Final Report
300 W Ku-Band Single FPM

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DVS-No. TD01202923

CHANGE RECORD

Issue	Details of Change	Date
A	Initial issue	2016-12-12

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1 Introduction

1.1 Scope

This document is the final report for the development and qualification activity "300W Ku-Band Single FPM". The work has been carried out within the ARTES 3/4 Telecom Program under the contract 4000106922/13/NL/CLP.

1.2 Abbreviations

Abbreviation	Description
ALC	Automatic Level Control
ATT	Attenuator
BB	Breadboard
BO	Back-Off
CAMP	Channel Amplifier
CAN	Controller Area Network
COB	Chip On Board
EPC	Electronic Power Conditioner
EQM	Engineering Qualification Model
FGM	Fixed Gain Mode
FPGA	Field Programmable Gate Array
FPM	Flexible Programmable MPM
HV	High Voltage
LCAMP	Linearized Channel Amplifier
LV	Low Voltage
MPM	Microwave Power Module
OPA	Output Power Adjustment
TM/TC	Telemetry/Telecommand
TWTA	Traveling Wave Tube Amplifier

2 Background

The subject of this program was the development of a Flexible Programmable Microwave Power Module (FPM) providing a high-power RF output of 300W in the Ku-Band. A FPM consists of a Travelling Wave Tube (TWT) as the power amplifier, a Linearized Channel Amplifier (LCAMP) to preprocess the RF input signal for the TWT and an Electronic Power Conditioner (EPC) with supplies the TWT with high voltages. While a TWT from another ESA supported development activity as well as an LCAMP with minor modifications compared to the applied heritage have been used for the final acceptance tests, the main objective of this qualification program was on the required EPC adaptations.

Conventional EPCs are individually tuned on ground to a particular high-voltage operating point of a specific TWT. The new FLEX functionality allows an adjustment of the TWTs cathode current by Telecommand, even in orbit. Through this the maximum RF output power can be reduced in a way that is more efficient than reducing the RF input drive level of the TWT. The change of TWT gain, which goes along with the cathode current variation, is automatically compensated by the LCAMP. The digitally controlled FPM has implemented a non-volatile memory. This establishes the possibility to store different tuning data sets for EPC and LCAMP. The characteristics of the RF channel can be adapted to its actual needs by selecting an appropriate parameter set.

The main objective for the EPC development activity was to improve the power handling capabilities, to redesign the high-voltage part incorporating a 5 collector design and increasing the high voltage insulation. Furthermore a new TM/TC interface based on CAN has been implemented. It supports a second channel for redundancy as well as the corresponding automatic active bus detection.

The LCAMP design was revised to include minor changes only. The RF line-up was adapted to meet the desired properties of the assigned TWT as well as the overall FPM performance specification.

3 Commercial FPM specification

An overall specification has been established to apply the developed high-power FPM to the market. It defines the electrical, mechanical and environmental requirements as well as the test conditions for the amplifier. They can be adapted to specific needs of a commercial program or as a basis to create a statement of compliance. The following tables summarize some of the the main parameters.

3.1 RF performance

Para.	Item	Requirement	Remarks
3.2.1	**Frequency Range** a) Frequency band b) Operating bandwidth, nominal	 within 10.7-12.75 GHz 500 MHz	
3.2.2	**Saturated Output Power , Pout(sat)** Min. vs. frequency and temperature FLEX range adjustable down to	 300 W min: -3 dB	 @ fcenter
3.2.3	**FGM & ALC Input Power, Gain** a) Power range for Saturation b) FGM Gain control range	 -60 to -24 dBm 36 dB in 100 steps	
3.2.9	**Noise Power Ratio** at Pout/Poutsat: -3 dB -5 dB	 14 dB 19 dB	
3.2.10	**Noise Figure**	min gain: 30 dB max gain: 13 dB	
3.2.16	**DC Input Power** saturation 1 dB FLEX OBO 2 dB FLEX OBO 3 dB FLEX OBO	 495 W 418 W 339 W 278 W	 Strongly depends on TWT DC power

3.2 Main Bus Interface

Para.	Item	Requirement	Remarks
3.3.1	**Power Bus**	50 V	
3.3.4	**Inrush current**	18 A peak	
3.3.9	**Return**	isolated from chassis ground > 1 MOhm and < 500 nF	
3.3.10	**Connector**	9-pin Power connector	see IDS

3.3 Discrete TM/TC Interface

Para.	Item	Requirement	Remarks
3.4.1	**Telecommand**	MPM ON/OFF	
3.4.3	**Bi-Level Telemetry**	Status of MPM (ON/OFF)	

3.4 Serial TM/TC Interface

Para.	Item	Requirement	Remarks
3.4.5	**Telecommands via CAN-Bus**	ARU Enable/Disable: Helix Protection Enable/Disable: ALC/FGM Selection: RF Mute ON/OFF: Output Power Setting: ALC power/FGM Gain setting: OPA Setting:	Enables/Disables the ARU (Enable = Wake Up state) Enables/Disables the Helix protection (Enable = Wake Up State) For LCAMP: select ALC or FGM mode For LCAMP: select RF Mute on/off For EPC and LCAMP: Setting of FLEX power For LCAMP: setting of power/gain level For LCAMP: setting of OPA
3.4.6	**Analogue Telemetries via CAN-Bus**	Helix current Main Bus current Anode voltage LCAMP Temperature LCAMP Input Power LCAMP Output Power	range 5 mA, 8 bits range 10 A, 8 bits range 3000V, 8 bits range 100°C, 8 bits range 35 dB, 8 bits range 15 dB, 8 bits
3.4.7	**Telemetries via CAN-Bus**	AR Enable/Disable AR Status Mode ALC-FGM Mute On/OFF Output Power (FLEX) Setting Power (ALC)/Gain (FGM) Setting OPA Setting Status of helix protection Parameter Set Selection Status	

