# Final review presentation (ESA-TRP PIM Interference)

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# Final Review Presentation
# ESA-TRP (PIM interference)

ESA Contract No.:
4000126012/18/NL/HK

ATUR-RP-ADSO-1001750212-01

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This document has been assessed by the following Technical Rater:

**Assessed and classified by: Thomas Thiry**

**Date classification completed: 25.07.2023**

# Introduction of TRP

ESA Contract No: 4000126012/18/NL/HK

- Subject: Test methodology investigations and parameters influencing Passive Inter Modulation (PIM) interference

- Aim of TRP For future ECSS work on PIM

- Contractor: Airbus Defence and Space GmbH
- Sub-contractor: HPS GmbH

| | |
|---|---|
| Kick-off | Feb. 2019 |
| MTR | July 2019 |
| CDR | Sept. 2020 |
| MRR | Nov. 2020 |
| TRR | Jan. 2021 |
| TRB | Jul. 2022 |
| FR | July 2023 |

- Funding: 700 k€



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# Contents

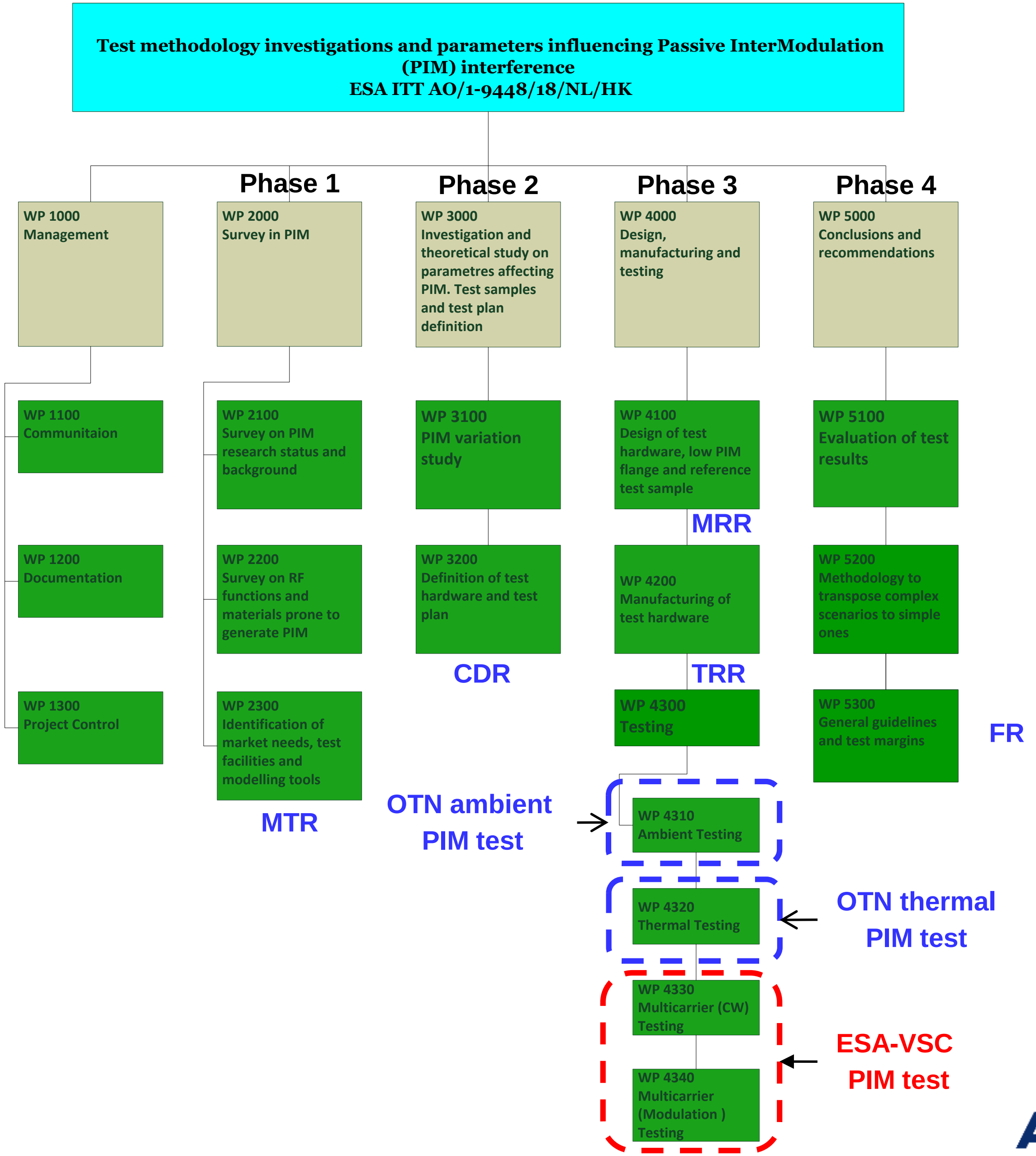
# ESA-TRP PIM Interference overview

Phase 1: Survey in passive intermodulation.

Phase 2: Investigation and theoretical study on parameters affecting PIM.
Test samples and
test plan definition.

Phase 3: Design, manufacturing and testing.

Phase 4: Conclusions and recommendations.



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# Phase 1

## Survey on PIM research status

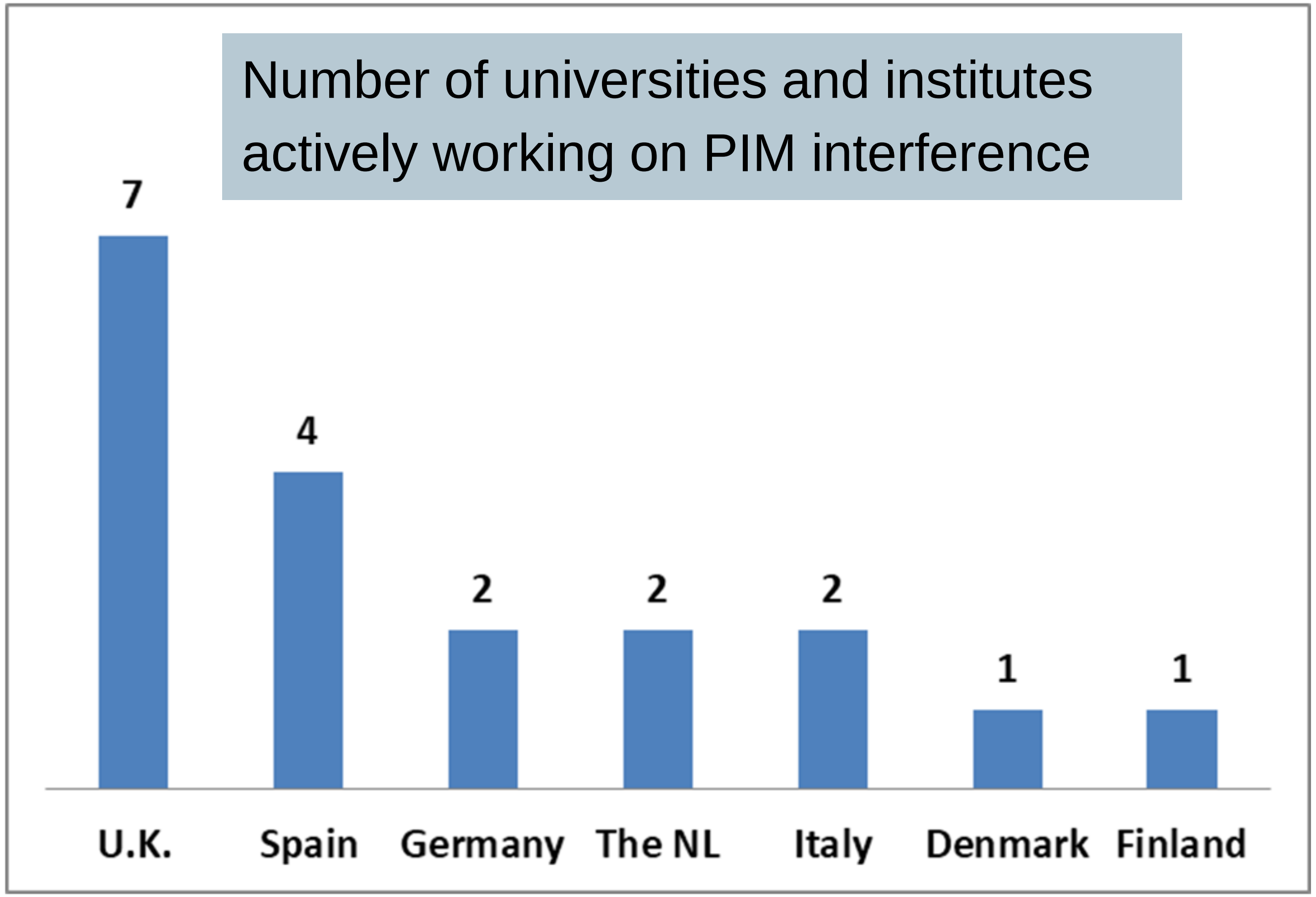
# Phase 1 overview

**Phase 1: Survey on**

- **PIM research status**
- **RF functions**
- **Market needs**
- **Test facilities**
- **Modelling tools**

# Institutes working on PIM research within ESA member states

| ESA Member State | Research Institute | University |
|---|---|---|
| Denmark | n.a. | TU Denmark |
| Finland | n.a. | TU Helsinki |
| Germany | n.a. | TU Darmstadt<br>TU Munich |
| Italy | CIRA | Univ. Florence |
| The Netherlands | ESTEC | TU Delft |
| Spain | VSC<br>INTA | Univ. Politècnica de València<br>Universitat de València |
| U.K. | Space Research Center (SRC) | Queen's Univ. Belfast<br>Univ. Kent Canterbury<br>Univ. of Leicester<br>Univ. of Surrey<br>Univ. of Sheffield<br>Univ. of Liverpool |



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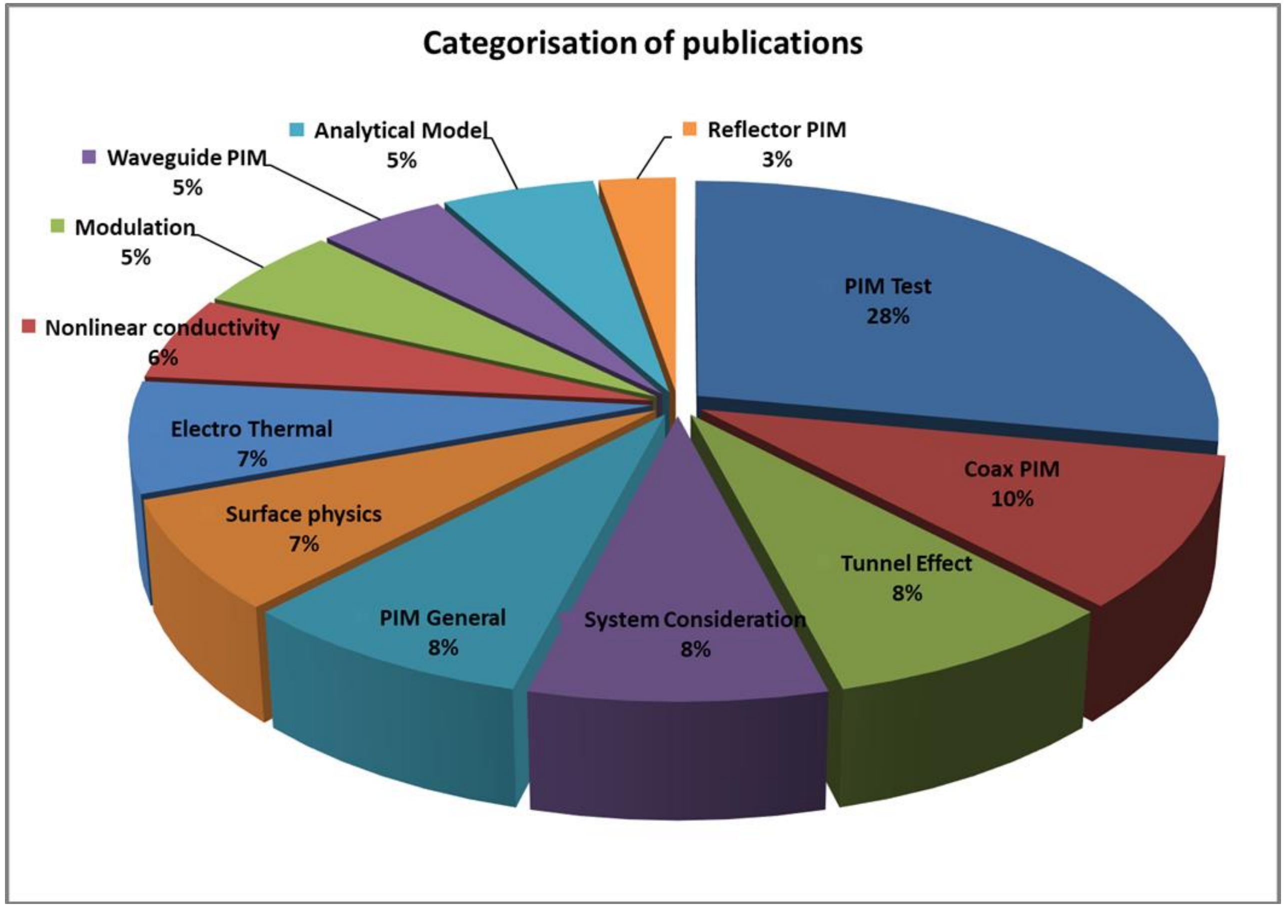
# Categorisation and statistics of publications on PIM




