HIGH DENSITY COAXIAL INTERCONNECT SOLUTION FOR SPACE APPLICATIONS REQUIRING HIGH ELECTRICAL STABILITY

Andrew Weirback

HUBER+SUHNER Astrolab, Inc.
4 Powder Horn Drive
Warren, NJ, USA 07059
Email: andrew.weirback@hubersuhner.com

ABSTRACT

This paper presents the Sub-Miniature Push-On Micro-Miniature Threaded (SMPM-T) interface RF connector. The SMPM-T connector provides the high electrical performance stability inherent to the Sub-Miniature Type A (SMA) while meeting the miniaturization requirements and higher operating frequencies of new space-flight electronic systems. The SMPM-T connector provides excellent phase stability during vibration at operating frequencies up to 67 GHz. This new design minimizes connector center-line spacing to 5mm through a significant reduction in physical geometry. The reduced geometry of the SMPM-T also translates to a total mass of 1 gram for a mated connector pair. This performance provides a 75% reduction in the connector center-line spacing and 85% less mass in comparison to SMA panel mount solutions.

INTRODUCTION

The design and performance requirements of space-flight payload electronics systems have been progressively tightening the geometric constraints of the system while concurrently moving toward higher operating frequencies. This has created a significant challenge at all tiers of the system design and manufacturing process. The parameters identified at the system level to meet these difficult program requirements are driving the development of novel miniaturized passive component solutions to support these emerging applications.

Through advancements in precision machining capabilities and printed circuit board material deposition controls, the components within RF modules and hermetic packages have been very successfully reduced in both size and mass. However, the potential reduction of the system's geometric footprint and its constituent components is limited by the availability of equally compact coaxial interconnect solutions that can meet the reliability and durability requirements of a space vehicle. As electronic systems have decreased in size, the preferred interface selection for RF connectors and cable assemblies in these applications has been the Sub-Miniature Type A (SMA) connector.

The selection of the threaded SMA connector interface requires that a technician has the ability to access the connector coupling nut with a torque wrench during the mating cycle. Based upon the size of the SMA connector and the assembly clearances that are necessary, the minimum connector center-line spacing is 19mm. The minimum geometric area of any surface of an RF module wherein multiple connectors are mounted must then be of sufficient size to contain the panel mount dimensions for each connector, provide the necessary assembly clearances, and structurally sustain the mechanical loads due to space vehicle environmental dynamics. All of these factors serve to limit the potential for reduction in the size and mass of RF components that utilize the SMA interface. The SMA connector, a low weight, compact, and reliable solution for years, is now itself becoming too large for many new programs and space-flight applications and is also unable to provide a connector solution for applications in new higher frequency bands. There are several alternatives to the SMA connector for applications operating at frequencies up to K_u band offering varying levels of electrical stability and performance. However, for higher frequency applications operating in the K and K_a bands the limitation to reduce the size and mass of the system is compounded by an even smaller selection of connector interfaces that are available.

The typical RF connectors selected for systems operating in the K and K_a bands are either the 2.9mm or 2.4mm interfaces. These interfaces do provide excellent electrical performance and stability but inhibit the reduction in the size of the RF components within the electrical system by the same form factor as the SMA connector. The use of push-on style RF connectors in high frequency applications with significant size and weight constraints has been widely accepted within several markets including aerospace and defense applications. This style of connector removes the bulky coupling nut that is typical to the SMA, Type N, 2.9mm, 2.4mm, and other traditional interfaces. Additionally, system clearances to allow for the application of mating torque during connector installation no longer have to be taken into consideration when establishing the position of surrounding components. This has lead to the ability to significantly increase the number connections in a given unit area through minimized connector center-line spacing requirements.