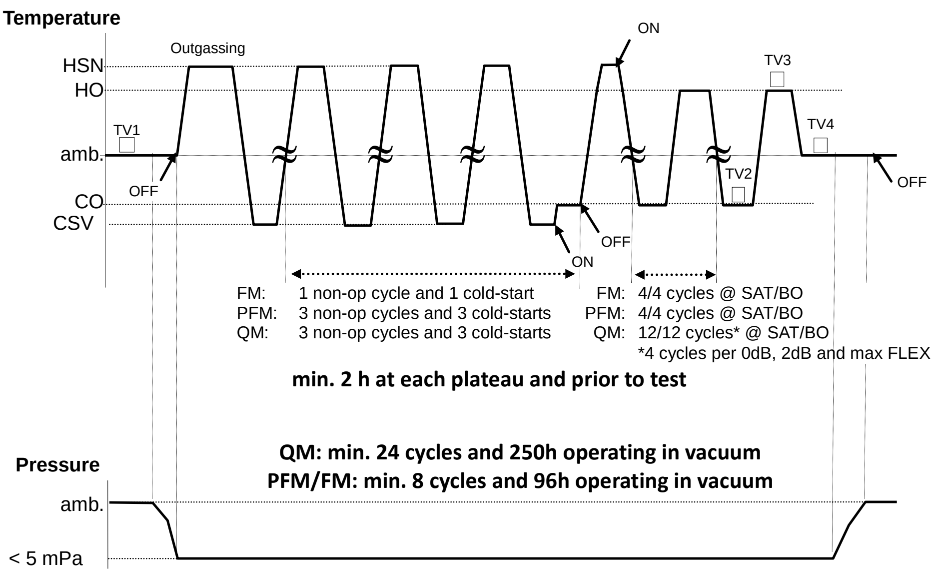
3.5 EMC and Environmental Requirements

EMC and environmental requirements have been derived from the existing broad heritage database. The values have been selected such that the corresponding envelope for the main European, US and Asian customer needs is covered.

3.6 Thermal Conditions and TV profile

The TVAC profile to be applied for the equipment acceptance test is given by the following table and the chart below.

	Condition		Qualification (QM)	Protoflight (PFM)	Acceptance (FM)
HSN	Hot survival temperature (non-operating)	EPC/LCAMP: TWT:	+75 °C +95 °C	+75 °C +95 °C	+70 °C +90 °C
HSV	Hot survival temperature (operating and hot start, maximum 5 min)	EPC/LCAMP: TWT:	+75 °C +95 °C	+75 °C +95 °C	+70 °C +90 °C
HO	Hot operating temperature	EPC/LCAMP: TWT:	+65 °C +85 °C	+65 °C +85 °C	+60 °C +80 °C
amb	Ambient temperature	EPC/LCAMP: TWT:	+30 °C +40 °C	+30 °C +40 °C	+30 °C +40 °C
CO-TT1	Cold operating temperature during thermal test and tuning	EPC/LCAMP: TWT:	-30 °C -5 °C	-30 °C -5 °C	-25 °C 0 °C
CO	Cold operating temperature	EPC/LCAMP: TWT:	-20 °C -5 °C	-20 °C -5 °C	-15 °C 0 °C
CSV	Cold survival temperature (cold start and non-operating)	EPC/LCAMP: TWT:	-35 °C -35 °C	-35 °C -35 °C	-30 °C -30 °C



4 EPC Development

The basis for the EPC development was a former EPC for TWTs up to 170 W RF output. The main new features realized in this project are

- 5 collector design
- Design for voltage generation up to 8.5 kV
- DC output power up to 510 W
- Application of a 13 kV HV-cable in the integration area
- FPGA Implementation “FRED4” with implementation of the CANopen protocol
- Discrete redundant CAN driver
- Definition and realization of Double Insulation requirements

Fig. 4-1 shows the typical structure of an EPC consisting of a HV- and a LV-section. In this way is also realized this project.

A general non-functional topic was the realization of a best trade-off between design for manufacturing, electrical functionality and weight/dimension.

4.1 LV-section

The LV-section itself can be divided into a power- and a logic part. The power part consists of an input filter and the subsequent converters. The boost converter provides the preregulated voltage for the power converter, which controls the HV-transformer on the HV-section. A further converter, the auxiliary converter, provides all voltages, for example for operational amplifiers, the FPGA supply voltages and the secondary power supply for the LCAMP.

The logic part includes amongst others the FPGA, which is responsible for interpreting alarm signals or for many control signals, for example for triggering the converters. Furthermore the logic part includes the TM/TC interface. The CAN transceiver itself is realized on a separate board, the so-called Interface-Board shown in Fig. 4-2. The CAN transceiver is realized in a discrete structure (build of comparators, transistors, diodes…) and no CAN driver IC (integrated circuit) is used. The CAN transceiver is galvanic isolated and is build up redundantly, which means two paths are realized. The path where the communication is actually running is automatically detected by the FPGA through edge-detection.

The so-called FRED4 FPGA was re-engineered. Now the CANopen protocol is implemented according to the recently issued ECSS recommendation.

On the LV-section Double Isolation areas are defined and measures for this purpose are defined and implemented in the layout.

