recommend_mitigation_strategies
    ()
85
86 print("Evaluación de Riesgo Tecnológico:")
87 for tech, risk in technology_risks.items():
88     print(f"\n{tech.upper()}:")
89     print(f"  Riesgo Técnico: {risk['technical_risk']:.3f}")
90     print(f"  Riesgo General: {risk['overall_risk']:.3f}")
91     print(f"  Nivel Riesgo: {risk['risk_level']}")
92
93 print("\nEstrategias de Mitigación para Riesgos Altos:")
94 for tech, strategies in mitigation_strategies.items():
95     print(f"\n{tech.upper()}:")
96     for strategy in strategies:
97         print(f"   {strategy}")
```

Listing 30: Evaluación de Riesgo Tecnológico NASA

# 24 TRL Assessment and Technology Roadmap

## 24.1 Subsystem TRL Assessment NASA SP-2016-6105

Table 67: Current and Target TRL Assessment

| Subsystem/Technology | Current TRL | Target TRL | Target Date | Critical Milestone |
|---|---|---|---|---|
| NEXIS Ion Propulsion | 5 | 8 | 2032 | 50,000 hour demo |
| ISRU $H_2O$-ICE | 4 | 6 | 2028 | Cryo chamber demo |
| Multi-Modal Anchoring | 4 | 7 | 2029 | Microgravity testing |
| DSOC Communications | 6 | 8 | 2027 | Deep space demo |
| Li-S Batteries | 6 | 8 | 2028 | 5000 life cycles |
| SiC Cryo Electronics | 4 | 6 | 2026 | Radiation testing |
| Science Sensors | 7 | 9 | 2025 | Final calibration |
| Composite Structure | 8 | 9 | 2024 | Flight qualification |
| Thermal System | 7 | 9 | 2025 | Thermal vacuum test |
| GNC Software | 5 | 7 | 2027 | Hardware simulation |

## 24.2 Technology Gap Analysis

```
import numpy as np
import matplotlib.pyplot as plt

class NASATRLAnalysis:
    def __init__(self):
        self.technologies = {
            'ion_propulsion': {'current_trl': 5, 'target_trl': 8, '
   criticality': 0.9},
            'isru_system': {'current_trl': 4, 'target_trl': 6, '
   criticality': 0.8},
            'multi_modal_anchoring': {'current_trl': 4, 'target_trl': 7,
    'criticality': 0.7},
            'dsoc_communications': {'current_trl': 6, 'target_trl': 8, '
   criticality': 0.6},
            'li_s_batteries': {'current_trl': 6, 'target_trl': 8, '
   criticality': 0.5},
            'cryo_electronics': {'current_trl': 4, 'target_trl': 6, '
   criticality': 0.7},
            'science_sensors': {'current_trl': 7, 'target_trl': 9, '
   criticality': 0.9},
            'composite_structure': {'current_trl': 8, 'target_trl': 9, '
   criticality': 0.8},
```

```
            'thermal_system': {'current_trl': 7, 'target_trl': 9, '
    criticality': 0.6},
            'gnc_software': {'current_trl': 5, 'target_trl': 7, '
    criticality': 0.8}
        }

        self.trl_development_times = {
            4: 12,  # TRL 4 to 5: 12 months
            5: 18,  # TRL 5 to 6: 18 months
            6: 24,  # TRL 6 to 7: 24 months
            7: 30,  # TRL 7 to 8: 30 months
            8: 36   # TRL 8 to 9: 36 months
        }

    def calculate_technology_gaps(self):
        """Calculate technology readiness gaps"""

        gaps = {}

        for tech, params in self.technologies.items():
            current_trl = params['current_trl']
            target_trl = params['target_trl']
            criticality = params['criticality']

            # Calculate development time
            development_months = 0
            for trl in range(current_trl, target_trl):
                development_months += self.trl_development_times.get(trl
    , 12)

            gap_severity = (target_trl - current_trl) * criticality

            gaps[tech] = {
                'trl_gap': target_trl - current_trl,
                'development_months': development_months,
                'gap_severity': gap_severity,
                'development_years': development_months / 12
            }

        return gaps

    def identify_critical_path(self):
        """Identify critical path for technology development"""

        gaps = self.calculate_technology_gaps()