- The PIM characterisation has been performed in the past decades through tests.
- The conducted PIM in waveguide contact interfaces and the illuminated PIM on reflector have been investigated.
- Analytical studies were concentrated in several topics:
  - ➢ Tunnel effect
  - ➢ Surface physics
    - ✓ Roughness
    - ✓ Coatings
  - ➢ Electro-thermal effects related to the local heating induced by the concentrated surface current density
  - ➢ Nonlinear conductivity of materials



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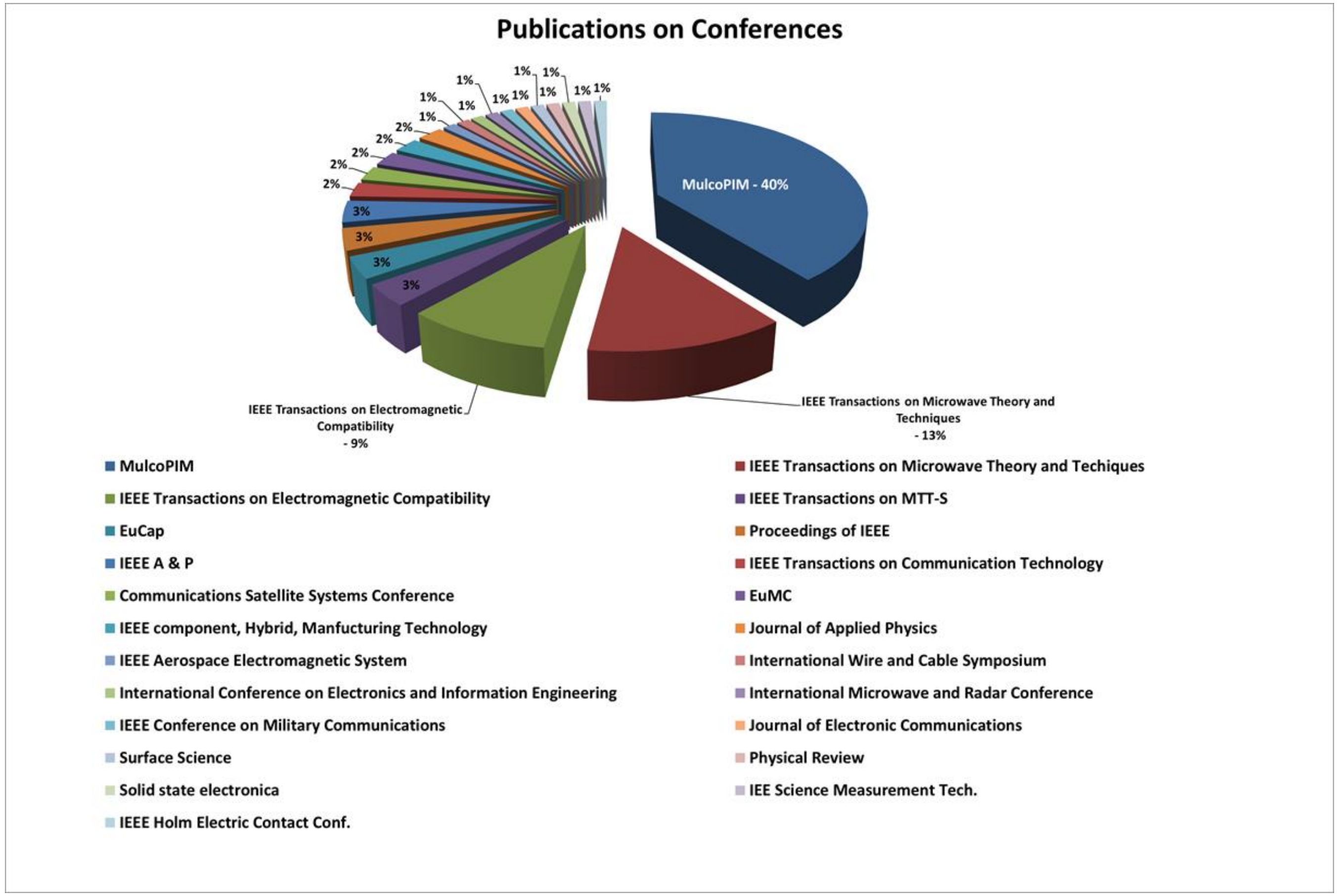
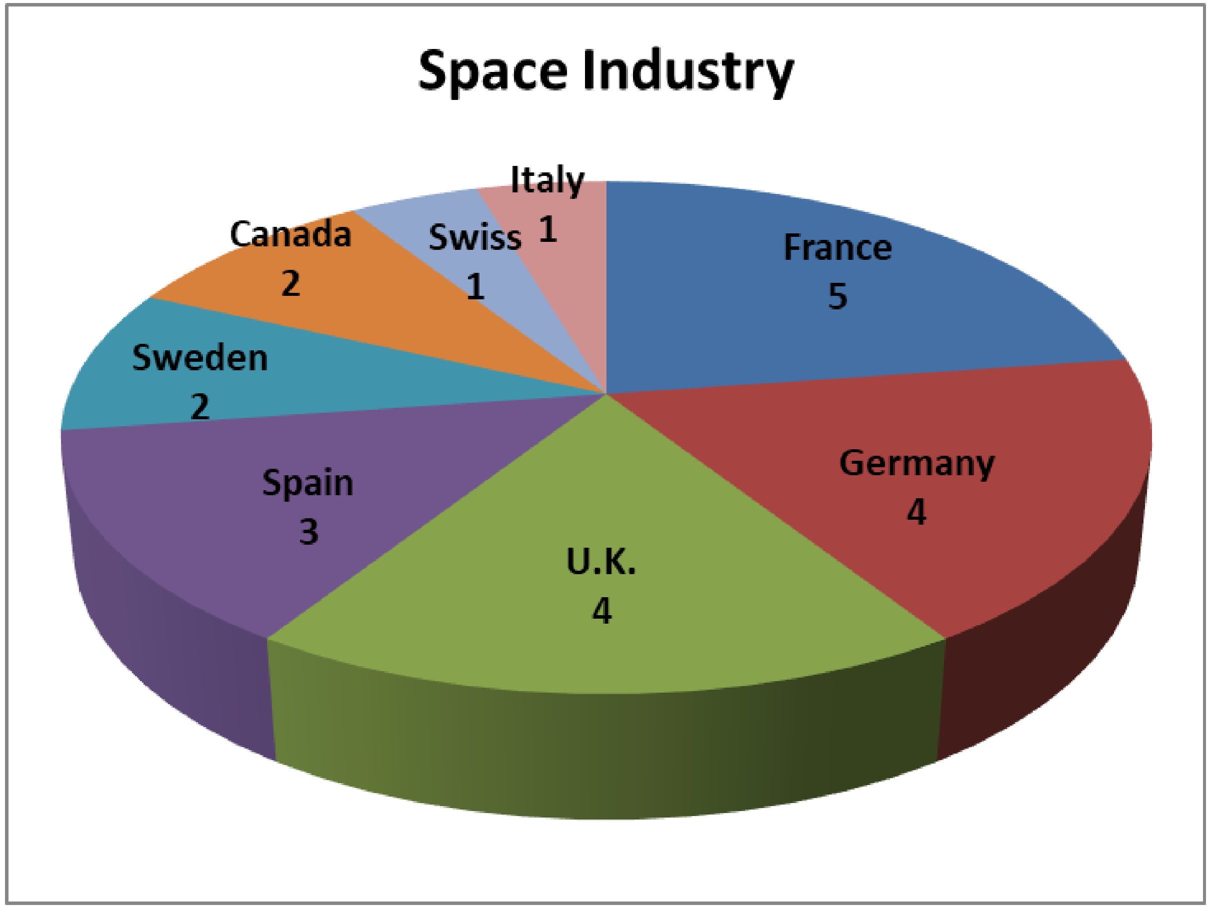
# Statistics of publication on conferences




- MulcoPIM (40 %)
  - The majority of the PIM research results were published and presented on MulcoPIM
- IEEE MTT (13 %)
- IEEE Electromagnetic compatibility (9 %)

# Companies working on PIM research within ESA member states

| ESA Member State | Industry |
|---|---|
| France | TAS France<br>Airbus @ Toulouse<br>Airbus @ Les Mureaux<br>Cobham<br>Radial |
| Germany | Airbus @ Ottobrunn<br>TESAT<br>OHB<br>HPS |
| Italy | TAS Italy |
| Spain | Airbus @ Madrid<br>TRYO(Rymsa)<br>TAS |
| Sweden | RUAG<br>Ericsson |
| Swiss | RUAG |
| U.K. | Airbus @ Stevenage<br>Airbus @ Portsmouth<br>Surrey Satellite Technology<br>Honeywell @ Aylesbury, Edinburgh |
| Canada | MDA<br>HONEYWELL(ComDev) |




Space companies working on the PIM research and mitigation are well distributed within the ESA member states.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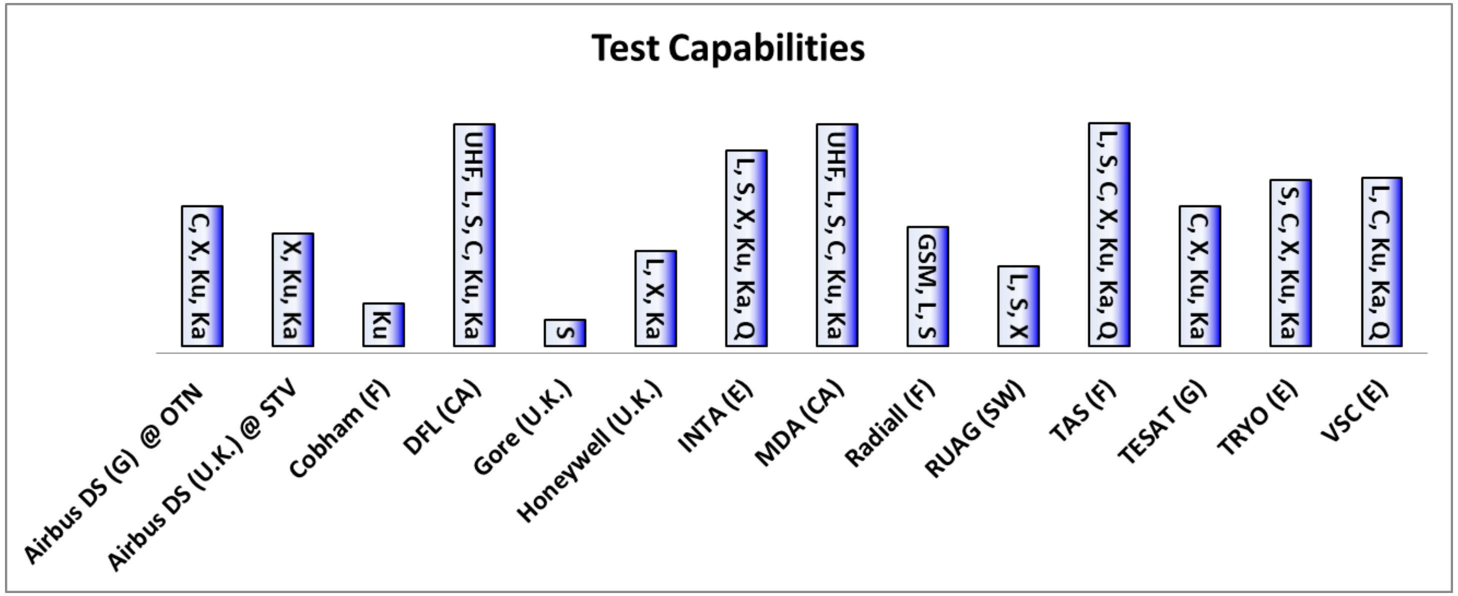
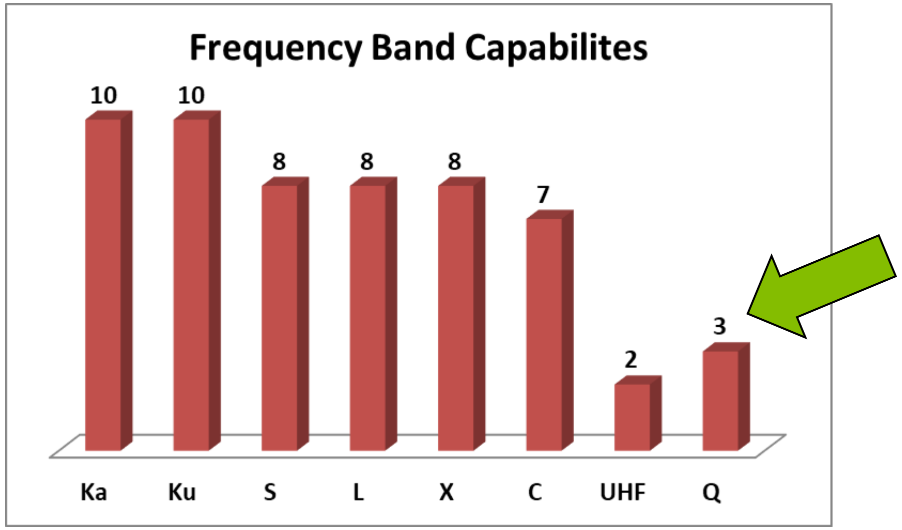
# PIM Test facilities and capabilities within ESA member states

