Power Sub-Miniature (PSM) Connectors for Space Applications

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ABSTRACT

This paper presents a newly developed SMA-like connector for High Power Space applications that can withstand more than 1500 Watts in the P- and L-Band for a pulsed signal of 2% duty-cycle. This implies an improvement of 50 per cent compared to other powerful connectors such as TNC while the mass is reduced by more than 60 per cent with respect to a TNC connector. In the L-band a 7th order PIM power of less than -140dBm has been measured for input powers of 47dBm per carrier. The frequency range is 0 – 18 GHz, the insertion loss <0.1 dB (typical <0.05 dB), and the VSWR <1.1 in the full range.

1 INTRODUCTION

The current trend in microwave devices, on board of space telecommunication systems, leads connector designers to deal with specifications of devices able to cope with higher frequencies as well as higher input powers without limiting any of their features, and still working properly. This trend is due to the market demand of increasing the amount of information that telecommunication satellites have to be able to manage within a framework of a society that has become more and more dependent on communications through different services as GPS, GSM, meteorology, space missions, etc…. At the same time, the need of reducing costs for launching satellites increasingly forces the weight of the devices inside them to be reduced. Also low Passive Intermodulation (PIM) performance is important as future satellites will be using multicarrier technology more often.

SMA RF connectors are still the preferred connectors in space telecom missions because of their light weight and small size. However, this type of connector has serious limitations in terms of the required RF power handling. Therefore, for power levels exceeding some 10W, one is still forced to use the heavy and bulky TNC connectors.

In this paper a new connector design is presented that has the size and the mass of the standard SMA connector but in terms of power handling comes close to or even exceeds the performance of TNC connectors. This connector can be used as a direct replacement of the SMA connector. It has been developed in the framework of the activity ”High Power SMA Connectors", (ESA Contract No.20967/07/NL/GLC), funded through the ESA Advanced Research In Telecommunications Systems (ARTES) programme.

To achieve this ambitious goal, first suitable theories of PIM, corona discharge, Multipactor and thermal heating in coaxial structures had to be established or adapted from known similar problems. Second, the power limiting effects in SMA connectors like the internal air gap and all the thermal issues had to be identified and eliminated by appropriate changes of the connector design. Third, suitable materials for the individual parts and the manufacturing process of the new high power PSM connectors were analysed and selected.

Engineering samples of PSM connectors for different cable types (EZ141, EZ250, UT215, SF304, SF106) and various cable assemblies have been fabricated and characterised. Additionally, chassis connectors and adaptors have been designed and manufactured.

Recent high power tests carried out at the joint ESA-VSC high power RF laboratory in Valencia (ES) at 438 MHz, showed that the PSM connectors withstand at least 1500 watts which implies an improvement of 50 per cent compared to other powerful connectors such as the TNC. Another test conducted at 1124 MHz showed the connectors could withstand at least 1500 watts (pulsed). Using CW signals (power handling tests) the PSM connectors were tested up to 100 watts at the same frequencies. All these results have been achieved without compromising the excellent low power
The achieved results are fully in agreement with the required specification values, in some cases even better.

2 DESIGN OF THE PSM CONNECTOR

The design of the PSM connector is shown in Fig. 1. Here a schematic drawing of a male and a female cable connector for Sucoflex 304 (SF304) cable in mated condition is shown. The overall diameter of the PSM connector is that of an SMA. Additionally, the same torque wrench can be used.
The basic design difference to a common SMA connector is the use of the hexagonal structure cut into the nut. This provides a maximum of the sizes of the inner conductor and the dielectric. Further differences to other connectors are the angled shape of the dielectric in the connector-connector interface and the stair-like shape of the dielectric in the interface towards the coaxial cables. Suitable venting holes guarantee a proper venting of the connectors.

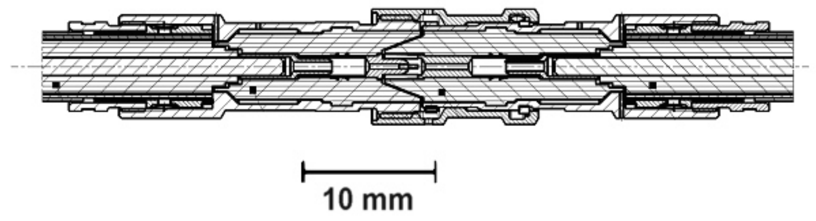

Fig. 1: Schematic drawing of the mated PSM connection


Fig. 2: Photograph of a ceramic coated PSM connector soldered to a EZ141 cable.