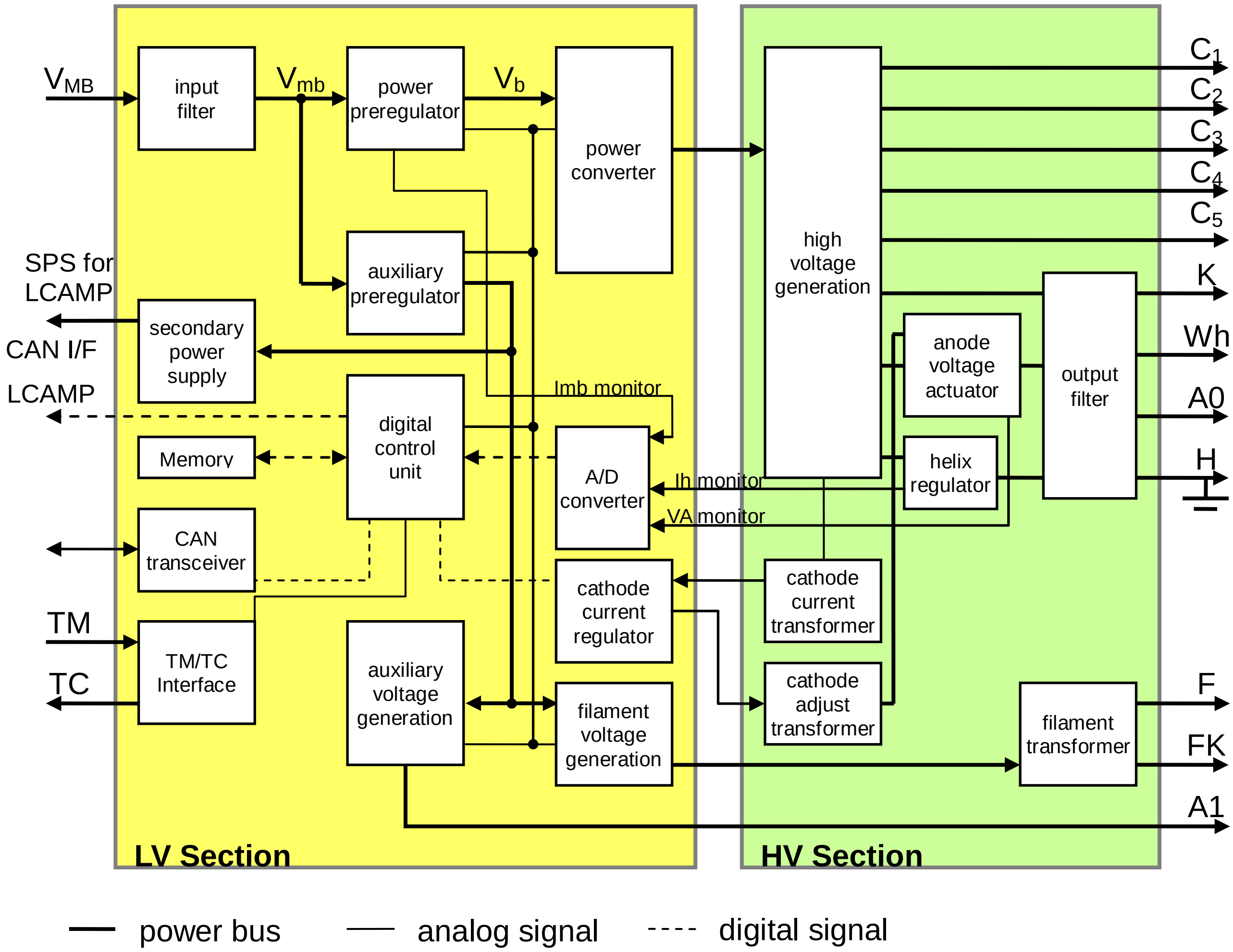


Fig. 4-1: EPC block diagram

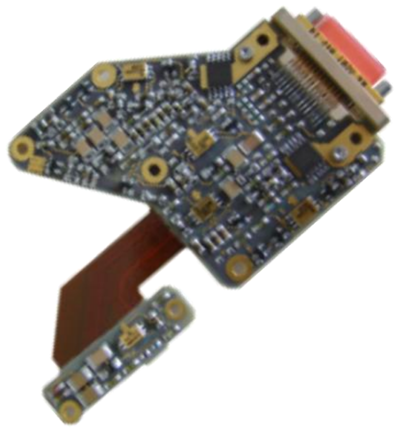


Fig. 4-2: Interface Board

4.2 HV-section

The HV-section generates the different high voltages for the TWT. In this project a 5 collector design was realized and the HV design had to be dimensioned for voltages up to 8.5 kV. This voltage is significant higher than in standard designs and therefore the design and also the components had to cope with this requirement. A good PCB layout was important to meet all necessary isolation distances between different potentials. Also new components had to be introduced, for example HV-capacitors.

Due to the high voltages the HV-cable between the EPC and the TWT is now a 13 kV cable, which has an influence to the thickness of the cable and its handling. The adapted integration area within the EPC where the TWT cable is connected to the EPC was successfully evaluated.

The output RF power is proportional to the cathode current. This current depends again on the regulated anode voltage. To fulfill the requirement of adjusting the output power in a wide range, it is also necessary to have the possibility to adjust the anode voltage over a large range. This task takes over the so-called COB-modules (chip-on board). The cathode current regulator placed on the LV-section can control these COB-modules on the HV-section which control the anode voltage in a range of around 2.5 kV.

4.3 Analysis

Beside all the hardware tests, the development had foreseen different analyses. These analyses were already done in the development process so that several iterations were possible to get the best design result. Below are all the performed analysis shortly presented.