SUB-MINIATURE PUSH-ON MICRO-MINIATURE CONNECTOR CAPABILITIES

Industry specifications have been written to recognize and incorporate the unique performance features of this interconnect solution. The interface dimension standards for the Sub-Miniature Push-On (SMP) and Sub-Miniature Push-On Micro-Miniature (SMPM) connectors have been documented in MIL-STD-348 [1]. The performance, materials, and finishes requirements of the SMP connector have been recently added to the United States Military general specification for high reliability coaxial radio frequency connectors [2]. The performance, materials, and finishes requirements of the SMPM connector have been published in several draft documents by the Defense Logistics Agency (DLA) defined under Project Numbers 5935-E838-001 and 5935-E838-002 that are undergoing review within industry working groups [3, 4].

The removal of the coupling nut to gain geometric and weight reductions requires that retention of the mated connectors be provided through a different mechanism. The focus of this paper is on micro-miniature solutions and thus the smaller of the two interfaces, the SMPM. In analyzing the SMPM connector mechanics, the body has been designed to serve not only as the outer conductor of the coaxial line but also as the structural support to maintain the connector junction. The connector body is manufactured from Beryllium Copper which is then slotted and hardened. The fingers of the body are expanded to provide positive contact while mated. These fingers are inserted through a tapered annular retention step and reopen in a larger diameter detent bore to provide positive contact at the connector reference plane and 22 N mated retention strength. The mating connector interfaces are designed to allow the slotted body to float and move while mated to compensate for any stresses due to connector misalignment, cable assembly mass behind the connector, and design tolerances.

This movement is an inherent part of the SMPM connector design to meet the mechanical durability and mating life performance requirements specified in the industry standards [3, 4]. Adding to this freedom of motion are the tolerance ranges of the SMPM interface features that create a cumulative allowance for the interface reference planes of a connector pair to have both axial and angular separation in the mated condition [1]. Fig. 1 displays the axial displacement that is allowed by the feature dimensions in the SMPM interface standard. In this case, Dimension “F” is only defined with a maximum material condition [1]. This can allow for a significant range of movement based upon the individual design of the connector. Fig. 2 also reveals the allowance for angular displacement to occur with the Dimension “A”, also only defined within the SMPM interface standard with a maximum material condition [1]. This dimensioning scheme yields a mated connection with very little restriction on the position of the interface reference planes in practical applications.

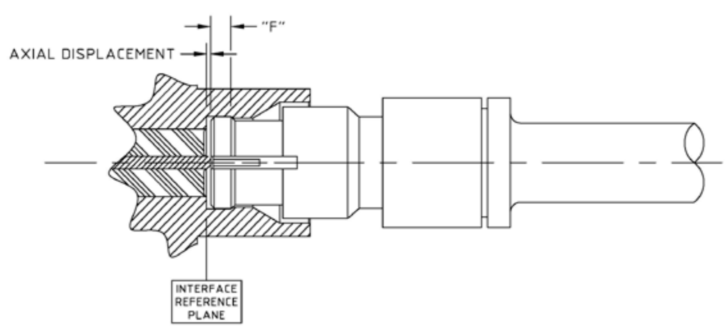

Fig. 1. SMPM interface axial displacement allowance

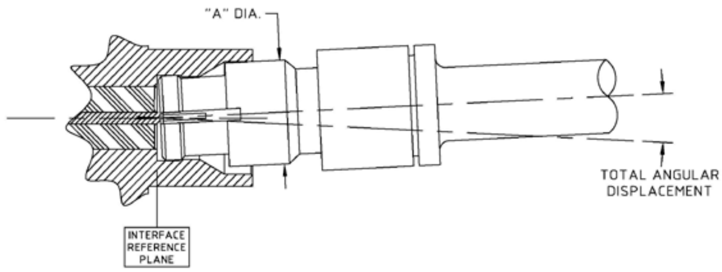

Fig. 2. SMPM interface angular displacement allowance

These two modes of interface reference plane separation pose a significant risk to the reflection, amplitude, and phase stability of an electronic system while subjected to space vehicle environment dynamics. The risk and magnitude of impact on the performance of the system is multiplied by the number of connections present. Reflection and amplitude changes will be evident but of a relatively small magnitude as electrical contact is maintained over the entire range of movement while the connectors are mated. However, this interface reference plane separation is of particular concern for systems that require electrical length matching or precision signal delay times from the coaxial interconnect solutions. The interface reference plane separation caused by the shock and vibration acceleration dynamics of the space vehicle environment creates a coaxial air line of unpredictable length which adds electrical length and signal delay at each mated connector. The magnitude of the additional signal delay due to SMPM interface plane separation is directly proportional to the frequency of the signal and is defined in Fig. 4. The phase differential due to interface separation can be calculated for any push-on style interface using the following equation:

