



RF Transmission Line Performance and Loss: A Technical Whitepaper for Aerospace Interconnect Engineers

Introduction

Aerospace RF (Radio Frequency) systems place exceptional demands on transmission lines. Unlike ground-based equipment, cables and connectors used in satellites, launch vehicles, aircraft, and unmanned platforms must deliver consistent performance despite extreme temperatures, altitude, mechanical vibration, radiation exposure, vacuum environments, and wide frequency ranges. Engineers responsible for these systems must consider not only the nominal electrical parameters of coaxial cables and assemblies, but also the complex interactions between materials, construction methods, and environmental stresses in airborne applications.

This whitepaper provides a detailed technical discussion—intended for RF and aerospace-system engineers—of the primary mechanisms that govern transmission-line performance. Topics include attenuation, impedance discontinuities, power handling, phase control, and specialized aerospace considerations such as vacuum effects, thermal cycling, and routing constraints. Throughout the discussion, we include expanded explanatory content to illustrate not just *what* each parameter means, but *why* it behaves as it does and how engineering decisions influence real-world system outcomes.

1. Understanding Attenuation in RF Transmission Lines

Every RF transmission line introduces loss. When a signal propagates down a coaxial cable, a portion of its energy is inevitably dissipated as heat or electromagnetic radiation. This phenomenon, known as attenuation, becomes increasingly significant as frequencies rise. Modern aerospace systems routinely operate well into the microwave regime, where attenuation characteristics can dominate overall link budgets.

1.1 Resistive (Conductor) Loss Mechanisms

Conductor loss stems from the finite conductivity of the metals used in the inner and outer conductors. At RF frequencies, current is confined to a thin layer at the surface of the conductor due to the skin effect. As frequency increases, this skin depth becomes thinner, meaning the effective cross-section available to carry current is reduced. The result is a rising resistance with frequency and thus rising insertion loss.

For this reason, larger-diameter conductors are advantageous—they provide more conductive surface area and therefore lower resistance. Silver plating is commonly used because silver offers the highest conductivity of any metal. Even a thin plating layer can significantly reduce high-frequency losses compared to bare copper. In aerospace environments, where weight is a constant concern, material engineers must strike a balance between conductor diameter, plating thickness, and overall cable mass.



1.2 Dielectric Loss and the Role of Material Selection

Dielectric loss originates from the dielectric material that separates the center conductor from the shield. As the electromagnetic wave travels through the cable, a portion of its energy is absorbed by the dielectric and converted to heat. This loss is dependent on the dielectric constant and loss tangent of the material.

PTFE (polytetrafluoroethylene) and its variants (ePTFE, taped PTFE) are widely used in aerospace coaxial cables due to their low loss characteristics and exceptional stability across a broad temperature range. One important consideration is that cables with more air content—such as those using microporous ePTFE—exhibit both lower dielectric loss and higher velocity of propagation. However, they may also be more mechanically delicate, requiring careful jacketing and strain relief.

1.3 Radiation Loss and Shielding Integrity

Radiation loss occurs when imperfections in the outer conductor or shield allow electromagnetic energy to escape the coaxial structure. These imperfections may take the form of insufficient braid coverage, micro-gaps in foil shields, dimensional discontinuities, or even damage incurred during installation.

At higher frequencies, where wavelengths are shorter, these discontinuities represent a larger proportion of the wavelength and therefore have a more pronounced effect. Aerospace cables typically employ multiple shielding layers—such as braid-over-foil or double- and triple-braid constructions—to ensure both electromagnetic isolation and mechanical robustness.

1.4 Engineering Strategies to Reduce Attenuation

Because attenuation depends on conductor, dielectric, and structural characteristics, engineers must consider all aspects together. Using higher-conductivity materials, selecting low-loss dielectrics, increasing conductor diameter, ensuring precise shield manufacturing, and minimizing cable length wherever possible all contribute to improved signal integrity.

2. Impedance Stability, Reflections, and Back-Propagating Energy

In an ideal transmission line, all power launched into the input is delivered to the load. In practice, any discontinuity along the RF path causes a portion of the signal to reflect backward. These reflections degrade system performance, distort signals, and increase stress on components such as power amplifiers.

2.1 Return Loss and Its Interpretation

Return Loss (RL) is a measure, expressed in decibels, of the ratio of forward power to reflected power. A high return loss indicates minimal reflection and therefore a well-matched system. Engineers often think



of RL in terms of power percentages: an RL of 3 dB corresponds to 50% reflection, while 6 dB represents 25%. A return loss of 0 dB indicates a complete reflection, as would be seen with an open or short circuit.

In aerospace systems, return loss is especially critical when dealing with antenna feeds, phased-array elements, and sensitive sensor electronics. Minor impedance deviations at connectors or transitions can degrade array beamforming accuracy or reduce radar detection sensitivity.