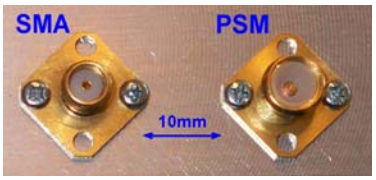

Fig. 3: Photograph of an SMA and a PSM chassis connector (top view)

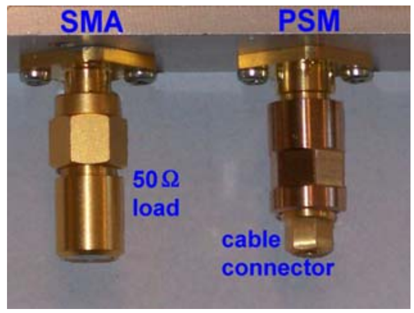

Fig. 4: Photograph of both connectors from the side mated with a 50 Ω termination (SMA) and a cable connector for semi rigid 141 cable (PSM)

A variety of different PSM connectors have already been fabricated including male cable connectors for semi rigid 141, semi rigid 215 and 250 cables, and flexible SF304 and SF106 cables, ½ " chassis connectors, and a few adapters to TNCA connectors. Fig. 2 shows a photograph of a male PSM cable connector soldered to an EZ141 cable. The silver looking nut of the connector is made of copper-beryllium plated with a special ceramic layer for achieving a higher emissivity value (for better heat removal in vacuum).
Fig. 3 shows a photograph of an SMA and a PSM chassis connector in top view, Fig. 4 a photograph of both connectors from the side mated with a 50 Ω termination (SMA) and a cable connector (PSM).
The chassis connectors have the same ½ " mechanical footprint. The outside diameters of SMA and PSM cable connectors or terminations are the same (Fig. 3). The interface dimensions, however, are different: the PSM has an inner conductor with a diameter of 1.7 mm and 5.5 mm for the dielectric whereas the corresponding dimensions of the SMA are 1.27 mm, respectively 4.1 mm. Additionally, the PSM connector has optimized air gaps inside reducing the risk of Corona and Multipaction breakdown and allowing higher operational powers than a standard SMA.

3 MULTIPACTION AND CORONA STUDIES

Making connectors more compact by reducing the dimensions of the waveguides leads to an increase of the electromagnetic field strength in the inside. This greatly increases the risk of Multipactor and Corona discharges to occur with the danger of destroying a part of or the complete telecommunication system.
Mechanical tolerances are inherent to any manufacturing process and lead to gaps within microwave devices where, in the framework of space applications, the motion of highly energetic electrons can be in resonance with the RF fields. Multipactor breakdown occurs when these electrons impact against the boundaries of the gaps with enough energy to

release other electrons from the boundaries. These electrons are accelerated as well and may also release new electrons when impacting against the walls of the gaps and so on, with the subsequent onset of the electron avalanche. The electron cloud produced generates noise inside the microwave devices degrading the performance of the system, it increases the return losses and it may also cause damage to the component over time, destroying it partially or completely.

Unlike Multipactor breakdown, Corona discharge occurs at higher pressures when electrons impact against gas molecules trapped within the above-mentioned gaps. If the energy of the electrons is high enough they can ionize the gas molecules releasing new electrons from their external shells. If the average number of collisions per unit time is near the RF frequency of the signal, the electron population within the gap increases quickly and a glow produced by the radiation of the electron cloud, accelerated by the RF fields, indicates the onset of the Corona discharge [1]. Corona discharge produces similar undesired effects as Multipactor, namely in the Telemetry, Tracking and Control system (TTC) of the satellite during launch as well as in the case of re-entry vehicles during the exploration of planets and their moons. The current produced by the moving electrons produces a highly local heat within the gap, being able to partially or totally destroy the onboard components.