4.3.1 Mechanical Analysis

The EPC housing with the integrated LCAMPs were mechanically analyzed with the finite element software ANSYS. The model verified successfully that the housing withstands all defined static and dynamic loads. This result is confirmed by a successful hardware vibration test.

4.3.2 Thermal Analysis

A thermal consideration and the results from it are very important in the development process. Therefore a thermal software model was build consisting amongst others of the EPC housing, PCBs and the mounting points. The power dissipations of the different parts and modules were added in the model and the resulting heat flow and the influence of different measures were evaluated. Finally a satisfied thermal concept was developed which is successfully confirmed in the thermal mapping of the hardware.

4.3.3 Worst Case Analysis

The Worst Case Analysis considers effects like initial tolerances, radiation effects, temperature effects and aging effects. The aim of this analysis is to understand the behavior of the device with influence of all these effects and to guarantee correct functionality over the whole life cycle. A test of all these mentioned influences in hardware is not or only very difficult to realize due to limited time and only one available test device. Within the Worst Case Analysis the EPC was divided into different sub circuits which were analyzed separately. In summary there were no weaknesses or problems detected.

4.3.4 Failure Modes, Effects and Criticality Analysis

In this analysis different functional blocks of the EPC are identified and for each block failure modes are assumed. Based on these failure modes the effects on other functional blocks or even the whole system are determined. Also single event effects and their impact on other blocks are taken into account. The provided analysis gives a good overview of failure propagation and detection. The received failure modes are categorized in different levels depending on their criticality.

5 LCAMP Development

The LCAMP RF line-up was slightly adapted to meet on the one hand the overall FPM specification regarding e.g. input power and dynamic range; and on the other to deliver sufficient RF output power to drive the new 300W Ku-Band TWT. This TWT requires a higher input power, therefore one more RF amplifier including its DC power supply was introduced into the LCAMP output section. Furthermore an additional RF amplifier was placed as a first element in the RF line-up to improve the noise figure. The LCAMP implements the operating modes FGM and ALC of the FPM as well as the OPA and supports the FLEX functionality by gain compensation.

5.1 Fixed-Gain Mode

In Fixed Gain Mode (FGM) the gain in the input channel amplifier section can be adjusted over a large dynamic range to cover the specified input power range.

To keep the requirement for a maximum step size of 0.5 dB, the nominal input dynamic range (36 dB) plus margin on the low and high end must be divided into a sufficient number of gain states. It was chosen to have 100 gain steps (state 0...100) to get a typical step size below 0.5 dB.

5.2 ALC mode

In Automatic Level Control mode (ALC) the detector inside the ALC module is used to keep the input level to the ALC attenuator constant. Variable gain modules are used to compensate for input drive level changes. For input drive levels above the specified input power range the ALC dynamic just extends to the maximum specified overdrive level. For drive levels below the specified range the ALC circuit operates continuous until it is below a certain level. This is to avoid a gain increase at very low input levels or no-drive with the effect of high noise output power. For ALC steps the attenuator inside the ALC module and variable gain module is used. The quantity of steps is 63 (state 0...63) to get a typical steps size below 0.5 dB.

5.3 OPA setting

The purpose of the OPA is to have the possibility for compensating the drift of the TWTs gain over life. The dynamic is typ. 6 dB with the setting of mid-range at BOL. The quantity of steps is 15 resulting in fine steps typically a bit less than 0.5 dB. With that small stepsize a good fine-tuning can be achieved. The OPA setting is available in all operating modes and is done with the last gain block.

5.4 FLEX setting

To compensate the variation of the TWT input power operating point over the FLEX range, the LCAMP will be stepped up and down synchronously with the FLEX-stepping of the EPC. Due to the fact that the TWT needs an increased input power for saturation drive at back-off, the LCAMP has to provide the required RF-power to operate the TWT for each setting of TWT operating point (FLEX setting). The range of 3 dB FLEX of the TWT corresponds to some typical 10-12 dB variation of input power to the TWT. The exact value varies from TWT to TWT and must be tuned individually for each TWT to achieve best performance and synchronization with the EPCs high voltage setting.

6 Equipment design

The electrical and mechanical design of the equipment has been carried out according to the established internal design rules to meet the above outlined requirements and functions. The manufactured EPC with integrated LCAMP is shown in the following picture.