$$\Delta\phi = 360\frac{V_p L}{\lambda} \tag{1}$$

Equation (1) shows that the phase change due to interface separation is a function of the velocity of propagation factor (V_p), in this case with the dielectric medium of air equal to a factor of one, axial length of separation (L) in centimeters, and the wavelength in air (λ) in centimeters. It is evident that the reduction in the size and mass of the connections and RF modules through the use of push-on style connector interfaces comes at the cost of system electrical stability and high frequency performance.

SMPM-T INTERFACE CONNECTOR DESIGN

The necessity of an electrically stable threaded interface with the significant reduction in geometry and mass found in the push-on style SMPM interface was identified for aerospace, commercial, and defense requirements. A feasibility study was performed to evaluate the development of an open-source, MIL-STD-348 defined connector interface solution that can provide the electrical stability inherent to a threaded interface within a smaller geometric envelope. The performance goals for the analysis were driven by customer applications requiring connector center-line spacing of 5mm, the use of a baseline interface that is not proprietary and has published industry standards, and the capability to provide high electrical stability at operating frequencies up to 67 GHz. The results of the mechanical analysis and RF simulations identified a novel design that meets all of these performance criteria while providing significant size and weight savings. A threaded variant of the SMPM connector interface, the Sub-Miniature Push-On Micro-Miniature Threaded (SMPM-T), was developed that is fully compatible with the original SMPM interface while introducing a threaded connector solution with a center-line spacing as small as 5mm and a maximum operating frequency of 67 GHz.

This SMPM-T capability for high connection density provides the opportunity to significantly reduce the size and increase the functionality of the RF modules it is connected to. The SMPM-T increased connection matrix density provides a 75% reduction in the connector center-line spacing in comparison to SMA panel mount connectors. The development of the prototype connectors was initiated based upon the results of the interface study. The design of the SMPM-T connector capitalizes on the already proven high frequency performance of the SMPM connector with the simple and elegant addition of a retractable coupling nut on the SMPM-T Female connector and external threads on the SMPM-T Male shroud as depicted in Fig. 3. The addition of the coupling nut creates a threaded interface that is capable of maintaining constant positive axial force at the interface reference planes and removes any possible separation after mating. This brings the inherent strengths of mechanical and electrical stability and repeatability during exposure to space vehicle environmental dynamics found in the traditional SMA style threaded interface to the much smaller geometric configuration of the SMPM-T connector. The design of the coupling mechanism does not incorporate a C-clip or snap ring that is common to SMA connectors. This removal of this component reduces the connector body rotation to less than 5° during the mating process and eliminates the need for any anti-torque features to be added to the connector. During the mating cycle, the required torque is applied axially using a torque-driver rather than radially with a traditional torque wrench. This also removes the need for engineered assembly clearances to mount the connectors within the system and minimizes the connector center-line spacing. The retractable coupling nut gives the user the option to mate this connector with traditional SMPM or the new SMPM-T interfaces to increase system test and analysis throughput. The significant reduction in the geometry of the SMPM-T also provides a total mass of 1 gram for a mated connector pair. This is a reduction of greater than 85% of the mass of existing SMA connector solutions.