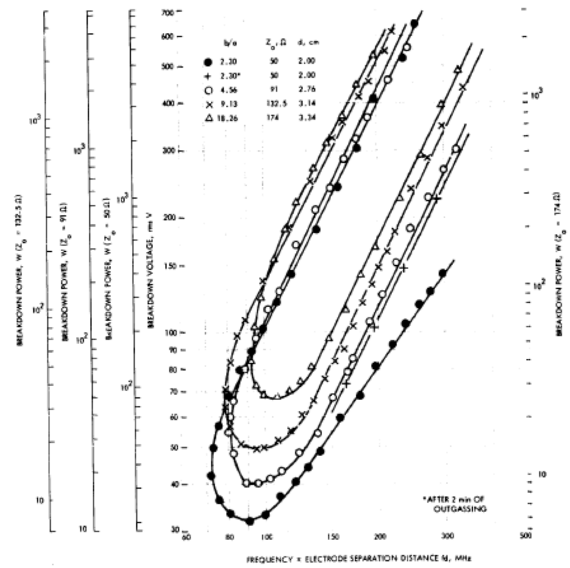

Fig. 5: Coaxial multipactor susceptibility chart

Avoiding Multipactor and Corona discharges for any device and any geometry still constitutes a challenge since both effects are not fully understood and different approaches, assuming different approximations, have to be considered. Fig. 5 shows a principal curve of the frequency-breakdown field strength relation of a coaxial wave-guide [2]. The main challenge is to find a connector design that shows a minimum as high as possible.

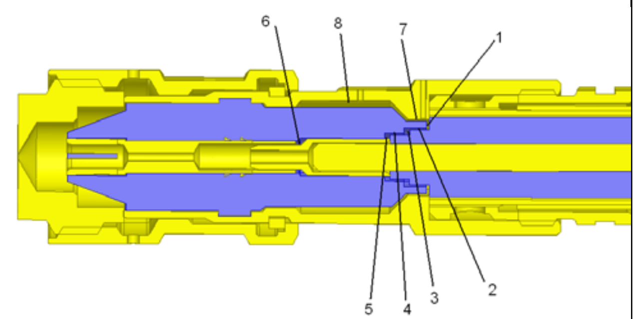

Fig. 6: Gaps in the connector cable interface area

Dealing with the multidisciplinary problem of optimizing the design of a light coaxial connector able to withstand high input powers avoiding Multipactor and Corona breakdown and still working properly at high temperatures is a non-trivial task. Frequently, improving some characteristic of the connector may make another one worse. Therefore, the design of a connector becomes a trade-off between the different properties that the connector must show according to the market requirements.

Fig. 6 shows details of the air gaps to be considered of the connector-coaxial cable interface of the current PSM design. Each gap has to be individually studied and optimized in order to achieve a satisfactory compromise.

4 THERMAL STUDIES

The cable assemblies are to be used for high power signal transmission in a vacuum environment. The knowledge of the overall power limits (in terms of maximum operating temperature) and the expected influences on mulcopim effects are highly desirable.

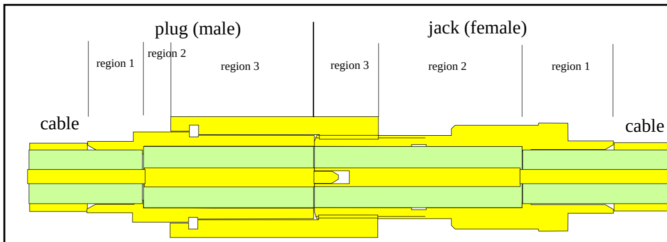

Fig. 7 General schematic of a mated connection (metals are coloured yellow, insulators green)

A theory for the temperature distribution in a coaxial cable assembly has been developed that provides local temperatures at (nearly) any point of the assembly including the inner conductor and connection points. The equivalent thermal circuit is used to derive the temperatures under cw- and pulsed conditions.

For the evaluation of the thermal circuit components of the coaxial cable assembly the cable and the connectors are split into a sufficient number of segments. For each segment an equivalent circuit is established.

A general schematic of a mated connection is shown in Fig. 7. Each connector (male and female) is split into 3 regions that are basically arbitrary but should make some physical sense. For very simple connectors sometimes a description with only one region is sufficient. The cables are described with a similar model (normally with 6 identical regions).
For each region the dissipated power, the heat flow and finally the temperature distribution are calculated with an appropriate simulation tool like ADS.