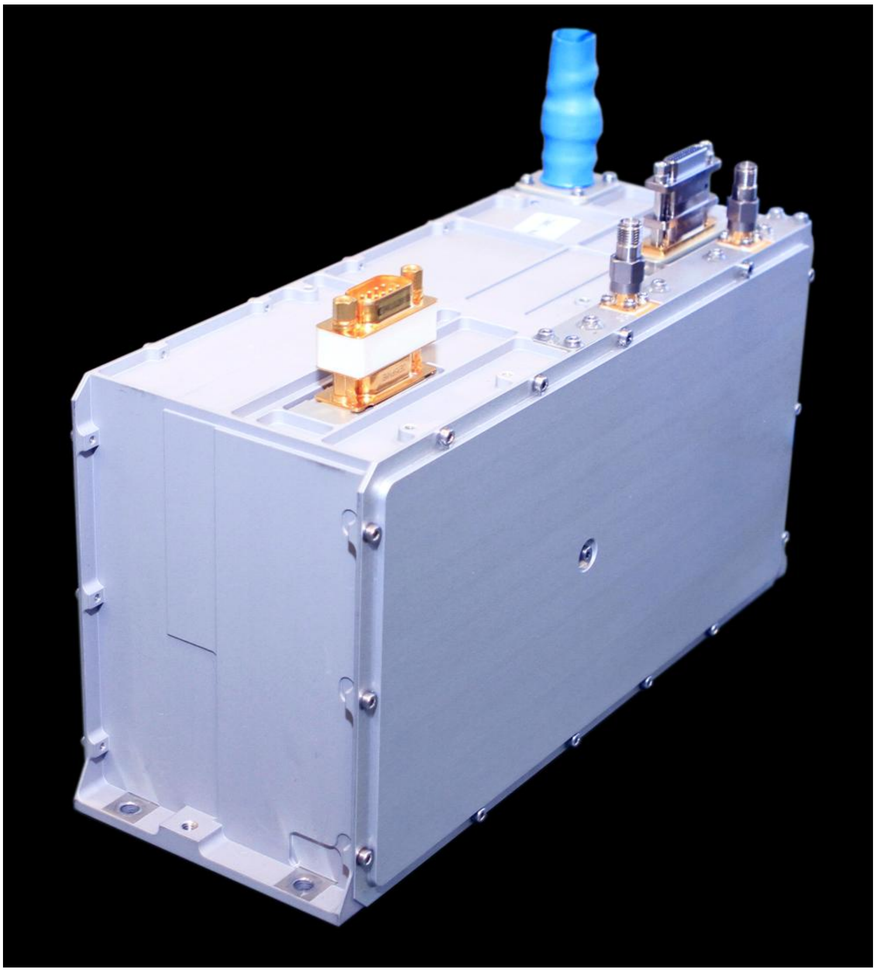


Fig. 6-1: EPC hardware

7 Qualification Test Campaign

The EQM of the 300W Ku-Band FPM was subjected to the following test flow:

Test	
INT	Integration Test
IFT	Initial Functional Test
TT1/2	Thermal Test cold/hot
VT	Vibration Test Resonance Survey Sine Vibration Random Vibration Resonance Survey
PVT	Post Vibration Test
Shock	Shock Test
PST	Post Shock Test
TVT	Thermal Vacuum Test Critical Pressure Test Functional Tests Cold / Hot Start Cycling Tests Total operating time of 250h Critical Pressure Test
EMC/ESD	EMC and ESD Test
FFT	Final Function Test

A full test plan, also covering most of the needs of usual commercial programs, has been developed and reviewed. It can be found in the corresponding CDR data package. The following FPM test matrix summarizes all performed tests on the 300W Ku-Band FPM:

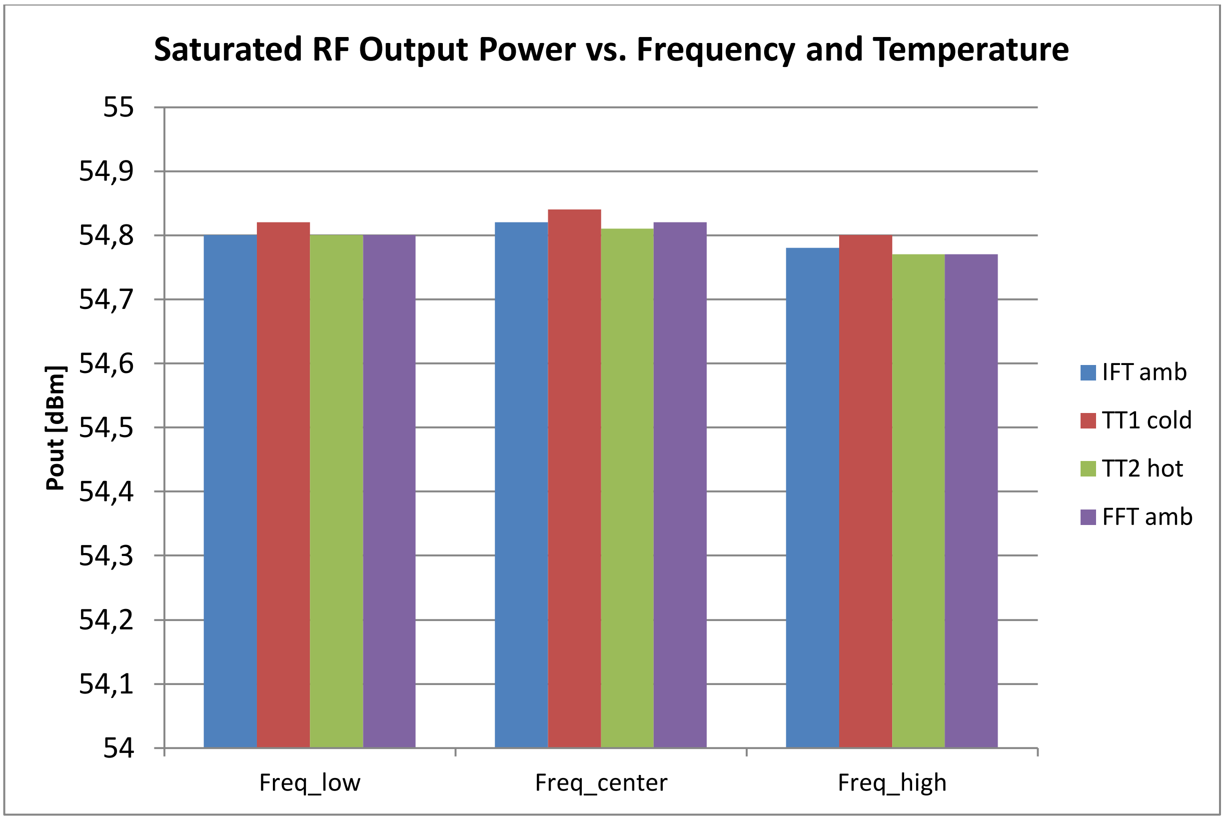
§	Test	Condi-tions	Drive	IFT	TT 1,2	VT	PVT/ PST	TV1	TV 2,3	TV4	FFT
1	Input Power, Output Power, Gain	F1-5, P	s,b,z,f /u	x	x	m	x	x	x	x	x
2	Output Power and Gain stability	F1-5, P	s,b,f /u	x	x				x	x	x
3	DC Power, TLM, TC-function	F1-5, P	s,b,z,f /u	x	x	m	x	x	x	x	x
4	IOA-Step Profile (Output & DC Power only)	F1-5, P	s	x	x					x	x
5	Overdrive capability	F3	o,n						x		
6	Gain flatness and slope	D,E	s,b,a	x	x		x				x
7	Group Delay variation	D	s,b	p/e/b			e				e
8a	FGM Gain Control (Range/Step Profile)	F1-5, P	b	x	x,i						x
8b	ALC Level Control (Range/Step Profile)	F1-5, P	d	x	x,i						x
8c	ALC Output Power Stability	F1-5, P	y	x	x				x,i	x,i	x
8d	ALC Dynamic Range	F3	w, tc	p/e/b	p/e/b						x
9	AM/AM, P_{DC}, P_{Diss}, TM U_{a0},I_h,I_{mb} vs. drive	F1-5, P	v, f, u	x	x		x	x	x	x	x
10	Phase shift , AM-PM conversion & transfer	F1-5, P	v, f, u	x	x						x
11	Out-of-band gain	H	b	e	e						e
12	Amplitude linearity (3^{rd} , 5^{th} order)	F1-5, P	v,h	x	x						x
13	Noise power ratio (incl. P_{DC}, AM/AM)	F1-5, P	v,h	x	x						x
14	Noise Figure	D	z,g	x,i	x,i						x,i
15	Return Loss	D,S		x							x
16	Spurious modulation	G,F3	s	x	x						x
17	Spurious outputs (inband, out-of-band)	H,F3	s	x	x						x
19	Radiated emission (Sniff Test)	F3	s								x
20	Radiated Susceptibility	F3,I	z								x
21	Inrush current	F3	s	x							x
22	TDMA	F3,J, P	s	p/e/b							
23	$Pout_{FGM}$ calibration ($Pout_{MPM}$ vs. TM_{Pout})	F1-5, P	f, v	x							x
24	Switch ON/OFF	P		x				x	x	x	x
25	Ground Isolation (MB-, TM- returns, SMA)										x
26	Physical measurements										x