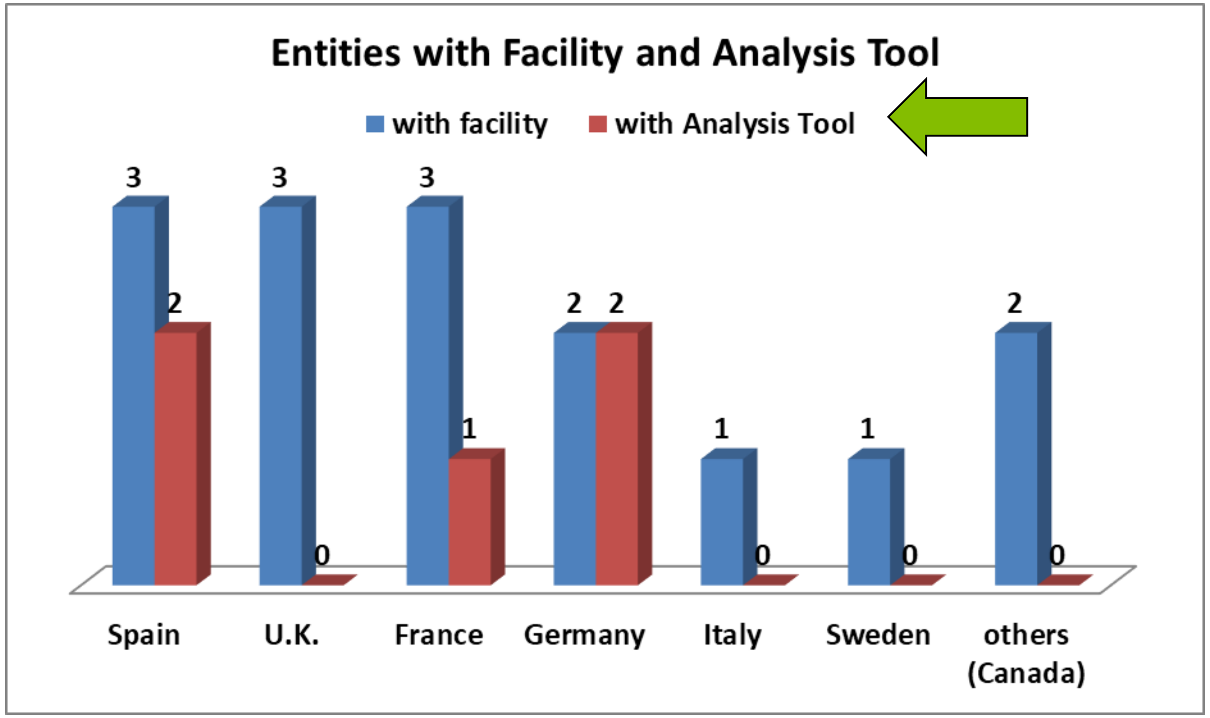
Frequency band occupation of PIM test facilities among ESA member states (alphabetical order)




- The occupation of the frequency band is an indication of the market needs
  - Telecommunication frequency bands (Ka and Ku) are dominant.
  - The demand on L-/S-Band PIM capability is also strong.
  - The demand on Q-Band PIM capability is growing.

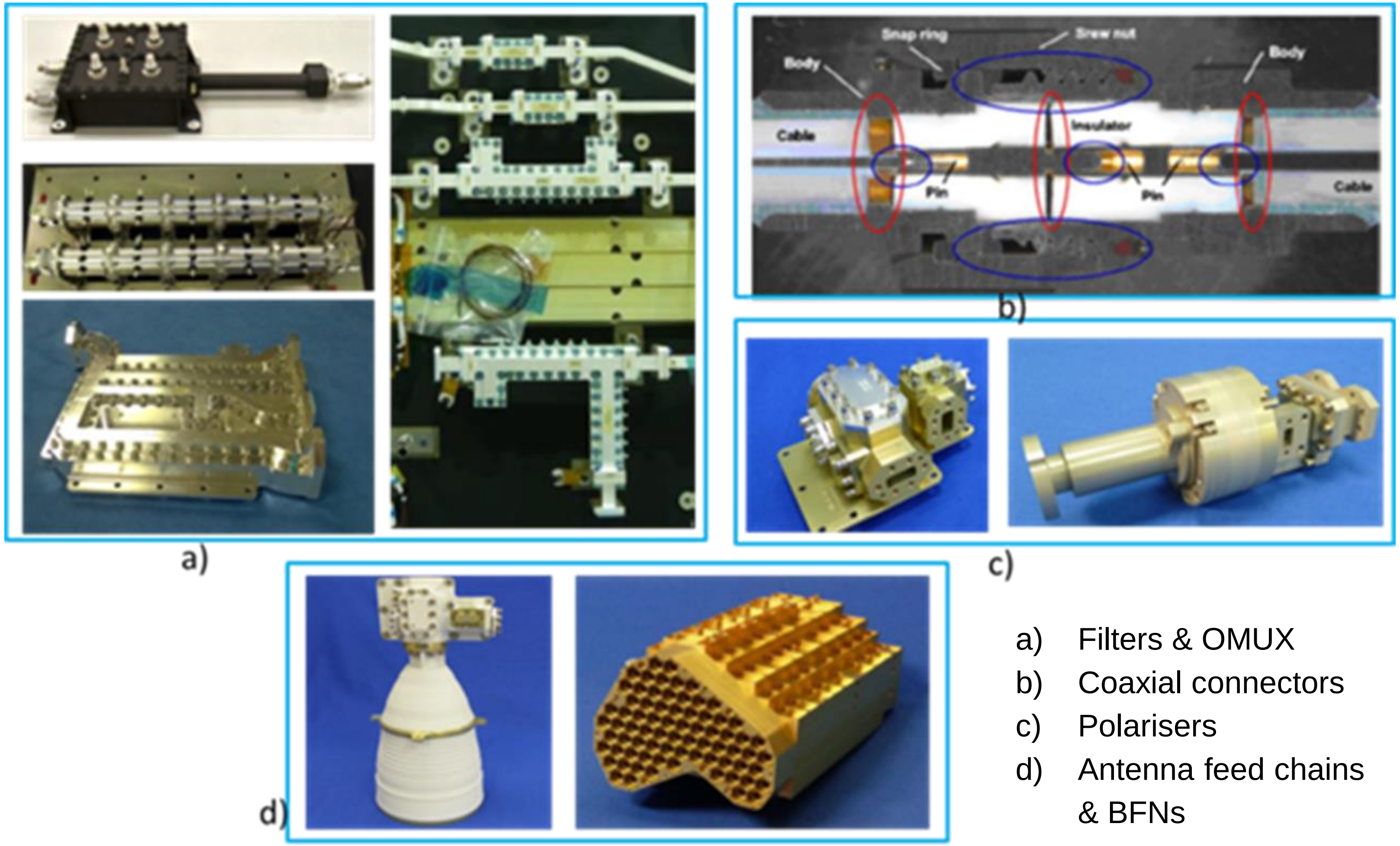


# PIM analysis capabilities within ESA member states




- The statistic on the PIM analysis tool indicates market need.
- PIM analysis tool is less in usage among entities than test capability.
- There is a motivation to develop a PIM analysis tool based on wide PIM test database.

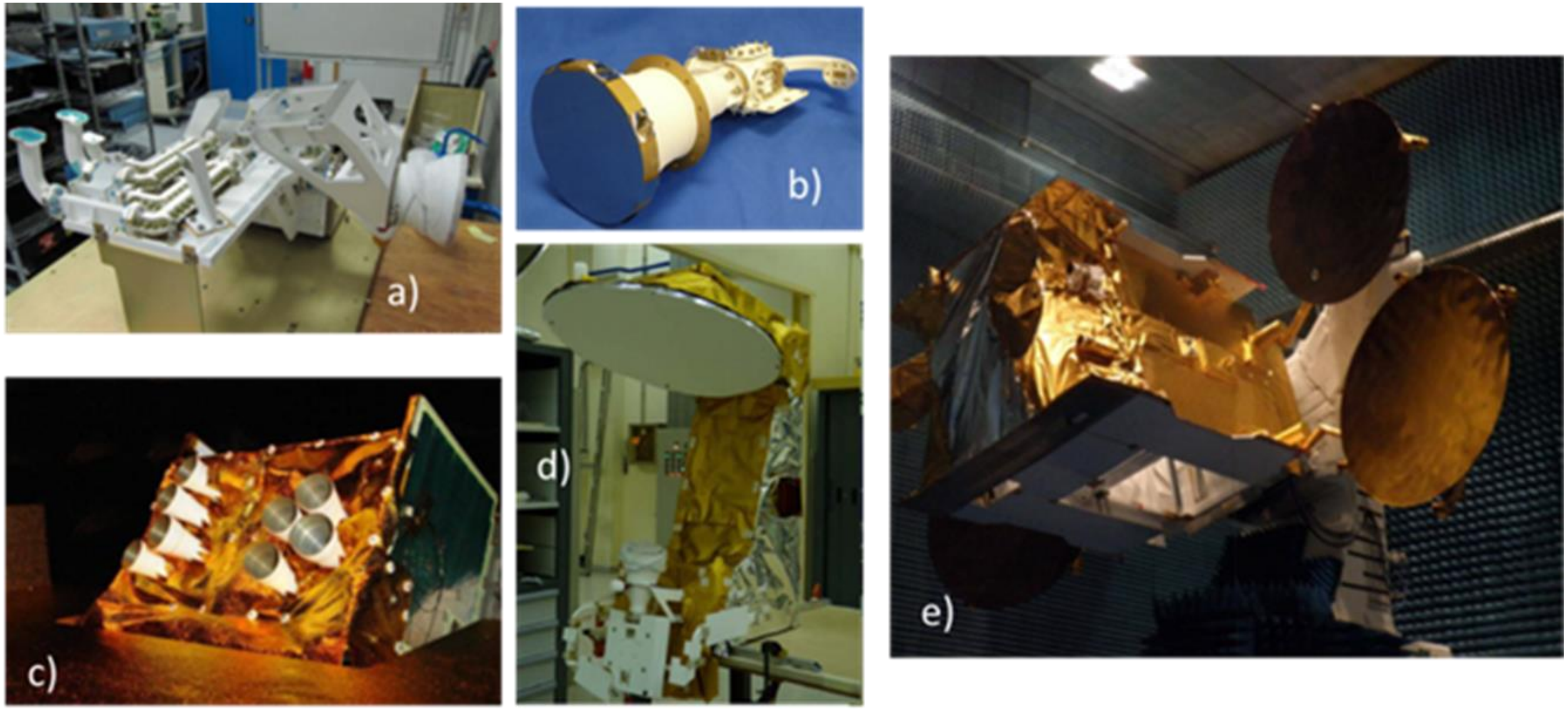
# PIM prone RF functions in guided wave parts




a) Filters & OMUX
b) Coaxial connectors
c) Polarisers
d) Antenna feed chains & BFNs

- Waveguide joints have been identified as PIM prone RF functions.
- PIM sources are distributed in the waveguide equipment interfaces as well as material nonlinearities on the RF signal transmit path.
- Typical PIM prone waveguide parts are
  - ✓ OMUX / Filters
  - ✓ BFNs
  - ✓ Antenna feed chains
- Coaxial cables & connector assemblies contains complex potential PIM sources.