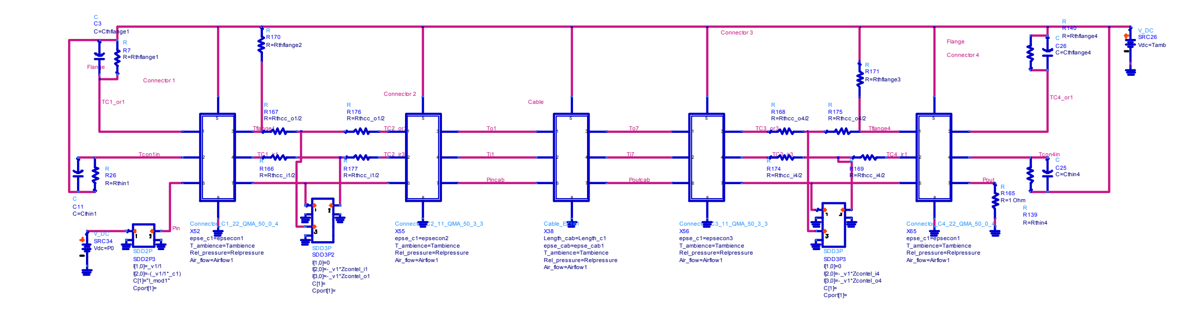

Fig. 8: Schematic diagram of a cable assembly mated on either side with a flange connector

The schematic diagram of a complete mated cable assembly including two flange connectors is shown in Fig.8. The cable and each of the connectors are represented by one sub-circuit each. The connectors are named (from left to right) C1, C2, C3 and C4. The RF-power is fed into C1 and goes through C2, the cable and the connectors C3 and C4 to the end load on the right.

As a typical example Fig. 9 shows the calculated temperature distribution along a PSM-SF106 cable assembly for 100W input power at three different frequencies. It can be seen that this assembly can be operated at all three frequencies with 100 W RF-power. The temperatures stay well below 160°C (160°C at the hottest point is regarded as criteria for maximum cw operating power of this kind of cable). The strong decay of the temperatures at either end are due to the relatively low thermal impedances of the connector flange to housing transitions.

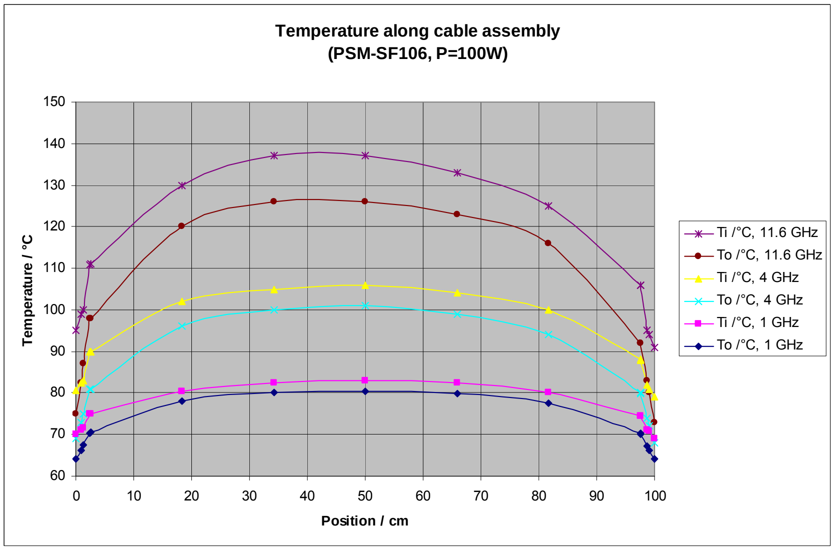

Fig. 9: Temperature distribution along a PSM-SF106 cable assembly for 3 different frequencies with input powers of 100W. (Ti = temperature of inner conductor, To = temperature of cable jacket)

5 PASSIVE INTERMODULATION

Passive Intermodulation effects have become of great importance especially for satellite communication applications. One of the devices that can be responsible for the generation of PIM is the coaxial connector. In metal-to-metal interfaces PIM can be expected due to both microwave current flow over nanometric hillocks on the relevant metal surfaces due to machining [3, 4] or via metal-insulator-metal tunnelling currents. In the former case this would be strongly dependent on applied pressure as demonstrated in Waveguides [5].
But measurements on coaxial components are more complex since there is no direct control of applied pressure available. Typical coaxial connector designs were used in the studies presented here, both experimentally and theoretically. The results indicate that PIM is again produced primarily by metal surface roughness. However other concepts are also being considered such as tunnelling across metal-insulator-metal junctions.
Of great importance to the generation of PIM is indeed the shape of the male and female conductor parts inside the connector pair. Especially the female conductor needs to be designed very well as it has to serve two functions: an electrical and a mechanical one. It needs to provide good electrical contact while being mateable, i.e. it is basically a

mechanical spring that provides sufficient pressure for the electrical contact and sufficient mechanical tolerance for the male part. There are a lot of constraints in designing a good conductor pair as the requirements are mostly opposing.