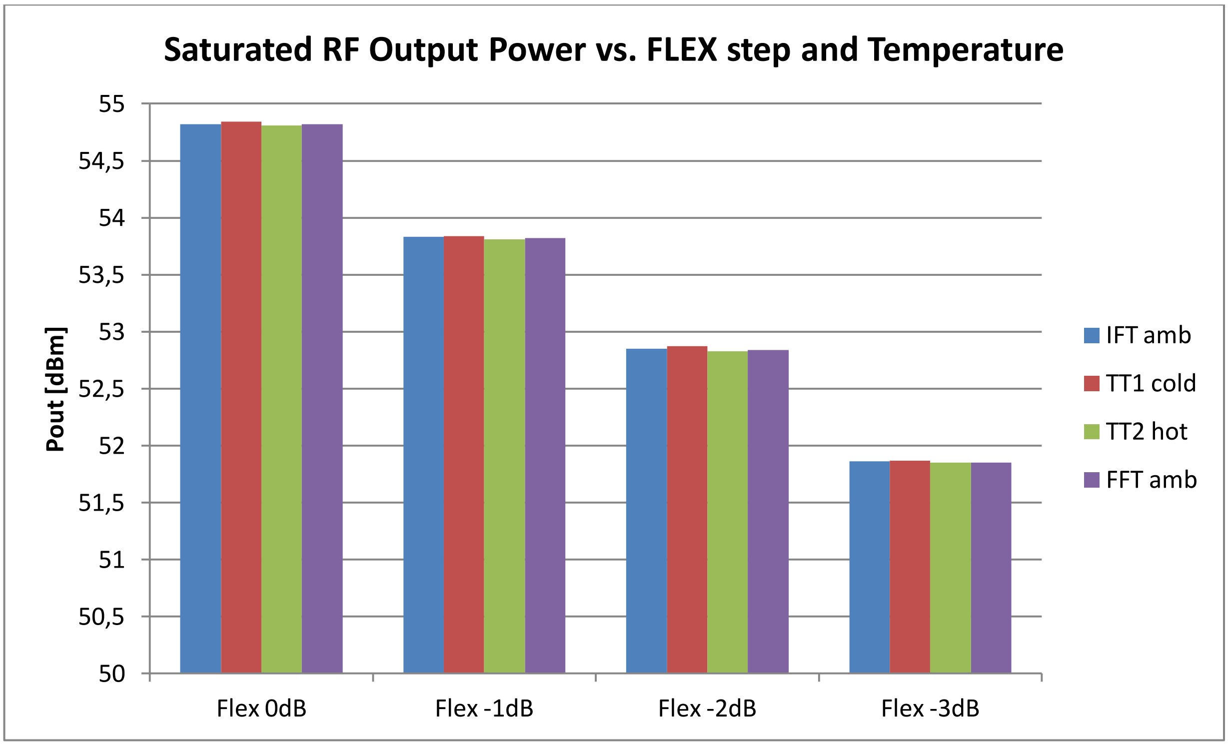
Notes:	x:	test for all units	i:	for information only
	p/e/b:	only for PFM/EQM/BB		
	n:	1h for FM / 24h for EQM/PFM at hot plateau	n.a.	not applicable for this project
	m:	continuous monitoring of TM Ih, Ua0, Pin, Pout Umb, Imb, ARU status (if applicable)		
Conditions:	F1-5:	see Table 4 Test frequencies	E:	Evaluation vs. full band and for defined channels
	D:	PFM/EQM: swept from F1 to F5 GHz BB: swept from 11GHz to 12.75 GHz	H:	8-18GHz range, RBW: 4kHz, add. 1MHz inband
	G:	0-200kHz, 0-1 MHz, 0-20MHz		
	K:	additional to standard measurement, 1st on TWT-A with TWT-B ON (SCS, zero drive), then vice versa		
	S:	measured at the RF input and output with the TWT ON (hot) and OFF (cold)		
	I:	RF input terminated and illuminated with 10 V/m (distance 15cm)		
	J:	amplitude + phase response measured @ 500Hz, 50kHz (50%duty cycle) TDMA		
	P:	PFM/FM/EQM: additional measurements with second parameter set BB: Switch ON/OFF with second parameter set only		
Drive:	s	Saturation drive (SCS)	a	additional @ ALC min step, Pin= -24 dBm
	b	15 dB IBO	d	ALC min(-60dBm) and max(-24dBm) i/p power
	z	zero drive	y	@ALC: min step, Pin= -24 dBm
	g	min and max gain step	tc	@ALC: EQM/PFM/FM: min, max
	o	+2dBm drive, max gain step	w	Pin = -63 ... -21dBm (only Pout vs.drive)
	h	FGM min gain, IOA @ 0dB, -3dB	u	IOA setting 0dB, -1dB, -2dB, -3dB
	f	min gain step , in TV only at min gain step		
	v	measured and tabulated vs. input drive from -20 dB IBO to +6 dB overdrive and vs. corresponding OBO, in 1 dB steps (RF power in dBm and relative to SCS, DC power in watts)		