# PIM prone RF functions in radiated paths




a) Structures in the vicinity of antenna radiating element
b) Sunshield assembly on the feeder aperture
c) Feeder array structures
d) Antenna structure assemblies and MLI with studs
e) Spacecraft wall & reflector

- Illuminated structures have been identified as PIM sources distributed on the surfaces

- Typical PIM prone elements and structures on the illuminated paths are

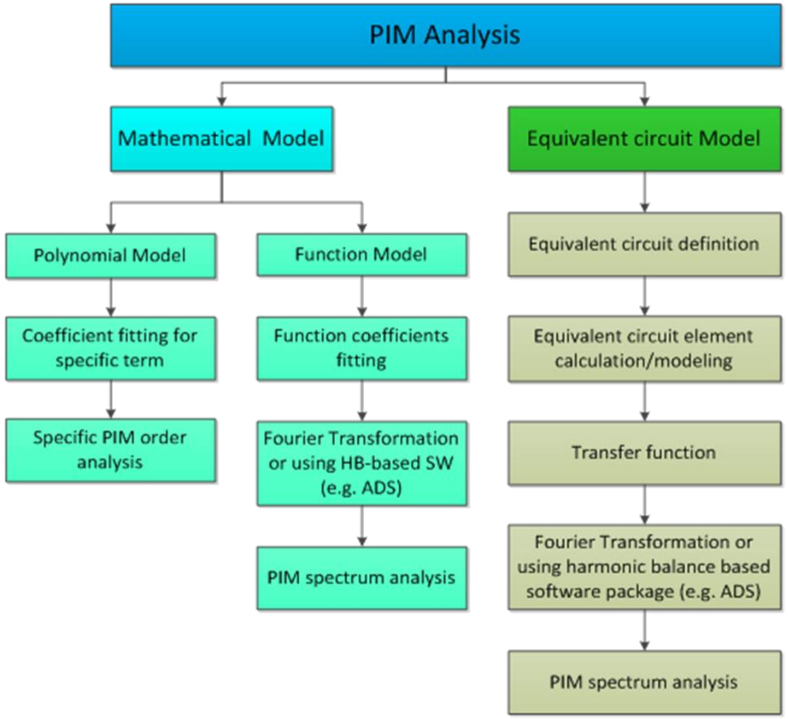
  - ✓ Sunshield
  - ✓ MLI + studs
  - ✓ Spacecraft structure joints
  - ✓ Reflector surfaces, rim and cut-outs

# PIM prone materials (typical)

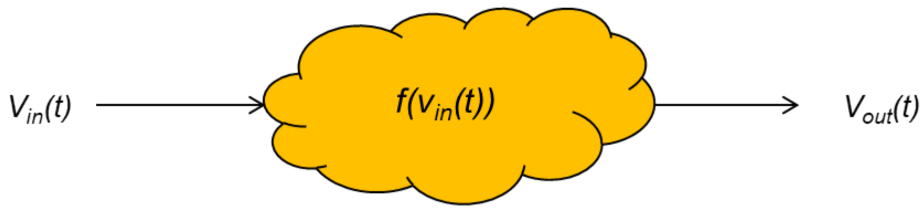
More detailed material list used in the space hardware is given in TN02_ATUR-TN-ADSO-1000546498

| **PIM source material properties** | **Description** |
|---|---|
| Ferromagnetic | Ferrites, nickel, steel, etc. - due to non-linearity and hysteresis effects |
| Contaminations | dirt, moisture or oxidised layer on electrically conducting surfaces |
| Inconsistency | Inconsistent metal - metal contact |
| Potential difference | Galvanic mismatch of metals at contacts |
| Multipath | Multipath with oxidised metal structures, |
| nonlinear dielectric properties | In PCBs, non-linear trace resistance and nonlinear dielectric properties (second order). |

# PIM analysis methodology & equivalent circuit model as selected baseline

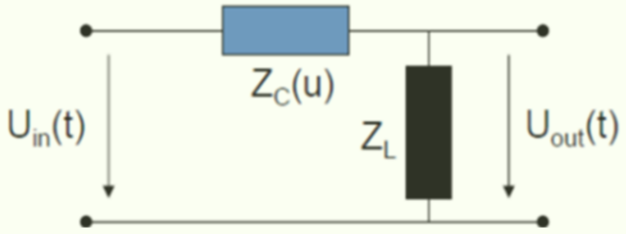



PIM Generating System




Power series expansion as a non-linear function model for PIM

$$V_{out}(t) = \sum_{k=0}^{\infty} g_k \left( \sum_{m=1}^{M} a_m V_m(t) \right)^n$$




$Z_c(U_{in}(t))$ = *voltage dependent impedance*

Equivalent circuit model for PIM

For both approach the test data are required to obtain the PIM model parameters !



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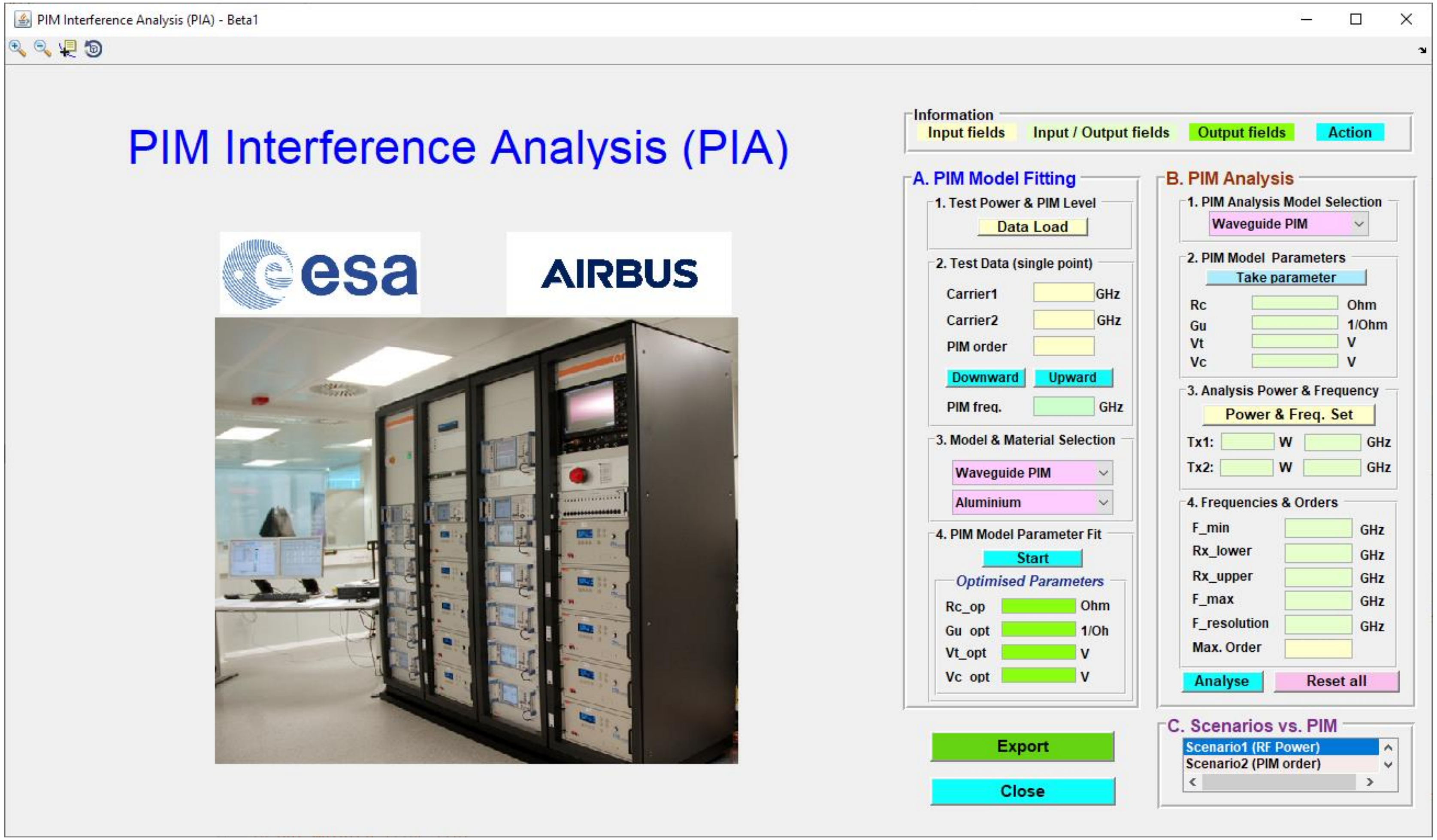
# PIM Interference Analysis Tool (PIA)
# - based on the equivalent circuit model developed at Airbus-G




- In the frame of the TRP a PIM analysis tool has been developed.
- The main features are
  - ✓ PIM model parameter fitting
  - ✓ PIM analysis using PIM model
  - ✓ Specified scenario analysis

# Phase 2

## PIM variation study & Definition of test hardware

# Phase 2 overview

**Phase 2: Investigation and theoretical study on parameters affecting PIM. Teste samples and test plan definition**

- **PIM variation study**
- **Definition of test hardware and test plan**

# PIM variation study

- PIM as an effective noise becomes a great challenge for the data communication.

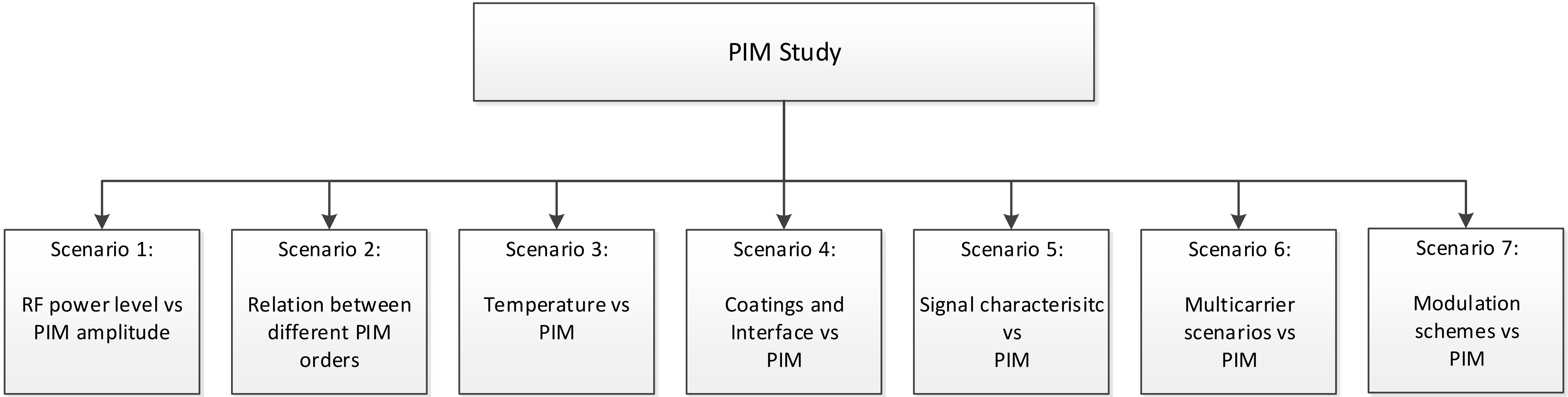
- PIM study main parameters are

  - RF power,
  - temperature,
  - pressure,
  - contact material,
  - carrier frequencies,
  - carrier frequency spacing,
  - carrier phase variation,
  - multi-carriers,
  - carriers with digital modulations.