        # Sort by development time (critical path)
        critical_path = sorted(gaps.items(), key=lambda x: x[1]['
    development_months'], reverse=True)

        return critical_path

    def calculate_overall_mission_trl(self):
        """Calculate overall mission TRL readiness"""

        trl_scores = []
```

```
        weights = []

        for tech, params in self.technologies.items():
            trl_scores.append(params['current_trl'])
            weights.append(params['criticality'])

        # Weighted average TRL
        overall_trl = np.average(trl_scores, weights=weights)

        return overall_trl

# TRL Analysis
trl_analysis = NASATRLAnalysis()
technology_gaps = trl_analysis.calculate_technology_gaps()
critical_path = trl_analysis.identify_critical_path()
overall_mission_trl = trl_analysis.calculate_overall_mission_trl()

print("Technology Gap Analysis:")
for tech, gap in technology_gaps.items():
    print(f"\n{tech.upper()}:")
    print(f"  TRL Gap: {gap['trl_gap']}")
    print(f"  Development time: {gap['development_years']:.1f} years")
    print(f"  Gap severity: {gap['gap_severity']:.2f}")

print(f"\nOverall Mission TRL: {overall_mission_trl:.2f}")
print(f"PDR Requirement: >4.0")
print(f"Compliance: {'YES' if overall_mission_trl > 4.0 else 'NO'}")

print("\nCritical Development Path:")
for i, (tech, gap) in enumerate(critical_path[:3], 1):
    print(f"{i}. {tech}: {gap['development_years']:.1f} years")
```

Listing 31: NASA Technology Gap Analysis

## 24.3 Integrated Technology Development Plan

Table 68: Integrated Technology Development Schedule

| Technology | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|
| Ion Propulsion | TRL-5 | TRL-5 | TRL-6 | TRL-6 | TRL-7 | TRL-7 | TRL-8 |
| ISRU $H_2O$-ICE | TRL-4 | TRL-4 | TRL-5 | TRL-5 | TRL-6 | TRL-6 | TRL-7 |
| Multi-Modal Anchoring | TRL-4 | TRL-4 | TRL-5 | TRL-5 | TRL-6 | TRL-7 | TRL-7 |
| DSOC Communications | TRL-6 | TRL-6 | TRL-7 | TRL-8 | TRL-8 | TRL-8 | TRL-9 |
| Li-S Batteries | TRL-6 | TRL-6 | TRL-7 | TRL-7 | TRL-8 | TRL-8 | TRL-9 |
| Cryo Electronics | TRL-4 | TRL-4 | TRL-5 | TRL-6 | TRL-6 | TRL-7 | TRL-7 |
| Science Sensors | TRL-7 | TRL-8 | TRL-8 | TRL-9 | TRL-9 | TRL-9 | TRL-9 |
| Structure | TRL-8 | TRL-9 | TRL-9 | TRL-9 | TRL-9 | TRL-9 | TRL-9 |
| Thermal System | TRL-7 | TRL-8 | TRL-8 | TRL-9 | TRL-9 | TRL-9 | TRL-9 |
| GNC Software | TRL-5 | TRL-5 | TRL-6 | TRL-7 | TRL-7 | TRL-8 | TRL-8 |

## 24.4 Technology Risk Assessment

$$\text{Technology Risk} = \frac{\text{TRL Gap} \times \text{Criticality}}{\text{Development Time}} \tag{26}$$

```
class TechnologyRiskAssessment:
    def __init__(self):
        self.technologies = {
            'ion_propulsion': {'current_trl': 5, 'target_trl': 8, '
   criticality': 0.9, 'budget_risk': 0.7},
            'isru_system': {'current_trl': 4, 'target_trl': 6, '
   criticality': 0.8, 'budget_risk': 0.6},
            'multi_modal_anchoring': {'current_trl': 4, 'target_trl': 7,
    'criticality': 0.7, 'budget_risk': 0.5},
            'dsoc_communications': {'current_trl': 6, 'target_trl': 8, '
   criticality': 0.6, 'budget_risk': 0.4},
            'cryo_electronics': {'current_trl': 4, 'target_trl': 6, '
   criticality': 0.7, 'budget_risk': 0.6}
        }

    def calculate_technology_risk_index(self):
        """Calculate technology risk index for each technology"""

```

```
        risk_assessment = {}

        for tech, params in self.technologies.items():
            trl_gap = params['target_trl'] - params['current_trl']
            criticality = params['criticality']
            budget_risk = params['budget_risk']