For the proposed PSM connector a low PIM performance has been achieved by a careful material selection and an appropriate design of the current path in the connector. In order to validate the PIM performance, the characterization of PSM connection has been performed by the European High Power RF Laboratory in Valencia.

For the PIM measurements, a setup as depicted in Fig. 10 has been employed. The continuous wave excitation tones are at 1530MHz and 1560MHz with a power of up to 50W per carrier. For combining the input carriers, a diplexer with low PIM level is used. A second low PIM diplexer is used to separate the PIM frequency from the input signals. The input signals are routed to a quiet load while the PIM frequency is amplified and detected by a spectrum analyzer. The measurement of the PIM level has been done at 1650MHz (7th order). The noise level of the detector was around -155dBm.

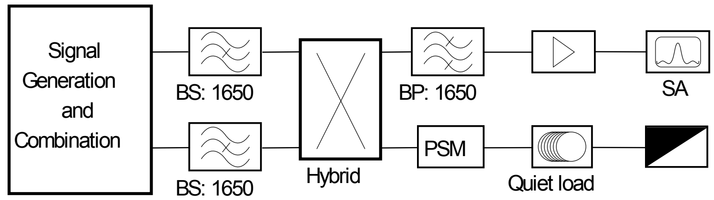

Fig. 10: PIM measurement setup. The connections from hybrid to band stop (BS), band pass (BP) filter and PSM are done with contact less connectors.

The device under test was a PSM to PSM connection: A cable assembly with a male PSM and a contactless connector was connected to a quiet load with a female PSM. The quiet load consists of a 15 m long coaxial cable with resistor terminator. The DUT is connected to the measurement setup via the contactless connector.

The dependency of the PIM level as a function of the combined power of the carriers has been checked. Fig. 11 shows the result of such a measurement where both carriers have the same power. As expected, the PIM level increases with the input power. At an input power of 47dBm per carrier, the PIM value is -140dBm. The internal PIM level of the measurement setup is not exactly known and the measured characteristic might be caused by the system itself. Therefore the PIM level of the connector is at least -140dBm at this input power.

The slope of the linear fit is about 3dB/dB. This is well below the value of 7dB/dB predicted by a 7th order Taylor expansion. This deviation can be explained by the saturation of the PIM level that normally is observed at high input powers [5]. We expect that at a lower input power the slope of the PIM level is increased.

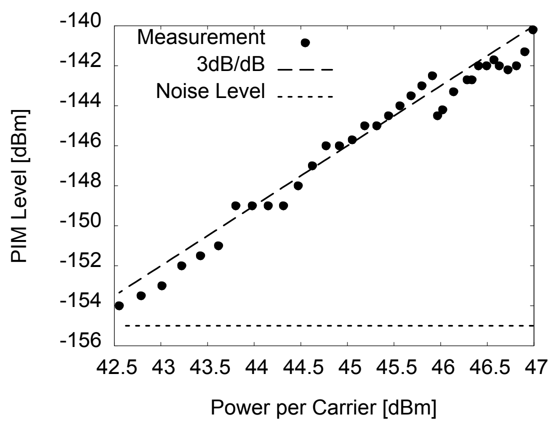

Fig. 11: Measured PIM level as a function of the power per carrier.

6 RESULTS

RF low power measurements showed an insertion loss of the PSM connector of less than 0.1 dB (typical <0.05 dB) and a VSWR of less than 1.14 in the full frequency range from 0 to 18 GHz.

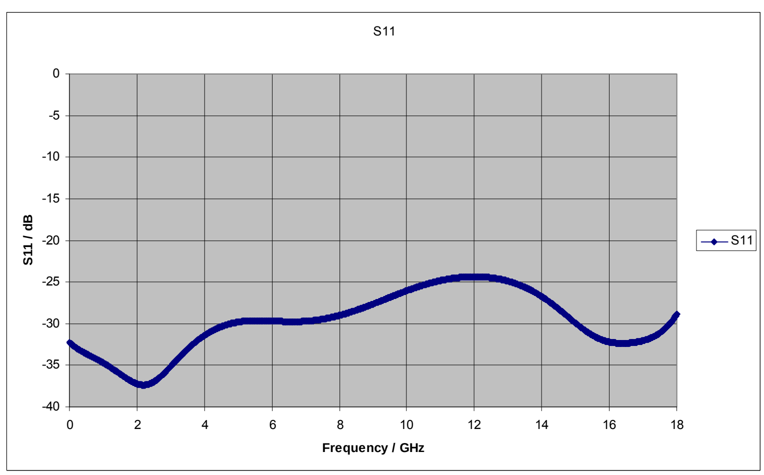

Fig. 12: Gated S-parameter measurement of the PSM connector.