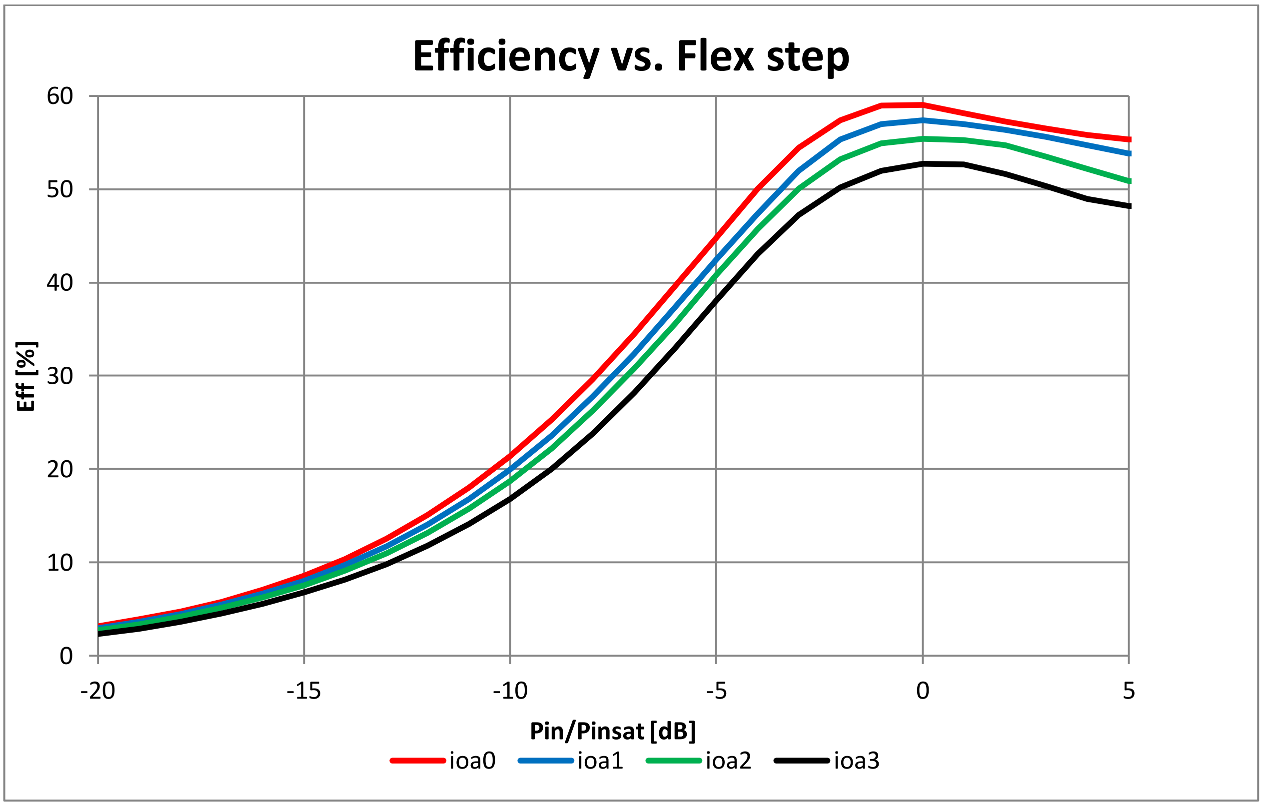
If not stated otherwise all tests are to be performed at the nominal mainbus voltage, in FGM min step and highest power setting.