            # Normalize development time (assume 12 months per TRL level)
            development_time = trl_gap * 12

            # Calculate risk index
            technical_risk = (trl_gap * criticality) / development_time
            overall_risk = technical_risk * (1 + budget_risk)

            risk_assessment[tech] = {
                'technical_risk': technical_risk,
                'overall_risk': overall_risk,
                'risk_level': self.classify_risk_level(overall_risk)
            }

        return risk_assessment

    def classify_risk_level(self, risk_value):
        """Classify risk level based on NASA standards"""

        if risk_value < 0.1:
            return "LOW"
        elif risk_value < 0.3:
            return "MODERATE"
        elif risk_value < 0.5:
            return "HIGH"
        else:
            return "VERY HIGH"

    def recommend_mitigation_strategies(self):
        """Recommend risk mitigation strategies"""

        risk_assessment = self.calculate_technology_risk_index()
        mitigation_strategies = {}

        for tech, risk in risk_assessment.items():
            if risk['risk_level'] in ["HIGH", "VERY HIGH"]:
                strategies = []

                if 'propulsion' in tech:
                    strategies.extend([
                        "Parallel development with alternative technologies",
                        "Increased testing and validation budget",
                        "Partnership with industry experts"
                    ])
                elif 'isru' in tech:
                    strategies.extend([
                        "Accelerated ground testing program",
                        "International collaboration for technology
```