- Literature study have been performed

# Definition of scenarios for the study

7 Scenarios were defined for the study as per the SOW (ESA ITT AO/1-9448/18/NL/HK) .



# Scenario #1 study
# RF power level vs. PIM amplitude

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# PIM amplitude variation with respect to the power variation

- There have not been conclusive statement about roll-off values for the specific PIM orders of 3$^{rd}$, 5$^{th}$ and 7$^{th}$ order with respect to the power variation.
  - ➢ 3$^{rd}$ order PIM level roll-off over the power variation was shown closed to 2.6 dB/dB for the typical carrier powers at waveguide contact interface.
    - ✓ However the contact pressure value was not fully defined for this roll-off value.
    - ✓ 3$^{rd}$ order PIM has some similarity with active intermodulation, which has a roll-off value close to 3 dB/dB.
    - ✓ 5$^{th}$ order PIM power roll-off showed different values between 3 dB/dB to 4 dB/dB in the passive components.
    - ✓ 7$^{th}$ order roll-off value was close to 5 dB/dB.
  - ➢ The roll-off values over power variation for PIM orders are, therefore, needs to be investigated with respect to the material and contact pressure for waveguide contact interfaces.
- Moreover a question shall be clarified.
  - ➢ Which carrier power of the two-tones has stronger impact on the resulting PIM level, when the total power of two tones are kept constant ?
    - ✓ Some analytic investigation about this question has been performed.

# Theoretical amplitude difference of PIM signal using two-carriers (I)

We take an input signal consists of two tone as below

$$x(t) = A_1 \cdot \cos(\omega_1 t + \varphi_1) + A_2 \cdot \cos(\omega_2 t + \varphi_2)$$

We think about an example.
What happens at output signal of *y(t)*, if the input signal *x(t)* is passing through a non-linear medium described by the function below.

$$y(t) = a_1 \cdot x(t) + a_3 \cdot x^3(t) + \ldots a_n \cdot x^n$$

The second term will contribute the flowing terms containing different frequencies and amplitudes to the output signal *y(t)*.

$$a_3 \cdot x^3(t) = a_3 \cdot [A_1 \cdot \cos(\omega_1 t + \varphi_1) + A_2 \cdot \cos(\omega_2 t + \varphi_2)]^3$$

$$= a_3 \cdot \{[A_1 \cdot \cos(\omega_1 t + \varphi_1)]^3$$
$$+ 3*[(A_1 \cdot \cos(\omega_1 t + \varphi_1)]^2 \cdot [A_2 \cdot \cos(\omega_2 t + \varphi_2)]$$
$$+ 3*[(A_1 \cdot \cos(\omega_1 t + \varphi_1)] \cdot [A_2 \cdot \cos(\omega_2 t + \varphi_2)]^2$$
$$+ [A_2 \cdot \cos(\omega_2 t + \varphi_1)]^3\}$$

$$(x+y)^3 = x^3 + 3x^2y + 3xy^2 + y^3$$



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# Theoretical amplitude difference of PIM signal using two-carriers (cont'd)

Using $\cos^2(x) = ½ \cdot [1+\cos(2x)]$

$$[A_1 \cdot \cos(\omega_1 t + \varphi_1)]^2 \cdot [A_2 \cdot \cos(\omega_2 t + \varphi_2)] = \frac{A_1^{\,2} \cdot A_2}{2} \cdot [1 + \cos(2\omega_1 t + 2\varphi_1)] \cdot \cos(\omega_2 t + \varphi_2)$$

$$= \underbrace{\frac{A_1^{\,2} \cdot A_2}{2}}_{} \cdot [\cos(\omega_2 t + \varphi_2) + \underbrace{\cos(2\omega_1 t + 2\varphi_1) \cdot \cos(\omega_2 t + \varphi_2)}_{}]$$

*PIM Case: A*

$$[(A_1 \cdot \cos(\omega_1 t + \varphi_1)] \cdot [A_2 \cdot \cos(\omega_2 t + \varphi_2)]^2 = \frac{A_1 \cdot A_2^{\,2}}{2} \cdot \cos(\omega_1 t + \varphi_1) \cdot [1 + \cos(2\omega_2 t + 2\varphi_2)]$$

$$= \underbrace{\frac{A_1 \cdot A_2^{\,2}}{2}}_{} \cdot [\cos(\omega_1 t + \varphi_1) + \underbrace{[\cos(\omega_1 t + \varphi_1) \cdot \cos(2\omega_2 t + 2\varphi_2)]}_{}$$

*PIM Case: B*

We concentrate on the product case A and B which give the intermodulation product again.

$$\textit{Case: A} = \frac{A_1^{\,2} \cdot A_2}{2} \cdot \cos(2\omega_1 t + 2\varphi_1) \cdot cos(\omega_2 t + \varphi_2)$$

$$\textit{Case: B} = \frac{A_1 \cdot A_2^{\,2}}{2} \cdot \cos(\omega_1 t + \varphi_1) \cdot \cos(2\omega_2 t + 2\varphi_2)$$



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# Theoretical amplitude difference of PIM signal using two-carriers (cont’d)

*cos(x) ·cos(y)= ½ ·[cos(x-y) + cos(x+y)]*

$$\textit{Case: A} = \frac{A_1{}^2 \cdot A_2}{2} \cdot \cos(2\omega_1 t + 2\varphi_1) \cdot cos(\omega_2 t + \varphi_2)$$

$$= \frac{A_1{}^2 \cdot A_2}{4} \cdot [\cos(2\omega_1 t + 2\varphi_1 - \omega_2 t - \varphi_2) + \cos(2\omega_1 t + 2\varphi_1 + \omega_2 t + \varphi_2)]$$

$$= \frac{A1^2 \cdot A_2}{4} \cdot [\cos\{(2\omega_1 - \omega_2)t + (2\varphi_1 - \varphi_2)\}] + [\cos\{(2\omega_1 + \omega_2)t + (2\varphi_1 + \varphi_2)\}]$$

$$\textit{Case: B} = \frac{A_1 \cdot A_2{}^2}{2} \cdot \cos(\omega_1 t + \varphi_1) \cdot \cos(2\omega_2 t + 2\varphi_2)$$

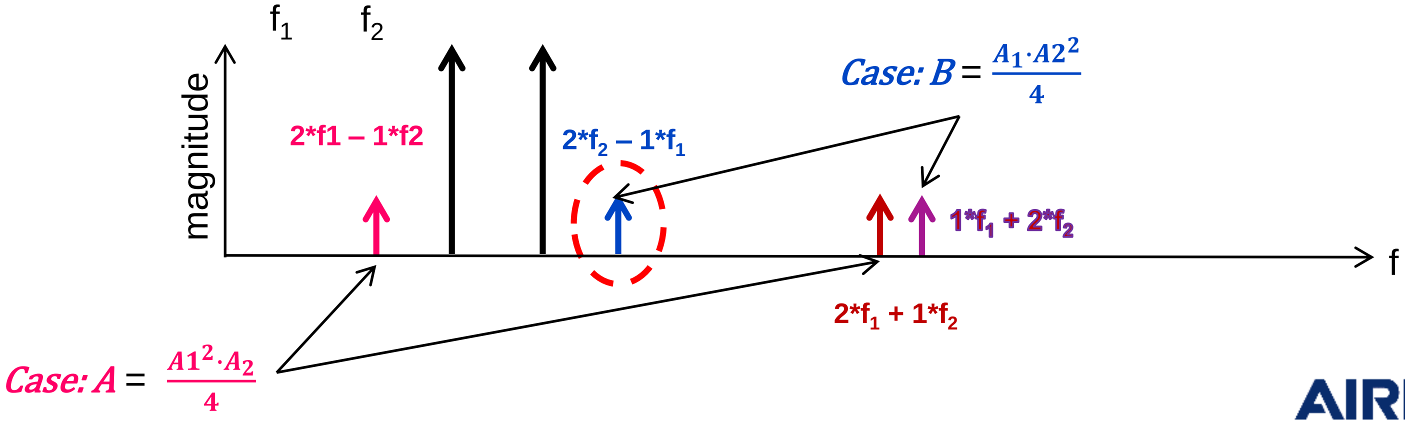
$$= \frac{A_1 \cdot A_2{}^2}{4} \cdot [\cos(\omega_1 t + \varphi_1 - 2\omega_2 t - 2\varphi_2) + \cos(\omega_1 t + \varphi_1 + 2\omega_2 t + 2\varphi_2)]$$

$$= \frac{A_1 \cdot A_2{}^2}{4} \cdot [\cos\{(\omega_1 - 2\omega_2)t + (\varphi_1 - 2\varphi_2)\}] + [\cos\{(\omega_1 + 2\omega_2)t + (\varphi_1 + 2\varphi_2)\}]$$

$$= \frac{A_1 \cdot A2^2}{4} \cdot [\cos\{(2\omega_2 - \omega_1)t + (2\varphi_2 - \varphi_1)\}] + [\cos\{(\omega_1 + 2\omega_2)t + (\varphi_1 + 2\varphi_2)\}]$$

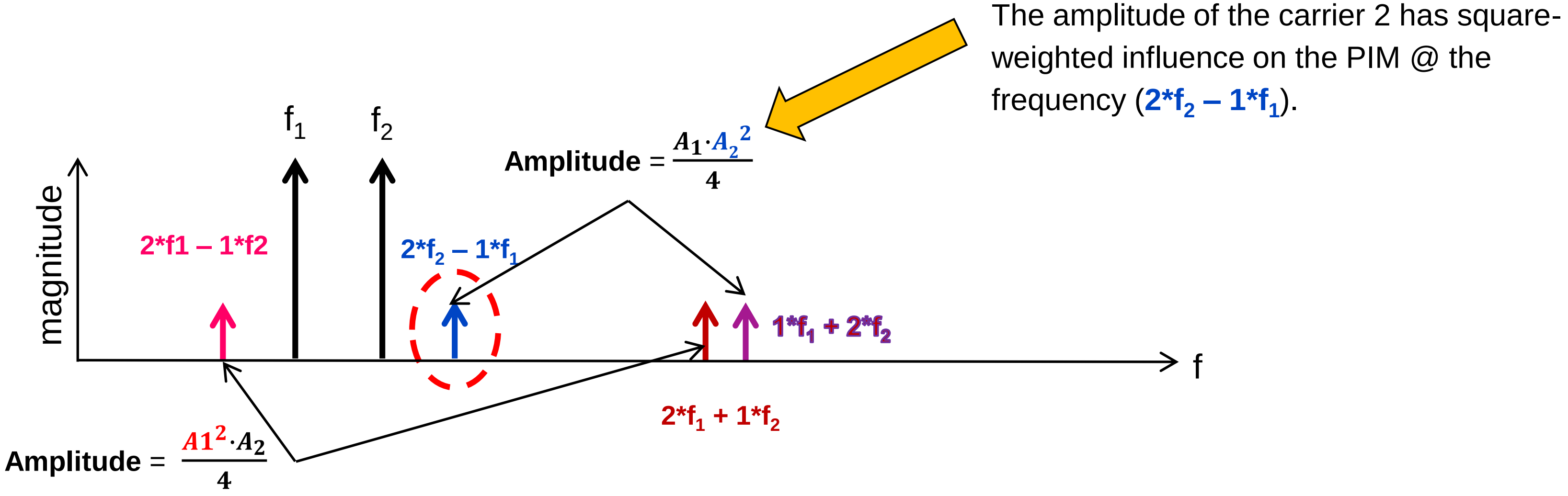
*„cos“ is an even-function*

There are four spectral components.
They have all the same amplitide, if $A_1$=$A_2$



# Theoretical amplitude difference of PIM signal using two-carriers

The amplitude for the PIM level at the frequency of $2*f_2 – 1*f_1$ increases with square of the amplitude $A_2$



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# Scenario #2 study
# Relation between different PIM orders

