Design requirements for space electronics

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***Abstract*—Space electronics demand rigorous design and testing standards due to the extreme environmental conditions encountered in space missions. This paper outlines critical design requirements for electronics used in space applications, with a focus on component selection, printed circuit board (PCB) layout, material choice, and testing protocols. Leveraging guidelines from the European Cooperation for Space Standardization (ECSS) and the European Space Agency (ESA), this document explores how space electronics are engineered to withstand conditions such as radiation, thermal cycling, vacuum, and launch-induced mechanical stresses. A comparative analysis between space-grade and terrestrial electronics emphasizes the stringent requirements for reliability, radiation tolerance, and environmental resilience necessary for successful space missions. This paper provides a foundational understanding of these design standards, with references to ECSS guidelines for PCB qualification, procurement, and reliability assurance, aiming to inform the development of electronics that are resilient and reliable in the challenging environment of space.**

I. Introduction

The development of electronics for space applications presents unique challenges due to the severe environmental stresses encountered in the space environment. Unlike terrestrial electronics, which prioritize cost-effectiveness, manufacturability, and ease of maintenance, space electronics are designed to ensure reliability and durability over long mission durations in harsh conditions. Space missions subject electronic components to factors such as ionizing radiation, extreme thermal fluctuations, and the vacuum of space, each of which can significantly affect component performance and operational lifespan.

Space-grade electronics are therefore subject to stringent design and testing standards. The European Space Agency (ESA) and the European Cooperation for Space Standardization (ECSS) provide comprehensive guidelines that outline the requirements for space electronics design. ECSS standards, such as Qualification of printed circuit boards [3] for PCB qualification, Procurement of printed circuit boards [4] for procurement, and Design rules for printed circuit boards [1] for design rules, specify practices for ensuring that electronic systems are reliable, resilient, and capable of withstanding mission-critical conditions. These standards play a critical role in guiding the design of components, PCBs, and systems intended for space applications, promoting a unified approach to engineering that enhances mission success rates.

In addition to the environmental challenges unique to space, designing electronics for space missions requires an understanding of how space conditions shape design priorities differently from terrestrial applications. For instance, radiation tolerance and environmental resistance are critical for space-bound components, whereas terrestrial systems may emphasize cost and maintainability over extreme resilience. By comparing the design requirements for space and terrestrial electronics, this paper aims to highlight the specialized practices and standards essential for space applications, offering insights into the technical adaptations that are necessary when designing for the space environment.

II. Environmental Conditions in Space

Space presents extreme environmental challenges that demand specialized design approaches for electronics. Each condition impacts the selection of materials, components, and overall system architecture, ensuring reliable operation in mission-critical environments.

A. Radiation Environment

Ionizing Radiation: Includes gamma rays, electrons, and protons, which can degrade electronic components over time. [6]

- Impacts:
  - Total Ionizing Dose (TID): Gradual degradation of semiconductor devices. [6]
  - Single-Event Effects (SEE): Momentary disruptions like bit flips, latch-ups, or burnout in microelectronics. [6]
- Mitigation:
  - Use radiation-hardened components (e.g., SOI-based designs, GaN technology).
  - Apply shielding materials like aluminum or tungsten.
  - Incorporate error-correcting codes (ECC) for memory reliability.

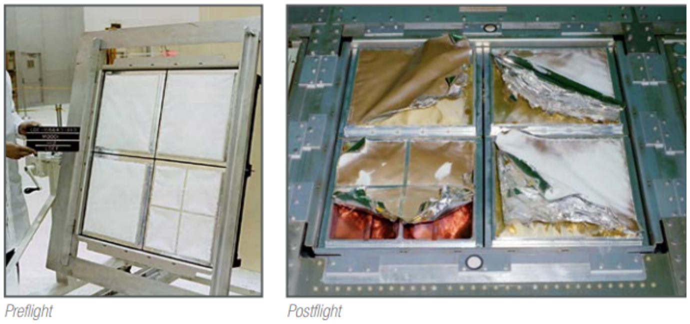

Fig. 1. Preflight and postflight Long Duration Exposure Facility M0001 Heavy Ions in Space experiment, indicating atomic oxygen erosion and ultraviolet degradation. [12]

Solar and Cosmic Rays: High-energy particles from solar storms and cosmic sources.