The simulated and measured RF high power results are shown and compared to the requirements in the following tables. The green fields simply indicate a pass. Generally we found that the design is – in terms of high power transmission - close to the physical limit of the chosen small geometry of connector and cable. With regard to the high power vacuum requirements shown in Table 1 all fields are in green, i.e. the requirements are met, especially those for real operation powers. The tests have as usual a 3 or 6 dB margin on top.
Moreover, recent high power tests of the PSM connector carried out at the joint ESA-VSC high power RF laboratory in Valencia (ES) showed a very good performance regarding Multipactor capabilities in P-band (438 MHz) as well as in L-band (1124 MHz), being able to withstand at least up to 1500 Watts input power, for a pulsed signal of 2% duty-cycle, without showing any trace of Multipactor discharge. This implies an improvement of 50 per cent compared to other powerful connectors such as TNC.
Concerning Corona breakdown the PSM was able to withstand more than 60 Watts input power, for a pulsed signal of 2% duty-cycle, without showing any sign of glowing or noticeably discharge, what constitutes a challenge for coaxial connectors at these input powers.
The results of the PIM measurements are listed in Table 2. It depicts a result of less than -140 dBm (7^{th} order) at a frequency of 1.65 GHz.

Table 1: List of high power vacuum requirements and results (green means pass)

type	band	f / GHz	operating power	test power	test	time
Corona	L-band	1	40 W	80 W		cw, 10 min
	C-band	4	30 W	60 W		cw, 10 min
	Ku-band	11.6	30 W	60 W		cw, 10 min
High Power CW	L-band	1	50 W	100 W		cw, 10 min
	C-band	4	50 W	100 W		cw, 10 min
	Ku-band	11.6	50 W	100 W		cw, 10 min
High Power Pulsed, Multipactor	L-band	1	200 W	800 W		T=1ms, 2% dc
	C-band	4	180 W	720 W		T=1ms, 2% dc
	Ku-band	11.6	150 W	600 W		T=1ms, 2% dc

Table 2: List of PIM requirements and results

	band	carrier frequencies	carrier power	acceptance criteria	test
PIM	L-band	1.65 GHz	50 W	3rd order power <-140 dBm	7^{th} order

Table 3 shows the compliance matrix of the measured cable assembly and the specifications

Parameter	**Value**	**Unit**	**Compliance**	**Remark**
FREQUENCY RANGE	DC-18	GHz	yes	
IMPEDANCE	50	Ohm	yes	
VSWR	1.05 max 1.25 max	--	yes	At Lower band At higher band
INSERTION LOSS	0.05 max 0.15 max	dB	yes	At Lower band At higher band
RF LEAKAGE	< -60	dB	yes	EMC
INSULATION RESISTANCE	> 10	MOhm	yes	
CONTACT RESISTANCE	< 2.0	mOhm	yes	Centre contact
CONTACT RESISTANCE	<2.0	mOhm	yes	Outer contact
WORKING , DELECTRIC AND RF VOLTAGE	--	V		Driven by Multipactor requirements

Parameter	Value	Unit	Compliance	Remark
MULTIPACTOR THESHOLD	See Table 1	W	yes	2% duty cycle
HIGH POWER HANDLING	See Table 1	W	yes	cable limit at higher frequencies
CORONA THRESHOLD	See Table 1	W	Yes	OK in all bands
PIM PERFORMANCE	See Table 1	dBm	L-band yes, Ku-band tbd	no suited measurement setup available for Ku-band
Mechanical characteristics (as in MIL-STD-202)				
DURABILITY	100	mating	yes	
MATING/UNMATING (TORQUE)	< 150	N.cm	yes	result: < 30 N cm
RECOMMENDED MATING TORQUE	100	N.cm	yes	
PROOF TORQUE	150	N.cm	yes	OK with test force 170 N cm
COUPLING MECHANISM RETENTION FORCE	250	N	yes	
CABLING RETENTION FORCE	>250	N min	yes	Retention force OK. Cable not capable to handle the required torque and twisted in itself
CENTER CONTACT RETENTION	≥ 27	N	yes	
MASS	0.004	Kg	yes	Flange connector
VIBRATION	i.a.w. Levels specified in ECSS 3402 Para 9.10		yes	
SHOCK	i.a.w. Levels specified in ECSS 3402 Para 9.11		yes	
Environmental characteristics (MIL-STD-202)				
TEMPERATURE RANGE	-65 … +125	°C	yes	Thermal vacuum test
LEAKAGE (VENTING RATE)	Pressure 3.5 bars; duration 2 min. temperature 15°C to 25°C		yes	from pump down curves in measurements