```
    sharing",
68                          "Development of simplified backup systems"
69                      ])
70                  elif 'anchoring' in tech:
71                      strategies.extend([
72                          "Multiple design approaches in parallel",
73                          "Enhanced simulation and modeling",
74                          "Early prototype testing in relevant
    environments"
75                      ])
76
77                  mitigation_strategies[tech] = strategies
78
79          return mitigation_strategies
80
81 # Risk Assessment
82 risk_assessment = TechnologyRiskAssessment()
83 technology_risks = risk_assessment.calculate_technology_risk_index()
84 mitigation_strategies = risk_assessment.recommend_mitigation_strategies
    ()
85
86 print("Technology Risk Assessment:")
87 for tech, risk in technology_risks.items():
88     print(f"\n{tech.upper()}:")
89     print(f"  Technical Risk: {risk['technical_risk']:.3f}")
90     print(f"  Overall Risk: {risk['overall_risk']:.3f}")
91     print(f"  Risk Level: {risk['risk_level']}")
92
93 print("\nMitigation Strategies for High Risks:")
94 for tech, strategies in mitigation_strategies.items():
95     print(f"\n{tech.upper()}:")
96     for strategy in strategies:
97         print(f"   {strategy}")
```

Listing 32: NASA Technology Risk Assessment

# A NPR 7120.5E Compliance Matrix (Complete)

## NASA PROGRAM AND PROJECT MANAGEMENT REQUIREMENTS COMPLIANCE

**Purpose:** This matrix documents compliance with NPR 7120.5E. Each requirement is tracked with applicability, tailoring justification, evidence, and status.

**Legend:**

- **App:** Y = Applicable, N = Not Applicable, T = Tailored
- **Status:** C = Complete, I = In Progress, P = Planned

| NPR Ref | Requirement | App | Evidence / Tailoring | Status / Due |
|---|---|---|---|---|
| 1.1 | Project shall follow NPR 7120.5E unless formally tailored | Y | Tailoring Annex Sec. 1.5; Digital archive tailored to cloud repository | C / 2025-10-28 |
| 2.1.1 | Establish project roles, authorities and responsibilities | Y | Sec. 2.2 Roles Table; Appendix E Approval Record | C / 2025-09-30 |
| 2.3.1 | Conduct life-cycle reviews: SRR, PDR, CDR, TRR, FRR | Y | Mission Architecture Sec. 4; IMS Appendix D | C / 2025-Q4 PDR |
| 3.1.1 | Define technical requirements and maintain RTM | Y | Requirements Sec. 6; RTM Tables 6.1-6.3 | C / 2025-10-20 |
| 3.1.2 | Produce Verification and Validation Plan | Y | Appendix B (V&V Plan) | C / 2025-10-28 |
| 3.2.3 | Establish Configuration Management processes | Y | Appendix C (CM Plan) | C / 2025-10-28 |
| 3.3.1 | Establish and maintain Integrated Master Schedule | Y | Appendix D (IMS) | C / 2025-10-28 |
| 4.1.3 | Conduct Hazard Analysis and document controls | Y | System Safety Sec. 2; FMEA Sec. 3 | C / 2025-10-10 |
| 5.1.1 | Implement Risk Management processes | Y | Risk Analysis Sec. 1.5; FMEA Sec. 3 | C / 2025-10-05 |
| 8.1.1 | Use standardized WBS and numbering | Y | WBS defined in Mass Budget Sec. 5 | C / 2025-09-20 |

# B Verification & Validation (V&V) Plan (Complete)

## B.1 Scope and Methodology

This plan establishes the strategy for verifying and validating all ULISES mission requirements using Test (T), Analysis (A), Inspection (I), and Demonstration (D) methods.

## B.2 Verification Matrix

| Req ID | Requirement | Method | Acceptance Criteria | Responsible |
|---|---|---|---|---|
| REQ-001 | Measure volatile composition ś10% | T/A | Mass spectrometer m/m > 2000; Calibration with NIST samples | Payload Team |
| REQ-002 | Continuous monitoring 76 years | A/T | System reliability > 0.95; Full lifecycle simulation | Systems Engineering |
| REQ-003 | >95% anchoring success | T/D | P(success) > 0.97; 200+ tests + Monte Carlo analysis | Mechanical Team |
| REQ-004 | >25 Mbps data rate | T | Laser communications 267 Mbps peak; Deep space link test | Communications Team |
| REQ-005 | 100m internal structure | T/A | Penetrating radar 20-60 MHz; Ice/regolith penetration test | Science Team |

## B.3 Verification Log Template

| VLog ID | Req ID | Method | Evidence | Status / Date |
|---|---|---|---|---|
| VLOG-001 | REQ-001 | T/A | TestReport_Payload_V1.pdf | Verified 2025-10-12 |
| VLOG-002 | REQ-004 | T | CommLinkTest_DSOC.pdf | Verified 2025-10-20 |

# C Configuration Management (CM) Plan (Complete)

## C.1 Configuration Items (CI) Identification

- **Format:** ULI-CI-[Subsystem]-[Type]-[Index]-[YYYYMMDD]-[Rev]
- **Example:** ULI-CI-PAY-DRW-001-20251012-R01 (Payload drawing)

## C.2 Change Control Process

1. Change Request (CR) submission with impact analysis
2. Technical review by relevant engineering teams
3. Configuration Control Board (CCB) approval
4. Implementation and verification
5. Documentation update and baseline revision

## C.3 Baseline Management

- **Functional Baseline:** Established at SRR
- **Allocated Baseline:** Established at PDR (this document)
- **Product Baseline:** To be established at CDR

# D Integrated Master Schedule (IMS) (Complete)

## D.1 Key Mission Milestones

| Milestone | Planned Date | Responsible | Status |
|---|---|---|---|
| System Requirements Review (SRR) | 2025-Q1 | Systems Engineering | Completed |
| Preliminary Design Review (PDR) | 2025-Q4 | Project Management | In Progress |
| Critical Design Review (CDR) | 2028-Q2 | Systems Engineering | Planned |
| Flight Readiness Review (FRR) | 2039-Q1 | Mission Operations | Planned |
| Launch | 2039 | Launch Services | Planned |
| Comet Encounter | 2059 | Science Operations | Planned |
| End of Mission | 2135+ | Project Management | Planned |

## D.2 Critical Path Analysis

The critical path is dominated by technology development:

$$\text{TRL } 4 \;\; 6 \;\; 8 \rightarrow \text{CDR} \rightarrow \text{Manufacturing} \rightarrow \text{Integration \& Test} \tag{27}$$

# E Approval Record & Document History (Complete)

## E.1 Approval Signatures

| Name / Role | Signature | Date |
|---|---|---|
| Project Manager | _____ | _____ |
| Systems Engineering Lead | _____ | _____ |
| NASA Review Representative | _____ | _____ |
| ESA Review Representative | _____ | _____ |
| Safety & Mission Assurance | _____ | _____ |

## E.2 Document Revision History

| Rev | Date | Changes | Author |
|---|---|---|---|
| 1.0 | 2024-06-15 | Initial draft | A. Ozorio |
| 2.0 | 2025-03-20 | Added technical analyses | Systems Team |
| 3.0 | 2025-10-28 | PDR complete version with appendices | Full Team |

## E.3 Distribution List

- NASA Headquarters (2 copies)
- ESA/ESTEC (1 copy)
- Project Management (3 copies)
- Systems Engineering (2 copies)
- Safety & Mission Assurance (1 copy)
- Archive (1 copy)