- Impacts: Short-term damage during solar flares.
- Mitigation: Implement fault-tolerant designs with redundant systems.

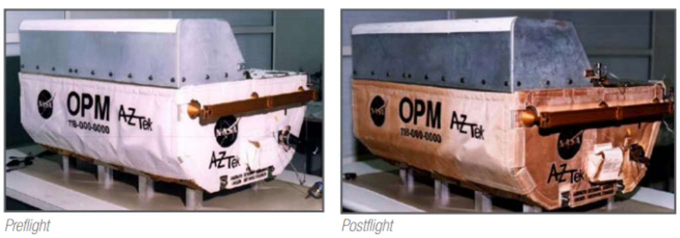

Fig. 2. Preflight and postflight images of the Optical Properties Monitor shown with ultraviolet-darkened insulation after nine months of exposure on the Mir Space Station. [12]

B. Thermal Extremes

Temperature Variations: Space electronics face rapid thermal cycling, ranging from -150°C to +150°C in low Earth orbit (LEO). [3], [10]

- Impacts:
  - Thermal expansion and contraction leading to material fatigue.
  - Failure in solder joints and PCB layers.
- Mitigation:
  - Use materials with low coefficients of thermal expansion (CTE), such as ceramics and polyimides.
  - Integrate thermal management features:
    * Thermal Doublers: Spread heat evenly across PCBs.
    * Radiators: Dissipate heat into space.
    * Heat Pipes: Transfer heat away from critical components.

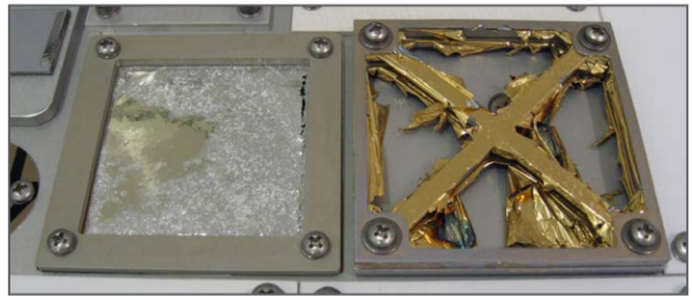

Fig. 3. Preflight and postflight Long Duration Exposure Facility M0001 Heavy Ions in Space experiment, indicating atomic oxygen erosion and ultraviolet degradation. [12]

C. Vacuum Conditions

Outgassing: Release of trapped gases from materials in a vacuum, leading to contamination.

- Impacts:
  - Fogging of optical sensors.
  - Contamination of mechanical parts.
- Mitigation:
  - Use low-outgassing materials compliant with Thermal vacuum outgassing test for the screening of space materials [5] (e.g., polyimides, Parylene coatings).
  - Avoid porous materials.

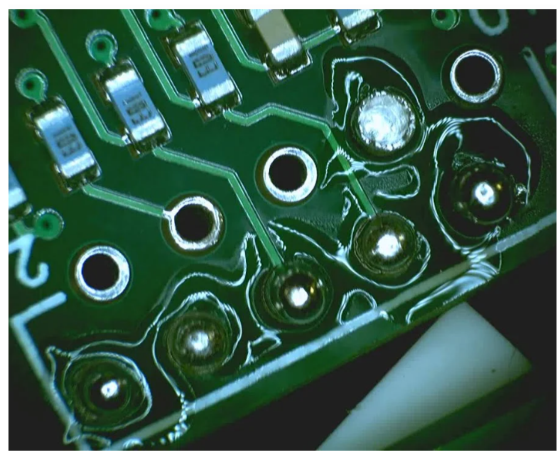

Fig. 4. Outgassing created in the solder joints after manual soldering [11].