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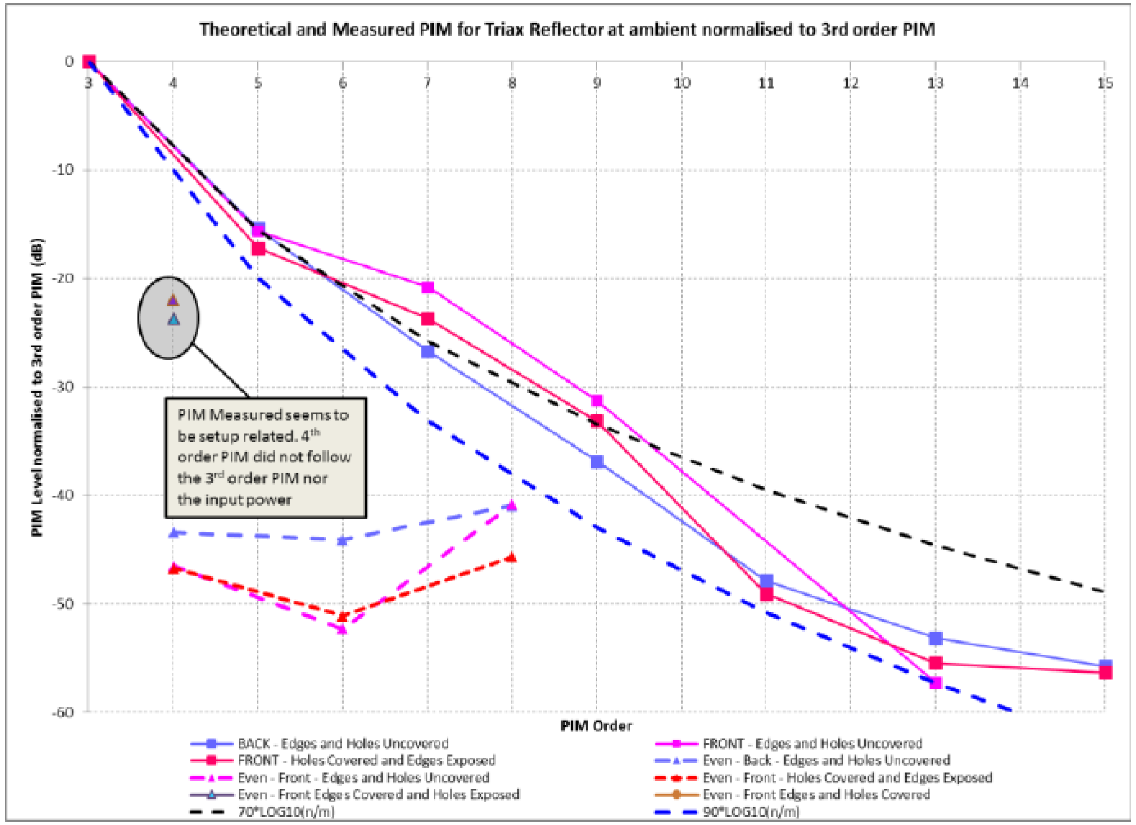
# PIM order relationship Roll-off based on the specific test data (MDA)




Theoretical and Measured PIM for Reflector at ambient temperature normalized to 3rd order PIM

## Reflector sample

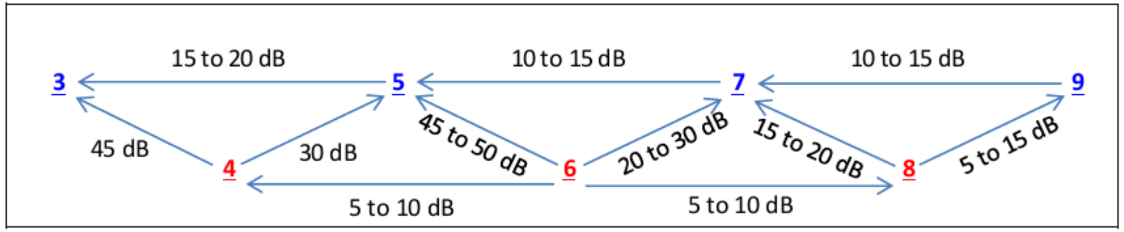



Fig. 8. Summary of relationship between each PIM order based on Reflector

## Steel wool and metallic nuts

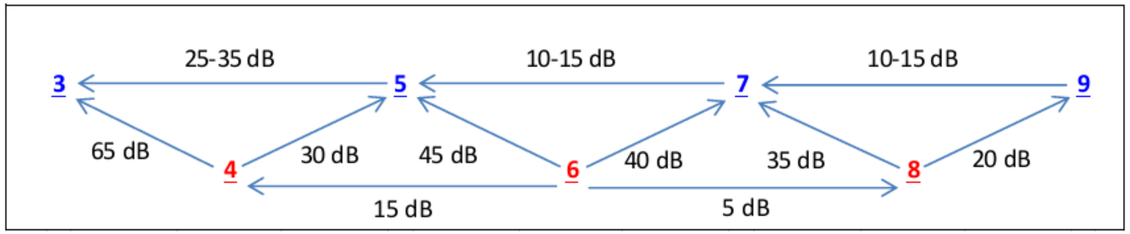



Fig. 9. Summary of relationship between each PIM order based on Steel wool and metallic nuts

The PIM order relationship is not unique but dependent on the material and contact pressure!

# “rule of thumb” (MDA)

- In RD7 an empirical formula was proposed to predict the relation between PIM orders.

- This formula was based on a specific Ku-Band reflector sample PIM test results using two carriers having 165 Watts per carrier.

- The proposed formula for minimum PIM level distance of two orders was

$$PIM\ level\ distance\ between\ orders = 70 \cdot log_{10}\left(\frac{n}{m}\right),$$ where $n$ and $m$ are two odd orders.

- A prediction for the relation 3rd and 5th order PIM level using this formula is about 15.5 dB between two orders.



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# Scenario #3 study
# Temperature vs. PIM

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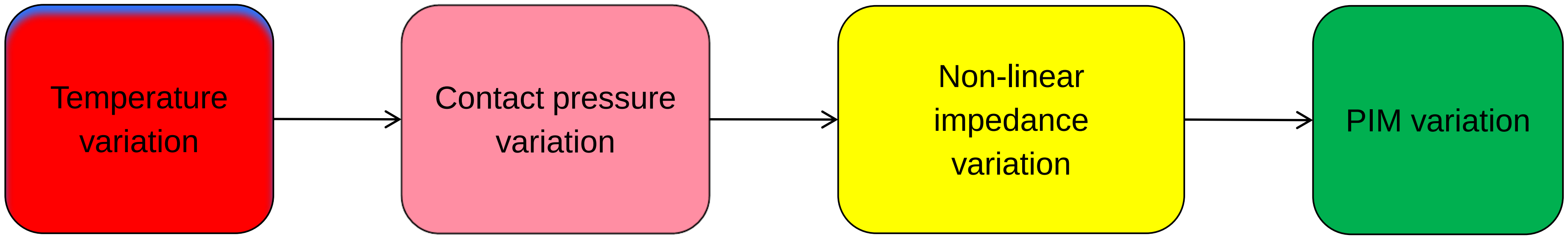
# Temperature related complex PIM behaviour

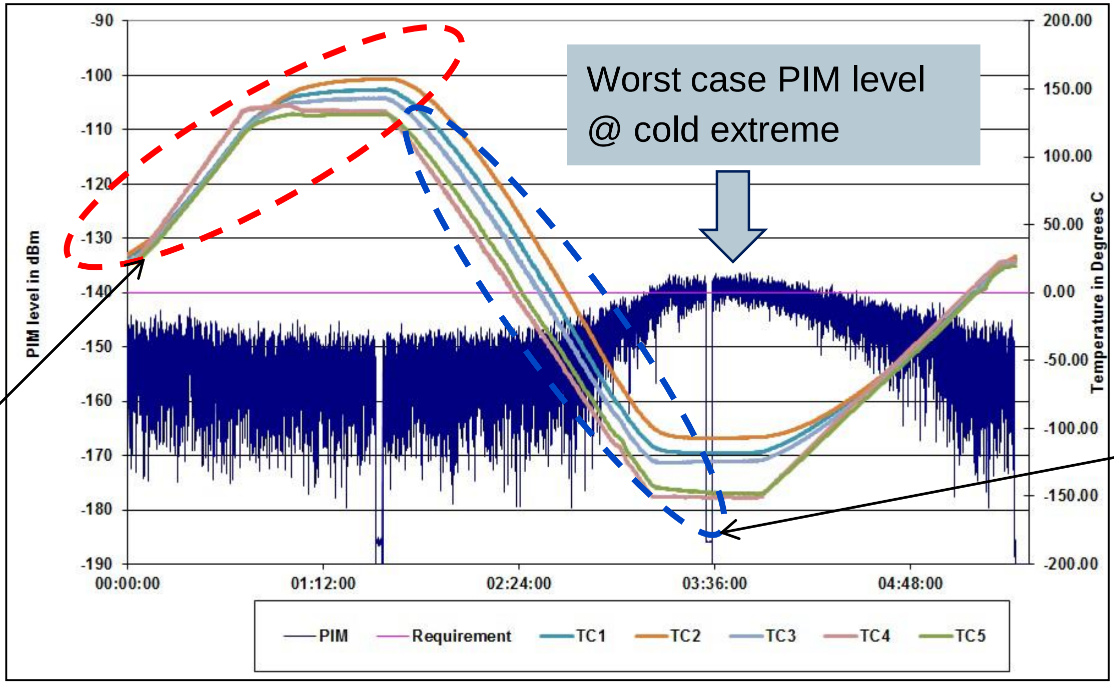
- Temperature variation initiates PIM level variation in complex mechanisms.
- Temperature related PIM behaviour and contact pressure related PIM behaviour of different materials are difficult to separate.
- Therefore specific case shall be considered individually. (initial contact pressure @ ambient temperature, expansion coefficients of specific materials and yield point for elastic/plastic deformation)
- As an example: typical yield strength of aluminium alloy (6082-T6) is about 250 MPa.



# Temperature vs. PIM test data as an example (Temperature initiated complex PIM behaviour)

**Temperature increases**

- Material **expansion** occurs with the growing temperature (depends on the materials).
- The **contact pressure** at the interface (I/F) **increases**.
- The **PIM level** is **low and stable** due to the high pressure @ I/F contacts.




**Temperature decrease**

- Material **contraction** occurs with the decreasing temperature (depends on the materials).
- The **contact pressure** at the interface (I/F) **decreases**.
- The **PIM level** is **high and instable** due to the loosen pressure @ I/F contacts.



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# Scenario #4 study
# Coatings and Interface vs. PIM

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# Different materials vs. PIM

There were no sufficient test data for the PIM variation induced by different materials !

The contact pressure values were unknown!

| Material/Coating type | Bare aluminium | Alodine | Silver | Gold[1] | Surtec[2] |
|---|---|---|---|---|---|
| Tested PIM order | 3rd | 3rd | 3rd | N/A | N/A |
| Tested PIM level | -116 dBm | -135.0 dBm | -140 dBm | N/A | N/A |
| Power à carrier | 110 W | 120 W | 110 W | N/A | N/A |
| PIM frequency | 14.1 GHz | 13.96 GHz | 14.1 GHz | N/A | N/A |
| Carrier 1 frequency | 11.1 GHz | 11.55 GHz | 11.1 GHz | N/A | N/A |
| Carrier 2 frequency | 12.6 GHz | 12.725 GHz | 12.6 GHz | N/A | N/A |
| Contact Type | High pressure Nib | High pressure Nib | High pressure Nib | N/A | N/A |
| Reference | Airbus internal document | RD 119 Fig. 16 | Airbus internal document | N/A | N/A |

1. There has not been found the test data for waveguide with Gold coating
2. There has not been found the test data for waveguide with Surtec coating



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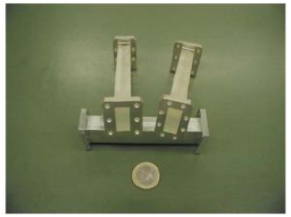
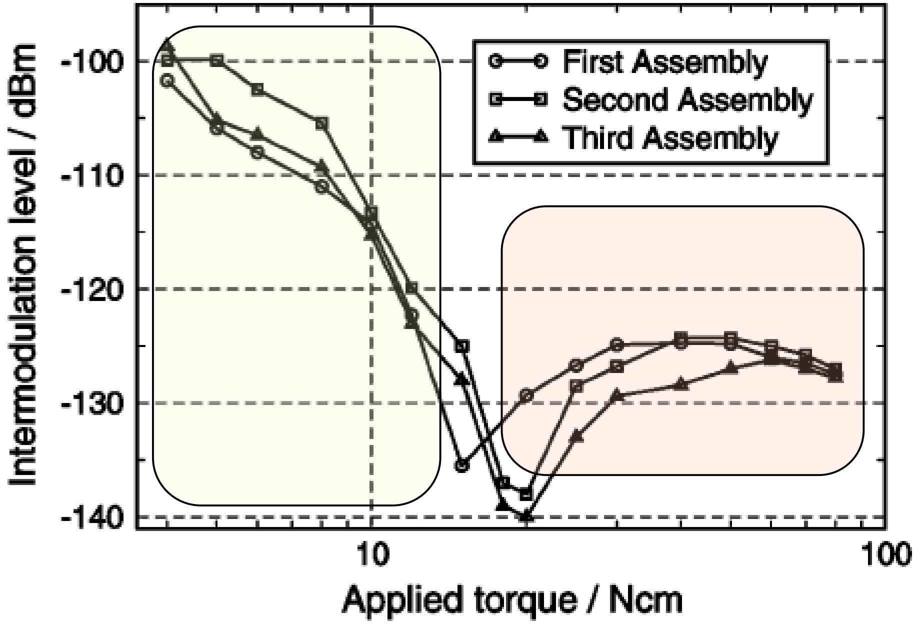
# PIM level behaviour related to the torque values



Aluminium waveguide test sample
(RD31, Fig. 5)




- The PIM level decreases rapidly in the low torque value range

- Responsible for the PIM level coming from the different physical phenomena.
  - Void regions between metals.
  - Metal-to-metal contacts separated by contaminant (i.g. oxid layer)
- The increasing PIM level due to the deformation of the contact interface.