6 COMPARISON WITH COMMERCIALLY AVAILABLE SPACE GRADED CONNECTORS

RF low power measurements showed an insertion loss of the PSM connector of less than 0.1 dB (typical <0.05 dB) and a VSWR of less than 1.1 in the full frequency range from 0 to 18 GHz. This is fully comparable to any other high-quality connector like the SMA.
In principle the PSM connector exceeds the low power performance of the SMA connector as the gap of the SMA interface has a large field of tolerance that can lead to high return losses above -20dB.

RF high power: First of all the simulated and the measured high power characteristics of the PSM cable assemblies are excellent. The design is – in terms of high power transmission - close to the physical limit of the chosen small geometry of connector and cable.

Moreover, recent high power tests of the PSM connector carried out at the joint ESA-VSC high power RF laboratory in Valencia (ES) showed a very good performance regarding Multipactor capabilities in P-band (438 MHz) as well as in L-band (1124 MHz), being able to withstand at least up to 1600 Watts input power, for a pulsed signal of 2% duty-cycle, without showing any trace of Multipactor discharge. This implies an improvement of 50 per cent compared to other powerful connectors such as TNC. Fig. 13 shows a graph indicating the different Multipaction threshold levels of PSM and SMA connectors. Additionally, an indication of the level of the best TNC connectors is given. The difference between PSM and SMA is huge.

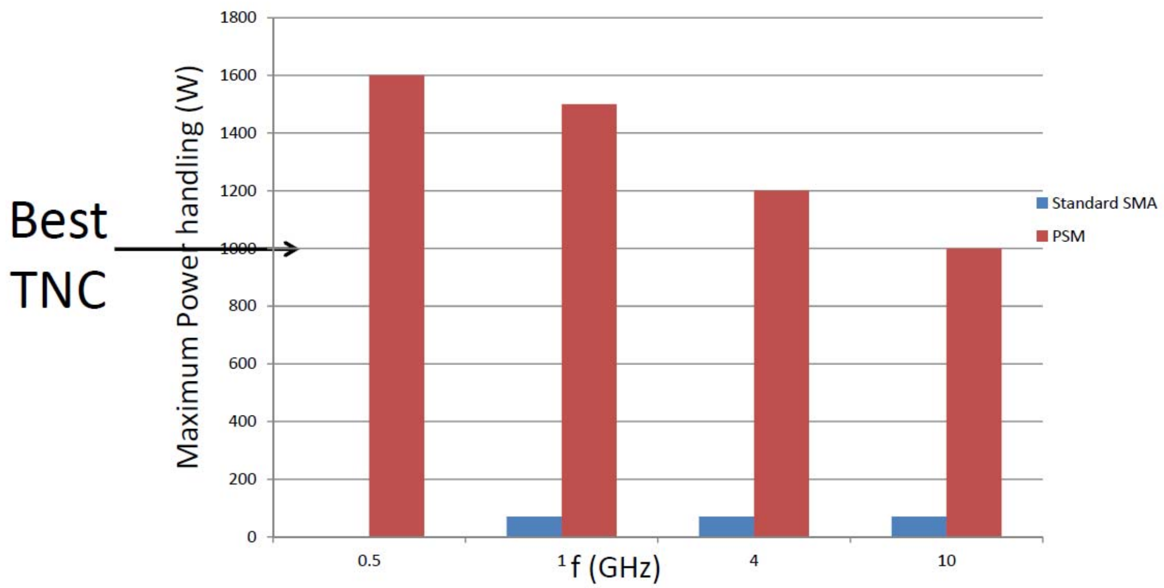

Fig. 13: Comparison of multipactor threshold of PSM and SMA connectors

Concerning Corona breakdown the PSM was able to withstand more than 60 Watts input power, for a pulsed signal of 2% duty-cycle, without showing any sign of glowing or noticeably discharge, what constitutes a challenge for coaxial connectors at these input powers.

Comparisons of power performance of space grade connectors is a difficult task as hardly any data is available. Moreover, the maximum cw power frequently is limited by the applied cable and not the connector. So, to really justify about the power performance of a cable assembly one need to know all details of the assembly and on the way it is mounted.