Heat Dissipation: In a vacuum, heat transfer relies solely on conduction and radiation.

- Impacts: Overheating of high-power devices.
- Mitigation:
  - Employ copper layers and thermal vias in PCB design.
  - Design systems for efficient radiative heat transfer.

D. Mechanical Stresses

Launch Vibrations: Frequencies up to 2 kHz, with accelerations exceeding 20g during rocket launches.

- Impacts:

– Cracking of solder joints and mechanical failure of components.

- Mitigation:
  – Reinforce PCBs with stiffeners and brackets.
  – Conduct vibration and shock tests as per ECSS standards.

Microgravity Effects: Altered material deformation and fluid behavior.

- Impacts: Non-uniform stress distribution in structural components.
- Mitigation:Validate designs under simulated microgravity conditions.

E. Electromagnetic Environment

Electromagnetic Interference (EMI): Generated by onboard systems or external sources.

- Impacts: Disruptions in signal integrity and communication.
- Mitigation:
  – Use shielding and grounding techniques.
  – Design PCB layouts with controlled impedance traces.

Plasma Interactions: Surfaces in certain orbits interact with plasma, causing charging.

- Impacts: Electrostatic discharge (ESD) leading to system damage.
- Mitigation: Apply conductive coatings and grounding paths to minimize charge buildup.

III. DESIGN RULES FOR SPACE-GRADE PCBS

A. Track Width and Spacing Requirements

Typical Values:

- External Layers: Minimum track width and spacing depend on the copper thickness. For 35 µm copper, the values are typically 0.1 mm (track width) and 0.15 mm (spacing) [1], [2].

TABLE I
MINIMUM AS-MANUFACTURED TRACK WIDTH AND SPACING FOR EXTERNAL LAYERS AS A FUNCTION OF COPPER THICKNESS

Basic Cu [μm]	**Plated Cu** [μm]	**Thickness category** [μm]	**Pitch**	**As-manufactured**	
				width [μm]	**spacing** [μm]
17	1x25	$17 < \text{Th} \leq 60$	fine/normal	120/160	120/160
17	2x25	$60 < \text{Th} \leq 70$	fine/normal	120/160	120/160
35	1x25	$17 < \text{Th} \leq 60$	normal	160	160
35	2x25	$70 < \text{Th} \leq 95$	normal	240	240
70	1x25	$70 < \text{Th} \leq 95$	normal	240	240

- Internal Layers: Similar or slightly lower values due to reduced accessibility during manufacturing.

TABLE II
MINIMUM AS-MANUFACTURED TRACK WIDTH AND SPACING FOR INTERNAL LAYERS AS A FUNCTION OF COPPER THICKNESS

Thickness category [μm]	**Pitch**	**As-manufactured**	
		width [μm]	**spacing** [μm]
$\text{Th} \leq 17$	fine/normal	80/104	96/104
$17 < \text{Th} \leq 60$	normal	120	120
$60 < \text{Th} \leq 70$	normal	160	160
$70 < \text{Th} \leq 95$	normal	240	240

- Manufacturing Tolerances: Track width tolerances range from ±5% to ±20% depending on technology [1].
- Controlled Impedance: Tracks for high-frequency signals or differential pairs require precise width and spacing to maintain impedance, typically within ±10% of the target value [2].

B. Material Selection

Base Materials:

- FR-4: Limited for general use; not ideal for high-frequency or radiation-hardened applications.
- Polyimide Laminates: Preferred for their high thermal resistance and low outgassing properties [4], [5].

Material Properties:

- Outgassing: Total Mass Loss (TML) ¡ 1.0%; Collected Volatile Condensable Material (CVCM) ¡ 0.1% [5].
- Thermal Conductivity: Should exceed 0.3 W/mK for thermal management.
- Radiation Resistance: Materials should withstand a total ionizing dose of up to 100 krad [2], [6].