- With the high pressure at the interface, PIM reduces again and converges to a stable level



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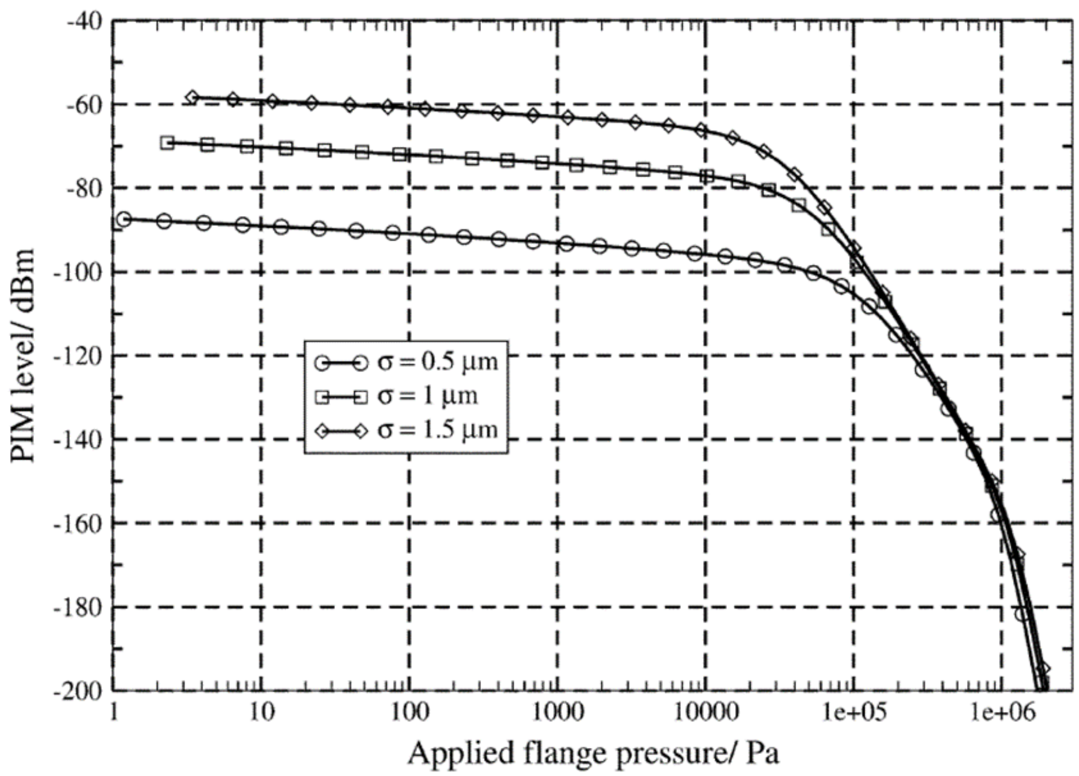
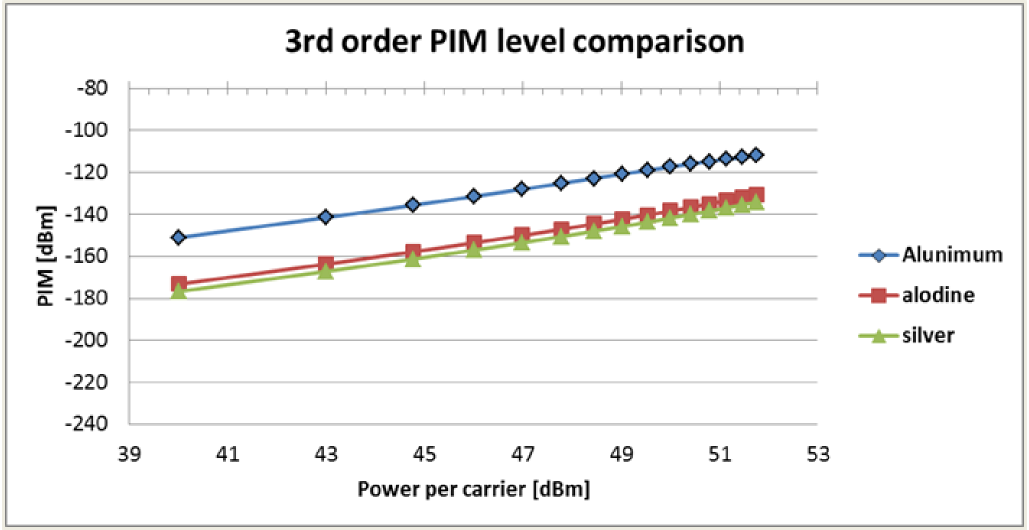
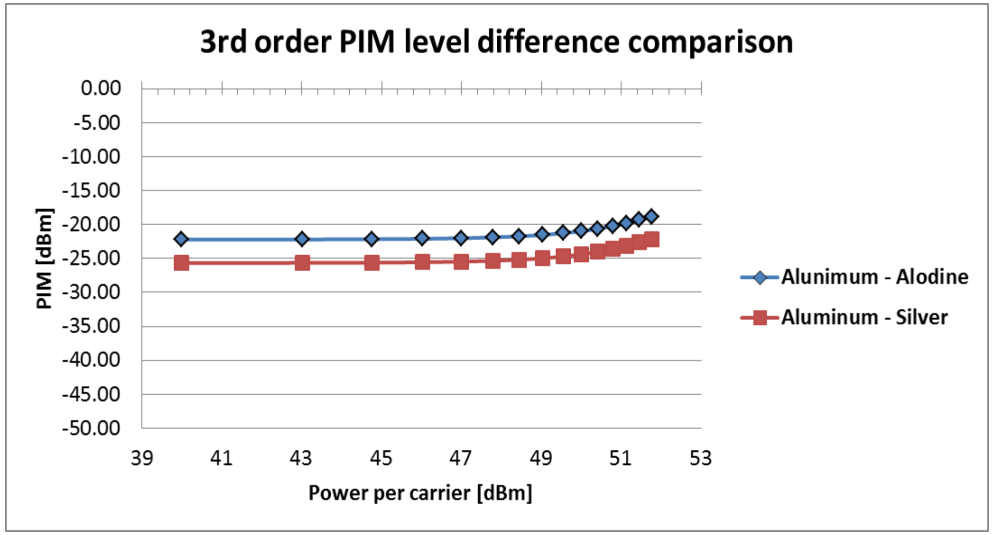
# Surface roughness and PIM behaviour




- Surface roughness shows effect on high PIM level in the low contact pressure region.
- The PIM level is, however, converging with the high contact pressure. (> ~ 1 MPa for silver)

# Different materials vs. PIM analysis




| Contact Material | PIM level distance in average [dB] |
|---|---|
| Aluminium vs. Alodine | -21.12 |
| Aluminium vs. Silver | -24.53 |

# Contact pressure calculator for waveguide interface

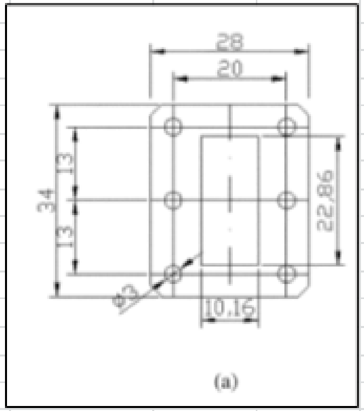
## Contact pressure = Force / area

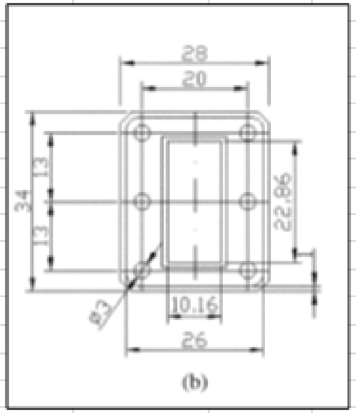
| | | | | |
|---|---|---|---|---|
| torque to a bolt | Tb | 95 | N*cm | |
| nut-factor | K | 0.2 | empirical # | |
| bolt diameter | Db | 2.85 | mm | i.g. M3 |
| contact area | An | 182 | mm^2 | |
| force | F | 1667 | N | |
| number of bolt | N | 6 | | |
| **pressure** | **P** | **54.96** | **Mpa** | |

$$P = (F)/(A_n),$$

$$F = \frac{T_B}{K \cdot D_B}$$

$$P = \frac{F}{A} = \frac{T_B}{K \cdot D_B \cdot A} \cdot N\ [Pa]$$




| Plane Flange | | | | Nib Flange | | |
|---|---|---|---|---|---|---|
| An | 677 | mm | Contact area | An | 182 | mm |
| af | 34 | mm | flange wide dimension | af | 34 | mm |
| bf | 28 | mm | flange narrow dimension | bf | 28 | mm |
| a_rf | 22.86 | mm | RF wide dimension | a_rf | 22.86 | mm |
| b_rf | 10.16 | mm | RF narrow dimension | b_rf | 10.16 | mm |
| Db | 3 | mm | Bolt hole diameter | hole dia | 3 | mm |
| | | | | nib thickness | 1.5 | mm |

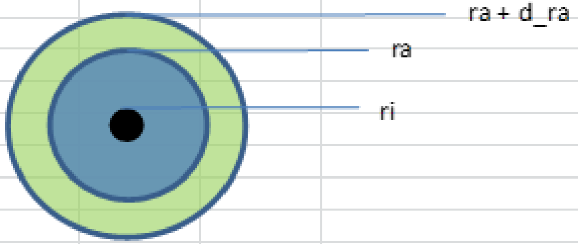
# Contact pressure calculator for coaxial interface (informative)

Contact pressure at coaxial connector is dependent on the mechanical structure and belongs to supplier confidential information. Therefore the torque values of the supplier recommendation is to reference.

| | | | |
|---|---|---|---|
| torque to the thread | Tb | 90 | N*cm |
| nut-factor | K | 0.2 | empirical # |
| contact width | d_ra | 1 | mm |
| contact area | An | 102.1 | mm^2 |
| force | F | 4500 | N |
| **pressure** | **P** | **44.07** | **Mpa** |

$$P = (F)/(A_n),$$

$$F = \frac{T_B}{K \cdot D_B}$$




| | | | |
|---|---|---|---|
| An | 102.1 | mm | Contact area |
| ra | 3.5 | mm | outer conductor radius |
| ri | 1.52 | mm | inner conductor radius |
| d_ra | 1 | mm | contact area width |
| er | 1 | air | relative permitivity |

50 Ω coaxial line



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# Scenario #5 study
# Signal characteristics vs. PIM