The addition of the coupling nut removes the necessity to use a Full Detent SMPM Male interface to retain the Female connector when mated [1]. This allows the Smooth Bore SMPM Male interface to be used in applications whose environmental stresses have historically precluded the use of this interface [1]. The Smooth Bore SMPM Male

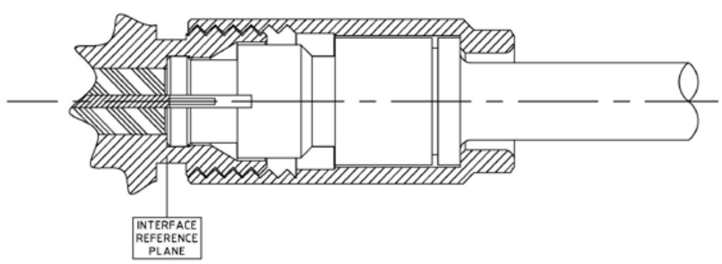

Fig. 3. SMPM-T Male and Female mated connectors

interface offers many beneficial improvements to the performance of the system components to which it is mounted. The connector disengagement force of the Smooth Bore interface is specified at 6.7 N typical. This is 30% of the disengagement force value specified for the Full Detent interface. This removes the risk of printed circuit board SMPM connectors pulling away or separating from the surface of the board, or even worse causing circuit board layer delamination, during the de-mating process. This also lowers the tensile stress that the solder joint is subjected to during the mating cycle. The reduced mechanical interference of the Smooth Bore interface also dramatically increases the mating life of the connector pair. The Full Detent SMPM interface is rated for a minimum of 100 mating cycles whereas the Smooth Bore SMPM interface is rated for 500 cycles minimum. The threaded interface thus serves to reduce the risk of degradation to surrounding components due to mating and de-mating.

Design verification testing performed on the SMPM-T connector design provided performance data that demonstrates excellent broadband electrical performance from DC-67 GHz. The mechanical performance of the SMPM-T connector also exceeds the requirements of MIL-STD-348 and industry performance specifications [3, 4]. The phase stability of the mated SMPM-T interface connector while subjected to low frequency vibration was verified

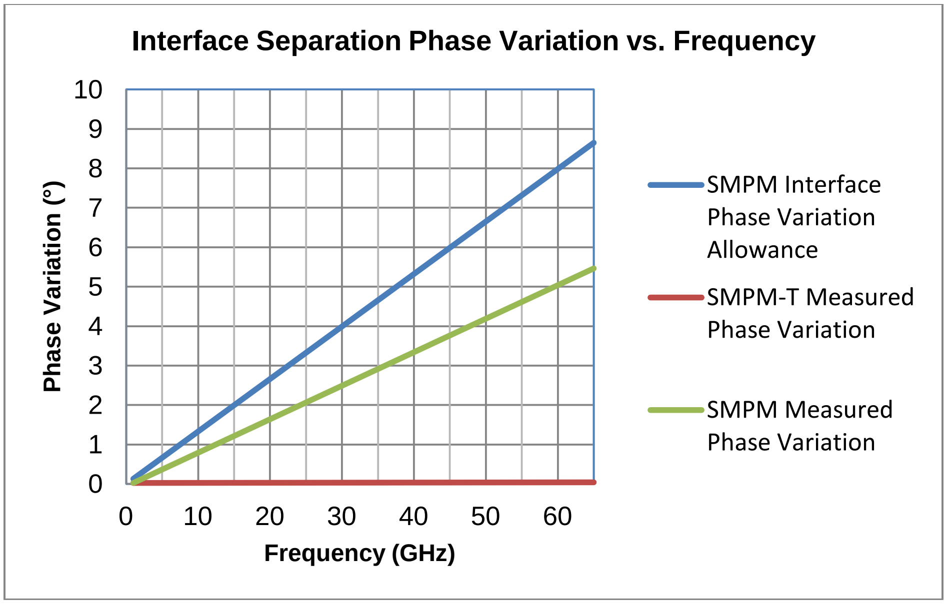

Fig. 4. Interface separation phase impact versus operating frequency

with the coupling nut fully engaged and a mating torque of 15.6 N-cm applied. A mated SMPM interface connector pair was also subjected to the same dynamic test to provide a comparative data set. Fig. 4 compares the phase differential versus operating frequency of the SMPM interface due to interface tolerance allowances, the measured performance data of the SMPM interface, and the measured performance data of the SMPM-T interface. The electrical stability of the SMPM-T connector is extremely high even at operating frequencies exceed 60 GHz with the measured maximum phase differential of less than 0.01°. This stability is equivalent to that offered by the much larger and bulkier space qualified threaded connector interfaces such as the SMA, Type N, 2.9mm, or 2.4mm.