2.2 VSWR and Standing Wave Formation

Voltage Standing Wave Ratio (VSWR) offers a different view of reflection. Instead of quantifying power ratios, it describes the voltage amplitude variations caused by the interaction of forward and reflected waves. Perfectly matched lines produce no standing waves, yielding a VSWR of 1:1. Higher ratios indicate poorer matching.

VSWR becomes particularly important for high-power transmitters, as elevated voltage peaks along the line can exceed dielectric breakdown thresholds or cause localized heating. For this reason, RF amplifiers used in aerospace platforms often include protective shutdown features based on VSWR thresholds.

2.3 Sources of Impedance Discontinuity

Common causes of mismatch include variations in dielectric thickness, poor connector termination, damage to the cable's outer conductor, or incorrect interface geometries between components. In aerospace environments, mechanical vibration or thermal cycling can gradually shift these geometries, making long-term stability a key engineering requirement.

A carefully controlled manufacturing process—including precision-machined connector parts, precise soldering methods, and cable organizer strain-relief design—is essential to maintaining low-reflection performance over the system's lifespan.

3. Understanding dBi in System-Level Analysis

Although not a property of the transmission line itself, antenna gain expressed in dBi (decibels relative to an isotropic radiator) is central to the link budget of any RF system. Engineers use dBi values to evaluate how effectively an antenna focuses energy in a given direction. Larger dBi values typically indicate narrower beams and greater range, which must be balanced against pointing accuracy and system mission profiles.



4. Power Handling in Aerospace RF Cables

Power handling is dictated by a combination of thermal, electrical, and environmental constraints. A cable that performs well at low power levels may fail if subjected to higher-average or peak-power due to conductor heating, dielectric stress, or corona discharge.

4.1 Influence of Cable Diameter and Materials

Larger cables can dissipate heat more effectively and exhibit lower resistive losses, allowing them to carry more power. Similarly, dielectrics with higher thermal stability and lower loss tangents raise the maximum allowable power. Care must also be taken to avoid trapped air pockets within the construction, as these can lead to internal ionization in low-pressure environments such as space.

4.2 Power Derating Factors for Aerospace Applications

In real-world systems, the power a cable can safely handle must be derated according to several conditions:

- **Frequency:** Higher frequencies increase conductor loss and therefore heating.
- **Temperature:** Elevated temperatures reduce the dielectric's breakdown strength.
- **Pressure:** In low-pressure environments, corona discharge can occur at lower voltages.
- **Reflections:** Poor return loss or high VSWR increases the voltage standing wave amplitude, raising the risk of dielectric failure.

Engineers must consider all these factors together when specifying cable assemblies for flight hardware.

5. Velocity of Propagation and Electromagnetic Wave Behavior

Velocity of propagation (V_p) describes how quickly an RF signal travels through the cable compared to the speed of light in vacuum. Materials with more air content tend to have higher V_p because air has a dielectric constant close to 1.

Extruded PTFE coaxial cables typically have a V_p around 69.5%. Taped PTFE and ePTFE constructions, which incorporate controlled air spacing, can achieve velocities of 80% or higher. The tradeoff is that increasing V_p often reduces mechanical strength, so designers must balance phase performance against durability.



6. Phase Matching, Stability, and the Impact of Temperature

Modern aerospace RF systems—especially phased arrays, precision timing networks, and multi-path sensors—rely on precise control of electrical phase. Any change in cable electrical length translates directly into phase error, which can compromise system performance.

6.1 Principles of Phase Length

A signal traversing a cable accumulates phase as it propagates. One physical wavelength corresponds to 360° of phase shift. The total electrical length is a function of both the physical length of the cable and the dielectric properties of its construction.

When multiple cables must deliver signals that are time-aligned, they must be both mechanically and electrically matched. Phase matching is typically performed either to an absolute value or relative to a reference assembly.

6.2 Temperature Effects and the "Teflon Knee"

Temperature is one of the most significant environmental variables affecting coaxial cable electrical performance. All dielectric materials exhibit some degree of temperature-dependent behavior, but PTFE—despite being an excellent low-loss dielectric—presents a particularly challenging characteristic: a sharp, non-linear change in its dielectric constant within a relatively narrow temperature band, typically between approximately 18°C and 25°C. This phenomenon is commonly referred to as the "Teflon Knee."

To understand the cause, it is important to consider the molecular structure of PTFE. PTFE is a semi-crystalline polymer that transitions between different molecular states as temperature changes. Below the knee region, the polymer chains are relatively rigid and highly ordered. Above the knee, increased thermal energy begins to activate molecular motion and relax certain internal bonding constraints. As PTFE passes through this transition region, the dielectric constant—and therefore the effective electrical length of any cable using it—shifts more rapidly than at temperatures outside this band.

Because electrical phase is directly proportional to the square root of the dielectric constant, even small variations in PTFE's permittivity can create measurable shifts in electrical length. In high-precision aerospace systems, where phase tolerances may be specified in fractions of a degree across gigahertz frequencies, this sudden phase drift can have substantial consequences. For example:

- In phased-array antennas, a small temperature-induced phase offset between adjacent channels can distort the radiation pattern, reduce gain, or misalign the beam.
- In radar systems, excess phase variation can degrade target resolution and Doppler accuracy.
- In satellite timing networks, unexpected shifts in electrical length may introduce synchronization errors.