TABLE III
MATERIAL PROPERTIES AND APPLICATIONS

Material	**Key Properties**	**Applications**
Polyimide	Low outgassing, high thermal stability	Insulation for wiring and PCBs
Teflon	Excellent insulation, minimal contamination	Vacuum-sealed enclosures, insulators
Aluminum Oxide	Radiation resistance, thermal stability	Structural components for thermal stability
Carbon-Fiber Reinforced Polymer	High strength-to-weight ratio, durable	Satellite body panels, structural reinforcements

General Procurement Requirements:

1) Specification:
   - Rigid, flexible, and hybrid PCBs must comply with pre-approved design specifications.
   - Suppliers must maintain traceability.
2) Quality and Inspection:
   - Visual and Dimensional: Criteria for defects like cracks, voids, and misalignments.

- Outgassing and Thermal Cycling: Components and PCBs must pass these environmental tests.

3) Delivery and Packaging:
   - PCBs must be properly packaged with test coupons for additional validation.
   - Handling procedures to prevent contamination.

Inspection and Acceptance Criteria:

1) Test Coupons:
   - Verification of PCB material, plating quality, and thermal resistance.
   - Coupons must undergo microsectioning for dimensional checks.
2) Electrical Tests:
   - Continuity and dielectric strength validation.
3) Traceability and Documentation:
   - Certificate of Conformance (CoC) required for all deliveries.

C. Radiation-Tolerant Components

Space electronics are particularly vulnerable to radiation-induced failures, making it essential to use radiation-hardened components in critical systems. Radiation-hardening techniques include physical shielding, using redundant system architectures, and selecting components manufactured with radiation-resistant technologies, such as silicon-on-insulator (SOI) and gallium arsenide (GaAs).

D. Via Design and Plating Thickness

Via Plating:

- Minimum plating thickness: 25 µm for plated-through holes (PTHs) [1], [3].
- Aspect Ratio: Typically $\leq$5:1 (via depth to diameter) to ensure proper plating.

Pad Design:

- Annular Ring: Minimum 0.15 mm for internal layers, 0.2 mm for external layers [1].
- Non-functional Pads: Should be removed unless required for structural support [1].

E. Thermal Management

Heat Dissipation:

- Incorporate thermal vias under high-power components to enhance heat transfer.
- Use thick copper planes (e.g., $\geq$ 70 µm) for heat spreading [2].

Thermal Cycling:

- PCBs must endure -55°C to +125°C for standard cycles and up to +180°C for extreme applications [3], [4].

F. Solder Masks and Surface Finishes

Solder Mask:

- Provide coverage over all traces except pads.
- Minimum clearance of 0.1 mm from pads to avoid solder bridging [1], [2].

Surface Finish:

- Gold over Nickel (ENIG): Preferred for fine-pitch components.
- Hot Air Solder Leveling (HASL): Use with caution due to uneven surfaces, unsuitable for high-density interconnects (HDI) [1].

G. Electrical Design and Insulation

Voltage Rating:

- Rigid PCBs: Minimum insulation distance of 0.5 mm per 100V (as manufactured) [1].
- Flexible PCBs: Insulation distance typically 0.4 mm per 100V [1].

Controlled Impedance:

- Microstrip and stripline designs for high-speed signals should maintain impedance values (50 Ω single-ended, 100 Ω differential) within ±10% [1].

H. Mechanical Integrity and Cleanliness

Mechanical Robustness:

- Conduct tensile tests on copper layers to verify adhesion and resilience under vibration [3].
- Design PCBs to withstand launch stresses up to 20g [2].

Cleanliness:

- Ensure ionic contamination ¡ 1.56 µg/cm² NaCl equivalent to avoid corrosion [2].

I. Thermal Stability

Thermal stability testing ensures PCBs can withstand temperature variations and associated stresses encountered during space missions.