Design verification testing also revealed the improvement in the RF leakage of the SMPM-T interface through the addition of the coupling nut. As depicted in Fig. 3, the coupling nut completely enshrouds the slots on the SMPM-T body in the mated condition. This provides an improvement in the RF shielding of the SMPM-T interface across the frequency band over which the connector can operate. The RF leakage of the mated SMPM-T interface connector was measured using the Triaxial Chamber Method [5, 6]. This test method collects the leakage energy of the total coaxial system surrounding the mated connector pair [6]. A mated SMPM interface connector pair was also subjected to the same RF leakage test to provide a comparative data set. Fig. 5 displays the RF leakage performance of the SMPM and SMPM-T connector pairs over the specified test frequency range [5].

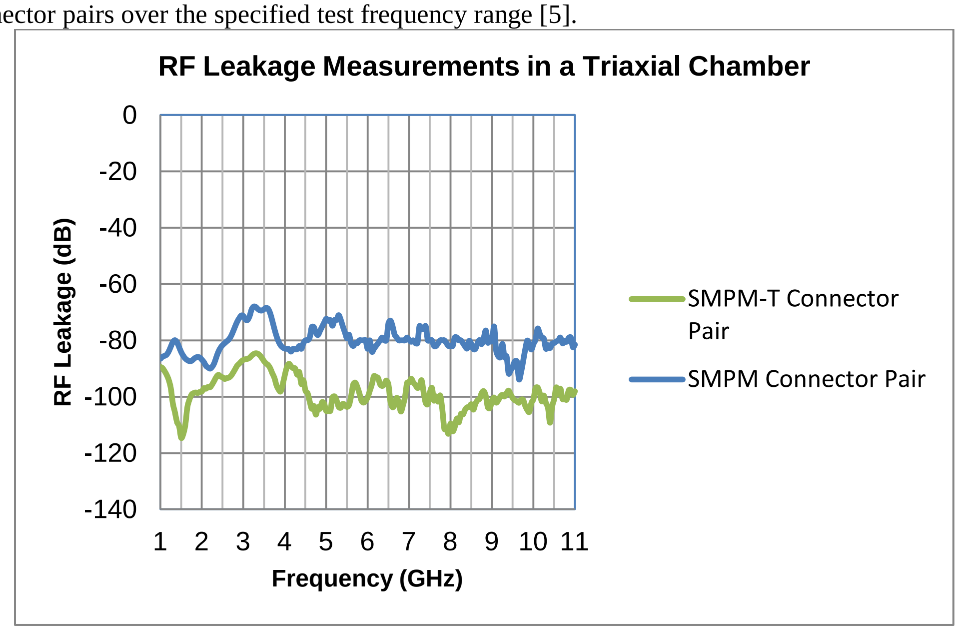

Fig. 5. RF leakage performance of SMPM and SMPM-T connector pairs

SMPM-T INTERFACE COMPONENT SOLUTIONS

The successful performance of the SMPM-T interface has lead to its utilization in the design of an extensive array of component solutions for electronic systems that require compact, high-density interconnections with high electrical stability. The connector product portfolio includes panel mount hermetic feed-thru connectors as well as a large variety of printed circuit board mounted solutions. The SMPM-T design is a comprehensive broadband interconnect solution with performance up to 67 GHz. This high frequency performance range has also lead to the design and development of SMPM-T connector solutions for printed circuit board coplanar waveguide transmission lines operating up to 67 GHz. The connector designs have been developed for commonly used printed circuit board dielectric materials and substrate layers yielding signal launches with very low reflection at the board to connector junction. SMPM-T connector solutions have also been developed for space-flight and defense applications in which gold embrittlement of the solder joint must be eliminated as a potential failure mechanism. To meet these industry requirements, a solder alloy coated option of each printed circuit board connector style is available. These connectors have had the gold plating of the connector body dissolved in solution with Sn63Pb37 solder through a process of two successive solder alloy coating and removal steps. This results in a solderable surface that has a gold content of less than 3% by weight and mitigates the formation of deleterious concentrations of $AuSn_4$ and $AuSn_2$ intermetallic phases [7, 8 and 9].