The situation gets worth when going to space applications. Some data about SMA and TNC connectors could be found in [6] . The (re-drawn) results of ref. [6] are shown in Fig. 14.

The Gore-data in this Fig. assume a two-foot free-floating cable, with connectors mounted to a 65°C plate and an ambient pressure less than 10^{-5} torr. The PSM data is also based on 65°C ambient temperature and a mounting of the flange connector to the chassis with thermal resistances of 20 K/W for the outer conductor and 1000 K/W for the inner conductor.

A comparison shows that the PSM is limited by thermal breakdown, it shows no corona and Multipaction. Both other are in the lower frequency region limited by Multipaction or corona. However, in all cases the power values of the PSM-assembly are higher than both others.

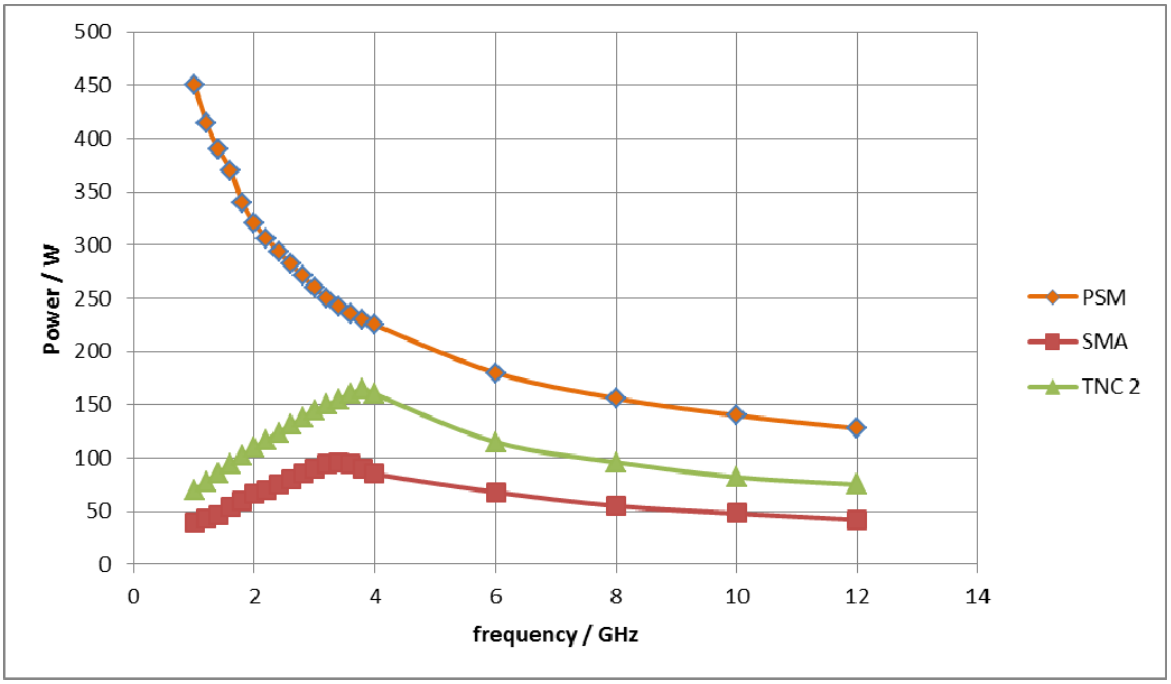

Fig. 14: Power ratings of cable assemblies in space environment
red 0.190”-SMA (from Gore), green: 0.290”-TNC (from Gore), blue SF106-PSM
Rth flange = 20 K/W, Rthi=1000 K/W ,Gore: The data in this chart assumes a two-foot free-floating cable, with connectors mounted to a 65°C plate and an ambient pressure less than 10^{-5} torr.

7 CONCLUSIONS AND FUTURE WORK

The compliance matrix shows that the cable assembly with PSM connectors and SF106 cable fulfills all of the required specifications. The only remaining uncertainty is the PIM performance in the Ku-band. no adequate measurement setup was available for this measurement.

All in all the PSM connector shows excellent performance data exceeding the SMA by far and, especially in terms of Multipaction, has a higher power capability than the much bigger TNC connector.

The next step will be the product development of the PSM connector with the goal of the ESA qualification. The development of an evaluation kit is an additional requirement.

The authors would like to thank ESA/VSC European RF High Power Laboratory for the Corona, Multipactor, High Power CW, and the PIM tests.

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