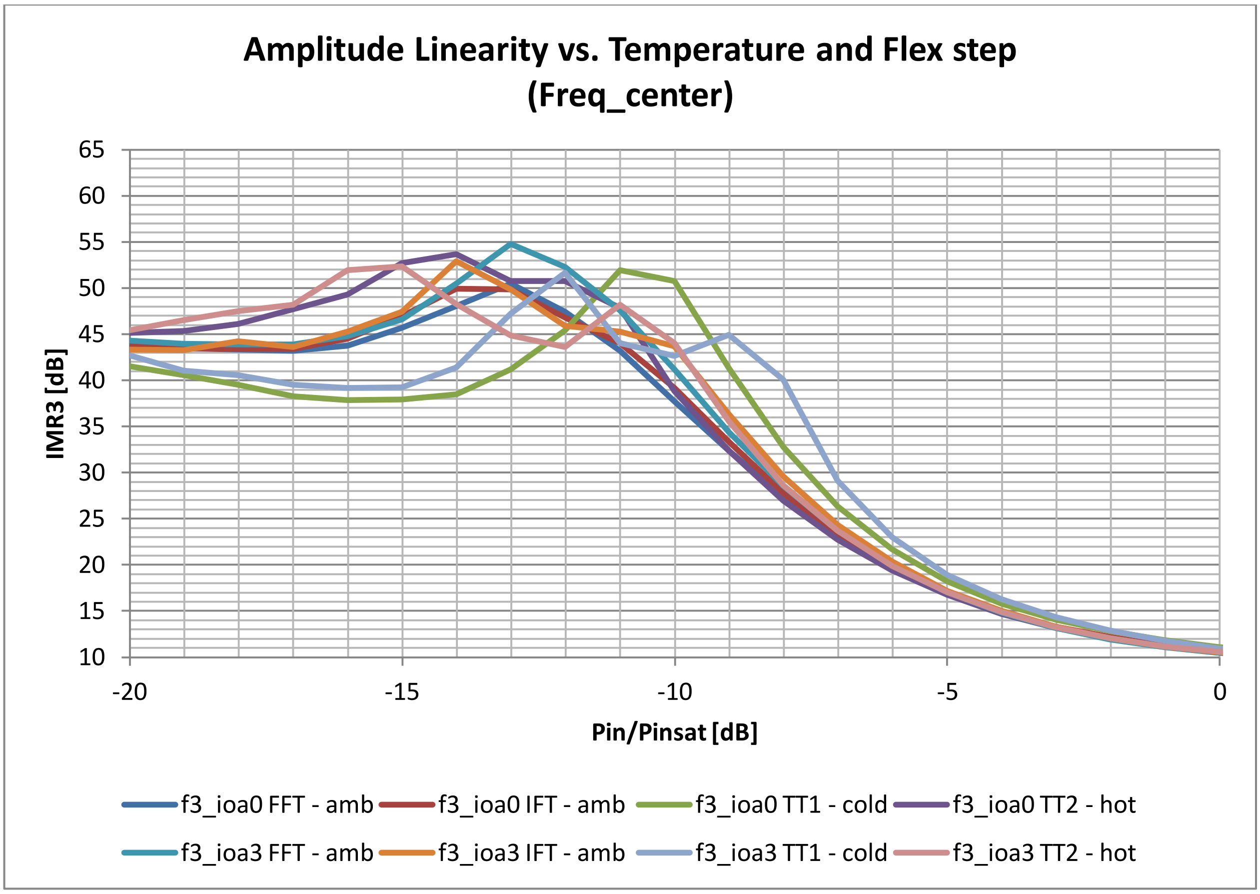
8 Test Results

8.1 RF performance






Efficiency vs. Flex step
Eff [%]
60
50
40
30
20
10
0
-20
-15
-10
-5
0
5
Pin/Pinsat [dB]
ioa0
ioa1
ioa2
ioa3


Amplitude Linearity vs. Temperature and Flex step
(Freq_center)
IMR3 [dB]
65
60
55
50
45
40
35
30
25
20
15
10
-20
-15
-10
-5
0
Pin/Pinsat [dB]
f3_ioa0 FFT - amb
f3_ioa0 IFT - amb
f3_ioa0 TT1 - cold
f3_ioa0 TT2 - hot
f3_ioa3 FFT - amb
f3_ioa3 IFT - amb
f3_ioa3 TT1 - cold
f3_ioa3 TT2 - hot

8.2 Environmental test results

The sensitivity against mechanical and thermal environmental conditions were tested by vibration test, shock test and thermal-vacuum test using the qualification levels mentioned above.

The EQM passed all these tests successfully without any problems.

8.3 EMC test results

The EQM of the 300W Ku-Band FPM was subjected to an extensive EMC test campaign. Similar EMC performance compared to usual commercial programs was verified and hence, the test was concluded to be successfull.

9 Analysis

A full CDR data package has been provided including all performed analysis for the 300W Ku-Band FPM:

- Thermal Analysis
- Mechanical Analysis
- Radiation Analysis
- Worst Case Analysis
- Interface Failure Mode Analysis
- Failure Mode Effects Analysis

All these analysis correspond to the requirements given in the specification and show an acceptable hardiness against an operating life in space for more than 15 years.

10 Conclusion

A high-power linearized Ku-band TWT amplifier development and qualification activity has been carried out. The equipment has been specified to meet typical requirements for commercial programs. The EPC showed the capability to handle more than 500W of DC power and the ability to adapt the RF output power of the TWT to an instantly in-orbit needed level in a range of 3 dB. A high-performance serial TM/TC interface (CAN) has proven its capability to control and observe the whole amplifier in operation. An EQM was built and has verified the specified performance needed for space environment. Hence, the herein outlined qualification program has been successfully completed.