The SMPM-T interface is also available for use as a cable connector for flexible cable assembly interconnections between RF modules. The cable connector has been designed to terminate microbend® style flexible cable assemblies. This cable assembly solution is used to replace 0.047 in. diameter semi-rigid cable interconnections. The microbend® cable is a true flexible, triple-shielded coaxial cable that has >35% less attenuation that 0.047 semi-rigid cable while still able to provide a miniaturized routing solution with a minimum static bend radius of 1.5mm. In addition, the microbend® connector attachment incorporates a unique solderless center and outer conductor termination method. With the absence of solder on the outer conductor of the cable, there is no solder wicking present in the braided shields and therefore no design constraint requiring additional strain relief to protect this rigid transition point. This allows the cable to bend immediately behind the connector as displayed in Fig. 6, providing an interconnect solution for the most congested applications. This SMPM-T cable connector design operates up to 67 GHz even without the use of solder at the conductor junctions. This solderless junction design has successfully flown on many global space-flight programs and also stands the test of reliability analysis with superior ratings when compared to traditional soldered conductor junctions found on semi-rigid cable assembly connectors. The reliability model used for the evaluation of the cable assembly is based upon the Parts Count Reliability Prediction of MIL-HDBK-217 [10]:

$$\lambda_e = \sum_{i=1}^{i=n} N_i \left(\lambda_g \pi_Q\right)_i \qquad (2)$$

Equation (2) defines the reliability prediction for equipment (λ_e) in failures per million hours is based upon the sum of the quantity of individual parts (N_i) within the system, the number of different generic part categories within the

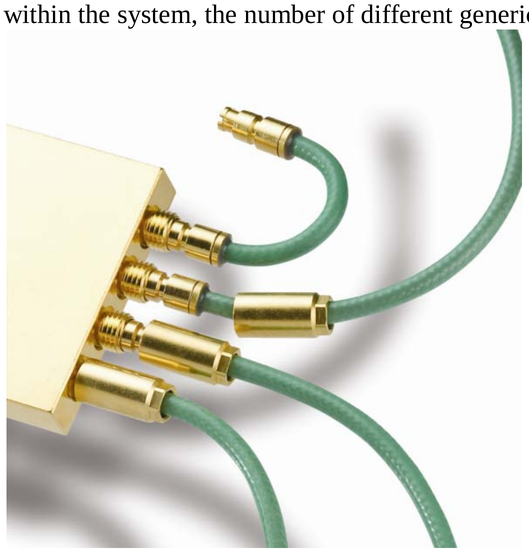

Fig. 6. SMPM-T connector and cable assembly solution for reducing system size and mass

equipment (n), the base failure rate for each part (λ_g), and the quality factor for each part (π_Q). The reliability prediction shows that for a standard semi-rigid cable assembly the mean time between failures in a space-flight environment is 0.0028 failures/10^6 hours. This is four times higher than that of the microbend® cable assembly which has a mean time between failures of 0.0007 failures/10^6 hours under the same conditions utilizing the solderless connector termination method. The microbend® SMPM-T cable to connector solderless junction is further strengthened through the addition of a low-outgassing, two part epoxy that provides a minimum connector retention force of 35 N along with the capability to resist multiple torsion cycles of ±90° in the mated condition.