IV. Testing in the Context of Space Electronics Design

A. Thermal Cycling Tests

Purpose:

- Simulates extreme temperature fluctuations in space, such as those experienced in low Earth orbit (LEO) where temperatures can range from -100°C to +120°C.

Design Implications:

- Materials with low coefficients of thermal expansion (CTE), such as polyimides and ceramics, are preferred to minimize mechanical stress.
- Reinforcement of solder joints and the use of thermal vias are essential to handle expansion and contraction without failures.

Key Parameters:

- Typical test cycles: -150°C to +150°C, up to 1,000 cycles.
- Failure modes: Cracking of vias, delamination, and solder fatigue.

B. Vacuum Outgassing Tests

Purpose:

- Evaluates materials for the release of volatile compounds in a vacuum environment, which can lead to contamination of sensitive electronics or optics.

Design Implications:

- Use low-outgassing materials like polyimides (CVCM $<$ 0.1%, RML $<$ 1%) as specified in the Thermal vacuum outgassing test for the screening of space materials [5].
- Avoid unsealed vias and use coatings like parylene for additional protection.

Key Parameters:

- Measured values: Collected Volatile Condensable Material (CVCM) and Residual Mass Loss (RML).
- Test standards: Thermal vacuum testing replicates the vacuum of space.

C. Vibration and Shock Tests

Purpose:

- Mimics mechanical stresses during launch, including vibrations and shocks that can damage components and PCBs.

Design Implications:

- PCBs should include reinforced mounting points and structural brackets.
- Selection of robust connectors and solder materials resistant to mechanical fatigue.
- Conformal coatings are applied to protect against microcracking.

Key Parameters:

- Frequencies: 20 Hz to 2 kHz.
- Acceleration: Up to 20 g.
- Standards: Space engineering Testing [8]

D. Radiation Testing

Purpose:

- Determines the resilience of components to ionizing radiation, including single-event effects (SEE) and total ionizing dose (TID).

Design Implications:

- Use radiation-hardened components such as silicon-on-insulator (SOI) or gallium nitride (GaN).
- Implement shielding and redundant architectures to mitigate radiation damage.

Key Parameters:

- TID tolerance: $>$100 krad.
- SEE thresholds: Measured in MeV-cm^2/mg.
- Standards:Radiation hardness assurance EEE components [6]

E. Electrical Testing

Purpose:

- Ensures signal integrity, insulation resistance, and dielectric performance under operational conditions.

Design Implications:

- Controlled impedance traces for high-frequency signals.
- Double insulation for critical circuits to prevent arcing.
- Selection of dielectric materials with low loss tangent for RF applications.

Key Parameters:

- Insulation resistance: $>$100 MΩ.
- Dielectric withstand voltage: Typically 500V to 1kV for multilayer PCBs.
- Standards: [3]

TABLE IV
RELEVANCE OF TESTING TO DESIGN PRINCIPLES

Test Type	**Purpose**	**Design Implications**
Thermal Cycling	Simulates temperature extremes	Use low CTE materials; reinforce joints
Vacuum Outgassing	Ensures minimal volatile release	Use low-outgassing materials
Vibration and Shock	Simulates launch mechanical stresses	Add structural reinforcements
Radiation Testing	Assesses tolerance to space radiation	Use radiation-hardened components
Electrical Testing	Validates signal and insulation integrity	Optimize impedance and insulation design

V. COMPARISON: SPACE VS. TERRESTRIAL ELECTRONICS

The design and engineering of space electronics differ significantly from those for terrestrial applications due to the contrasting environmental conditions and design priorities. While terrestrial electronics often prioritize cost-efficiency, ease of manufacturability, and maintenance, space electronics are designed to prioritize reliability, radiation tolerance, and resilience to extreme environmental conditions.