The practical challenge is that the Teflon Knee often occurs near typical room temperature—exactly where spacecraft undergo integration, testing, and handling. As equipment warms up from storage, cools down during testing, or experiences small ambient shifts during assembly, cables may repeatedly cross through the knee region, producing phase inconsistencies that complicate calibration and measurement.

Several engineering strategies have historically been used to mitigate these effects, including:

- **Pre-conditioning cables** by temperature cycling before final trimming or calibration.
- **Incorporating active temperature compensation** into system electronics.
- **Using hybrid dielectric constructions** that blend PTFE with materials of more stable thermal behavior.

However, these approaches have limitations—pre-conditioning effects diminish with time, active compensation adds system complexity and mass, and hybrid materials may increase loss or reduce environmental durability.

Glenair's advanced stabilized-dielectric constructions, such as those used in the 962-025 low-phase change cable family, address the problem at the material and structural level, significantly reducing the magnitude of the dielectric transition and producing a much flatter and more predictable phase-versus-temperature response.

6.3 Glenair's 962-025 Phase-Stable Cable Technology

Glenair's 962-025 cable is engineered to suppress the effects of the PTFE knee, reducing thermal phase sensitivity from 1300–1500 ppm to below 200 ppm. This substantial improvement enables stable phase behavior even during wide thermal cycling. The cable is available in -047 and -086, and -141 sizes and is jacketed in FEP with PFA primary insulation.

The stability of the cable is particularly valuable for aerospace radar systems, ECM/ECCM architectures, and satellite timing networks where even small phase deviations can lead to degraded accuracy or reduced system coherence.

7. Additional Aerospace Engineering Considerations

Because RF cables in flight hardware are exposed to unique stresses, engineers must consider factors beyond basic electrical parameters.

7.1 Shielding and Electromagnetic Compatibility

Proper shielding is essential to prevent both RF leakage outward and interference coupling inward. Aerospace platforms often include high-power transmitters, switching power supplies, and digital



electronics operating in confined spaces. Multi-layer shield constructions provide superior protection against EMI, lightning strike effects, and nuclear EMP events.

7.2 Connector Reliability and Long-Term Stability

Connectors are frequently the weakest link in an RF path. Precision machining, controlled plating processes, and stable cable dielectric supports are required to maintain consistent impedance. Glenair's aerospace-grade connector platforms are engineered to minimize dimensional drift under mechanical load, vibration, and thermal stress.

7.3 Routing, Flexure, and Mechanical Stress

Repeated movement or vibration can gradually alter the impedance of a cable assembly, especially in braided shields where strand reorientation occurs over time. Engineers should avoid tight bend radii, excessive torsion, and routing near high-current harnesses that may induce thermal or magnetic effects. Strain relief and proper cable management significantly extend service life.

7.4 Vacuum, Outgassing, and Thermal Cycling

Materials used in spaceflight systems must withstand high vacuum, harsh radiation, and extreme temperature swings. Dielectrics and jackets must exhibit low outgassing characteristics to avoid contaminating sensitive optical or thermal-control surfaces. Differences in coefficient of thermal expansion between metals and plastics must be managed to prevent dimensional drift or microcracking.

Conclusion

Aerospace RF transmission lines operate at the intersection of demanding electrical performance requirements and uncompromising environmental conditions. As this white paper has outlined, attenuation, impedance stability, phase control, power handling, and thermal behavior are not isolated design variables but tightly coupled characteristics shaped by material selection, mechanical construction, and system-level constraints. Even small variations in dielectric response, shielding integrity, or connector geometry can translate into significant performance consequences in missions where reliability, precision, and long operational life are mandatory.

For engineers developing next-generation flight hardware, understanding the underlying physical mechanisms—skin effect, dielectric loss, standing waves, temperature-induced permittivity changes, and vacuum-related phenomena—is essential to predicting how an RF cable assembly will behave from the laboratory to orbit. Modern aerospace platforms continue to push operating frequencies higher, phase tolerances tighter, and payload volumes smaller, intensifying the need for well-engineered transmission-line solutions.



Advances in stabilized dielectrics, precision connector interfaces, and high-integrity shielding architectures, such as those engineered by Glenair, demonstrate that the most effective way to meet these challenges is through ecosystem design: optimizing materials, construction methods, and manufacturing processes holistically. By applying these principles, aerospace RF engineers can achieve the low loss, stable phase, and long-term reliability required for high-performance antennas, radar systems, satellite communications, and mission-critical sensing architectures.

Ultimately, successful RF transmission-line design in aerospace is not merely a matter of selecting components—it is the disciplined integration of physics, materials science, and system engineering to ensure signal integrity in the harshest operational environments.