SMPM-T QUALIFICATION TEST RESULTS

Design validation testing was performed on the SMPM-T connector design for both discrete connector and integrated cable assembly applications. The validation test profile for the discrete connector applications was formulated based upon the screening and qualification test flows defined in MIL-PRF-39012 and NASA EEE-INST-002 [5, 11]. The SMPM-T connector was subjected to the screening test requirements of MIL-PRF-39012, Tables III and V as well as NASA EEE-INST-002, Section C2, Table 2E, Level 1. A random sample from the manufacturing lot of connectors that was subjected to the screening testing was then subjected to the qualification test requirements of MIL-PRF-39012, Table II as well as NASA EEE-INST-002, Section C2, Table 3E, Level 1. The SMPM-T connector design successfully passed the screening and qualification test requirements of these specifications.

The SMPM-T cable connector design validation effort was a more complicated endeavor because of the absence of industry guidance for the screening and qualification testing of cable assemblies. The North American and European industry standards defining product validation testing through a screening and qualification test process have recognized and comprehensively defined the test regimen for coaxial connectors and coaxial cable as discrete components [11, 12]. However, the definition of the validation testing profile for cable assemblies has been left in an ambiguous state by both defense and scientific industry standards. At this time, there is no recognition in published standards of the unique workmanship and performance requirements that are required for the proper attachment of a connector to a coaxial cable for space-flight applications that require qualification. This was addressed for a short period of time by a North American defense industry standard which endeavored to identify and screen for specific performance characteristics that are unique to cable assembly workmanship variances [13]. However, this specification was never developed completely to cover all of the product types or the screening and qualification criteria necessary and eventually fell into disuse and ultimately obsolescence.

To define the screening and qualification profiles necessary, a study was performed of both current and obsolete specifications issued by government and commercial standards organizations. A screening and qualification profile was developed that would completely define the performance, workmanship, and features of a coaxial cable assembly for space-flight applications. The SMPM-T cable connector, as a component of a microbend® cable assembly, was subjected to the screening test requirements of MIL-DTL-17, Tables V and VI, MIL-PRF-39012, Tables III and V, MIL-PRF-55427, Tables II and IV, ECSS-Q-70-20, NASA EEE-INST-002, Section C2, Table 2E, Level 1 and Section W1, Table 2C, Level 1, as well as non-destructive radiographic inspection [14, 15]. A random sample from the manufacturing lot of cable assemblies that was subjected to the screening testing was then subjected to the qualification test requirements of MIL-DTL-17, Table IV, MIL-PRF-39012, Table II, MIL-PRF-55427, Table I, NASA EEE-INST-002, Section C2, Table 3E, Level 1 and Section W1, Table 3C, Level 1, as well as non-destructive radiographic inspection and additional tailored environmental stress screening and highly accelerated life testing listed in Table 1 [16, 17]. The SMPM-T cable connector design successfully passed the screening and qualification test requirements of these specifications. During the entire duration of all of the screening and qualification test profiles, the coupling nut never loosened or backed off of the mating connector threads. The electrical stability and RF leakage of the SMPM-T interface maintained the improved performance levels identified during the design verification testing after completing the entire screening and qualification profile detailed in this section.

Table 1. SMPM-T cable connector dynamics testing in addition to industry standard requirements

TEST PARAMETER	TEST METHOD	PERFORMANCE LEVEL
Random Vibration	MIL-STD-202, Method 214	46.3 G rms
Sine Vibration	MIL-STD-202, Method 204	28 G peak
Mechanical Shock	MIL-STD-202, Method 213	11,000 G peak
	MIL-STD-883, Method 2002	1,500 G peak
Thermal Shock	MIL-STD-202, Method 107	210 cycles: -55°C/+125°C
Constant Acceleration	MIL-STD-883, Method 2001	3,000 G

CONCLUSION

The requirements of space-flight electronic systems to operate at higher frequencies while maximizing payload capacity utilization through the reduction of system geometry and mass is creating the need for miniaturized, highly stable components that is increasingly difficult to address. In this paper the design, performance, and qualification test results of the new SMPM-T connector interface have been presented. The SMPM-T connector has the proven capability to meet the industry demand of smaller size and mass with a reduction of 75% in connector spacing and 85% in connector mass versus SMA interface components while providing highly stable and repeatable reflection, amplitude, and phase performance for applications with operating frequencies of up to 67 GHz.

NOTES

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