A. Reliability and Radiation Tolerance

Reliability is critical in space applications, where maintenance and repair are not feasible. Space electronics employ radiation-hardened components, which can withstand high levels of ionizing radiation and protect against single-event upsets. In contrast, terrestrial electronics often use standard components that lack radiation-hardening, as radiation exposure on Earth is minimal.

Space electronics also incorporate extensive redundancy and fault-tolerant designs to mitigate the risk of failure. This contrasts with terrestrial electronics, where redundancy is less emphasized due to the accessibility of repair and maintenance services.

Space Electronics

- Designed for extreme reliability due to limited or no access for repair. Typical mission lifetimes range from 5 to 15 years or more.
- Require high radiation tolerance to withstand ionizing radiation (e.g., total ionizing dose of 100 krad or more).
- Materials and components undergo rigorous qualification, such as thermal cycling and radiation hardness testing [1], [6].

Terrestrial Electronics

- Focused on cost-efficiency and ease of replacement. Reliability often depends on use case (e.g., consumer electronics typically designed for 2-5 years of operation).
- Radiation tolerance is minimal, with standard electronics shielded for typical environmental exposure but not for high-radiation environments.
- Qualification processes emphasize manufacturing defects and environmental testing (e.g., temperature, vibration) for normal operating conditions.

B. Durability Under Environmental Stress

Space electronics must endure extreme temperatures, vacuum, and mechanical stresses, unlike terrestrial electronics, which generally operate in controlled or moderate environments. The design for space-grade durability includes materials with low thermal expansion coefficients, thermal insulation, and strong structural reinforcements to withstand vibrations and shocks.

In terrestrial electronics, durability considerations are often more focused on withstanding routine wear and tear or environmental exposure (e.g., moisture resistance), rather than the extreme conditions encountered in space.

Space Electronics

- Operate in a vacuum with no convection for heat dissipation [1], [3], [10].
- Must endure high radiation levels, wide thermal ranges (-55°C to +125°C or more), and mechanical stress during launch [2], [10].

Terrestrial Electronics

- Typically face less extreme conditions: atmospheric pressure, moderate temperature changes, and humidity [10].

C. Design Priorities and Application Context

Design priorities for space electronics center on environmental resilience, reliability, and mission longevity, while terrestrial electronics emphasize factors like cost, manufacturability, and rapid production timelines. For example, space electronics are designed with thorough testing and stringent quality standards, often sacrificing cost-efficiency for reliability. Terrestrial electronics, on the other hand, balance performance with affordability and ease of maintenance, making them more accessible and adaptable to diverse market needs.

This shift in design priorities reflects the application context; space missions demand high-stakes reliability where failure can result in mission loss, whereas terrestrial electronics can afford lower reliability with accessible support systems in place.

Space Electronics

- High emphasis on reliability, radiation shielding, thermal management, and long lifespan for multi-year missions [1], [10].
- Materials and components must meet rigorous outgassing and thermal cycling standards [2].

Terrestrial Electronics

- Focus on cost-efficiency, high production volumes, and adaptability for varying applications [10].

D. Testing Requirements

Space Electronics

- Extensive qualification testing including thermal vacuum, radiation resistance, vibration, and shock tests [2], [10].

Terrestrial Electronics

- Standard compliance tests (e.g., MIL-STD, IPC standards) for electrical performance and durability under everyday conditions [10].

TABLE V
COMPARATIVE ANALYSIS: SPACE VS. TERRESTRIAL REQUIREMENTS

Aspect	**Space Electronics**	**Terrestrial Electronics**
Radiation Tolerance	High; radiation-hardened components essential	Not required in most cases.
Thermal Performance	Wide range (-150°C to 150°C)	Moderate range (-40°C to 85°C).
Environmental Testing	Includes vacuum, radiation, and vibration tests	Limited to terrestrial conditions.
Material Selection	Low-outgassing, high-reliability materials	Focus on cost and manufacturability.
Design Priorities	Reliability and longevity	Cost-efficiency and ease of repair.

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