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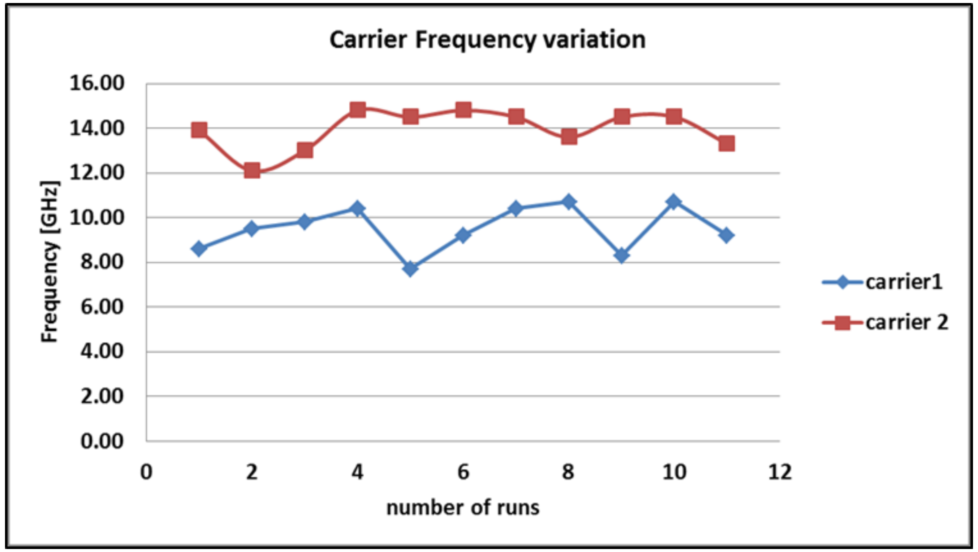
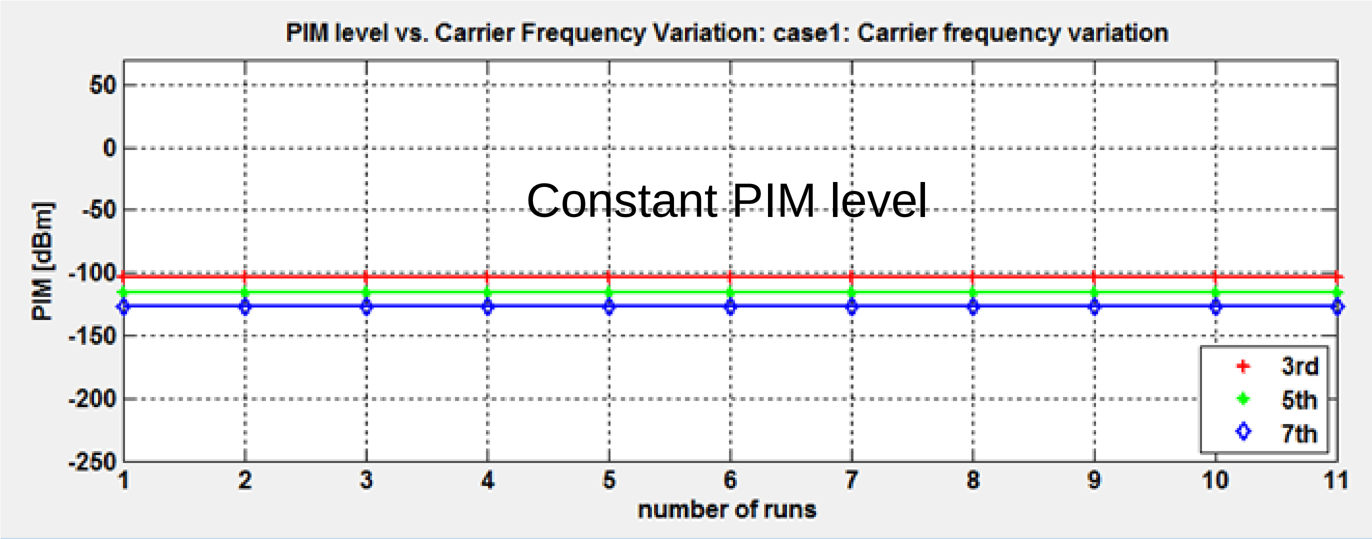
# Carrier frequency variation

Frequencies of carriers were varied.



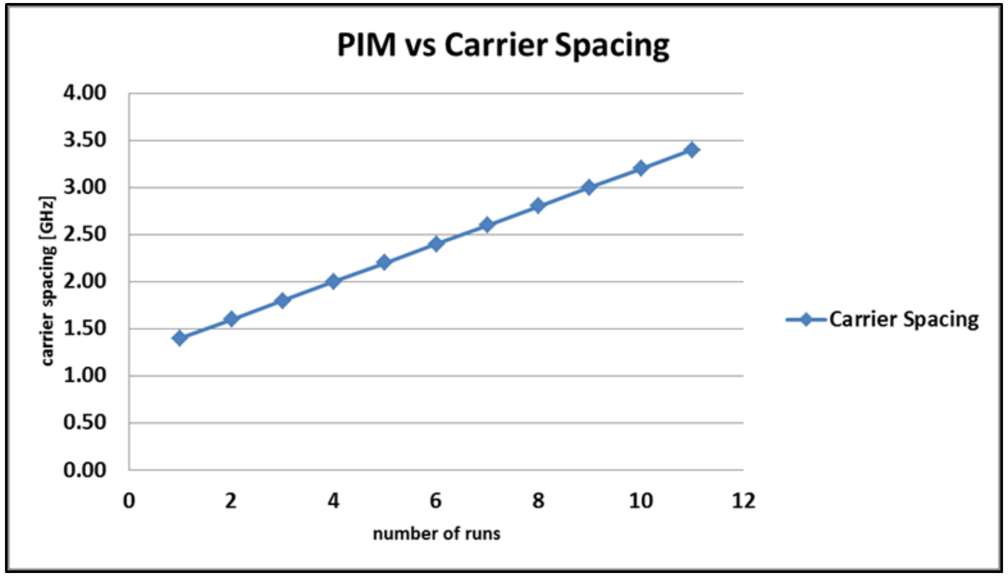

PIM levels at each frequency combination of carriers



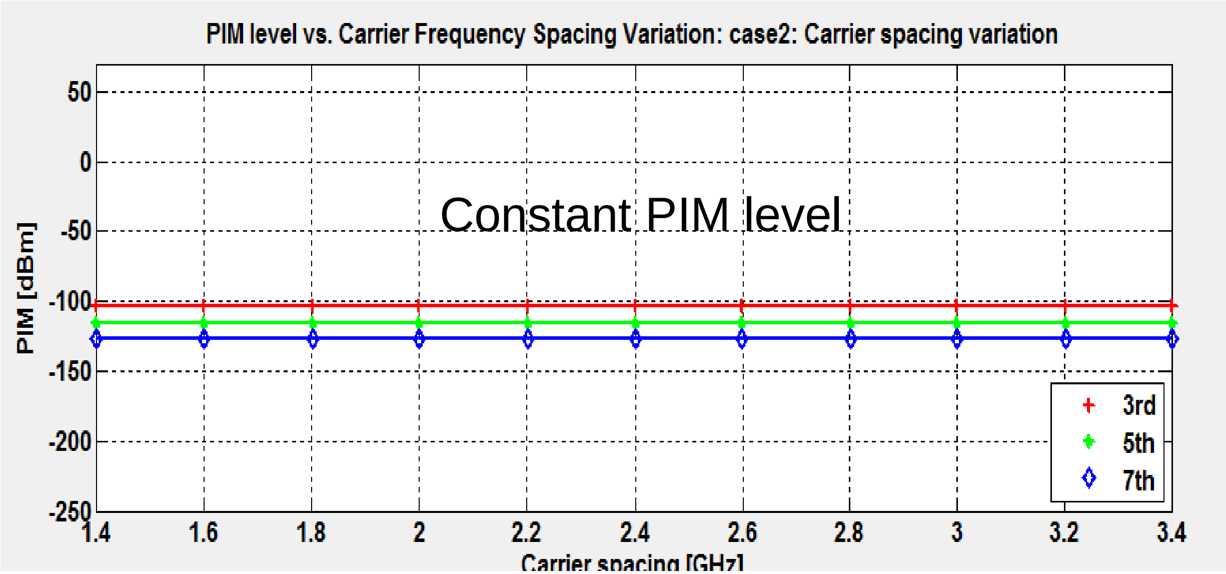

In waveguide transmission lines, PIM amplitude does not change with carrier frequency.

# Carrier spacing variation

Carriers spacing were varied.



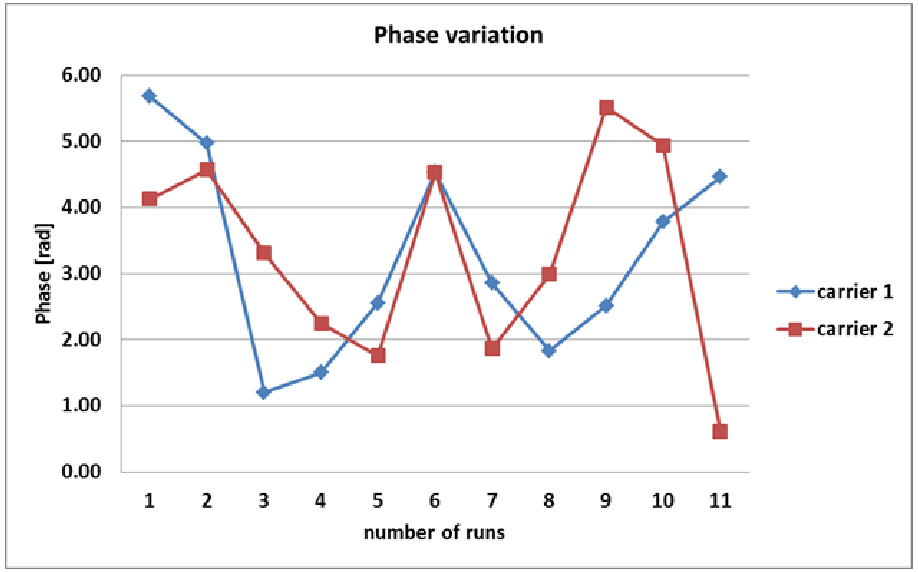

PIM levels at each frequency combination of carriers



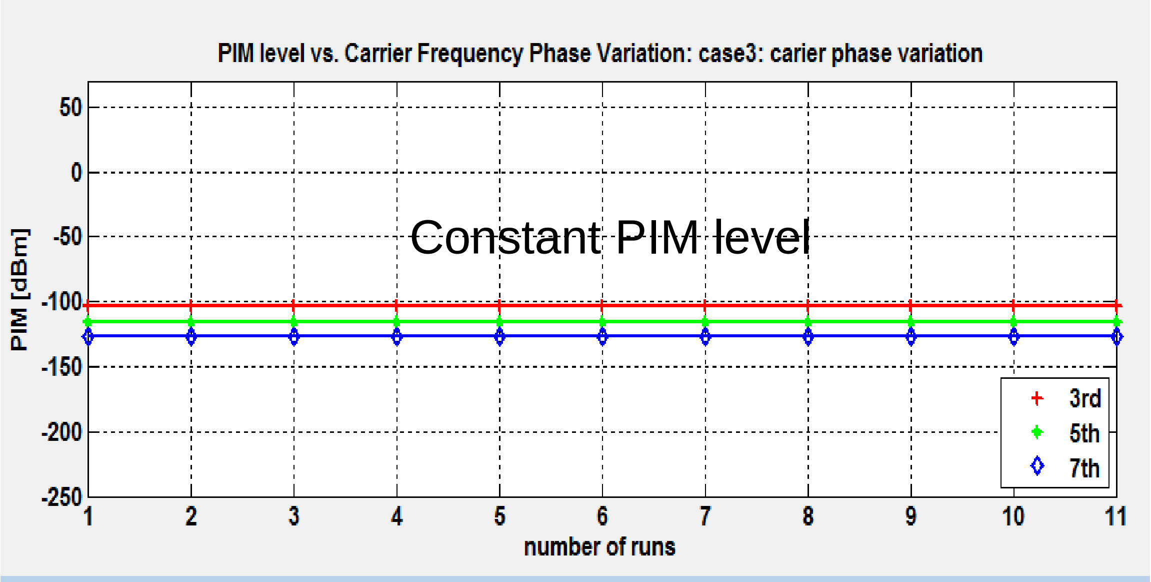

In waveguide transmission lines, PIM amplitude does not change with carrier spacing.

# Carrier phase variation

Carriers spacing were varied.




PIM levels at each frequency combination of carriers




In waveguide transmission lines, PIM amplitude does not change with carrier phases.



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# Signal characteristics vs. PIM: cable length dependency (Coaxial-Line)

Non-linear impedance change at a contact surface is assumed frequency independent.

The number of PIM prone contacts increases with the longer cable length.

A PIM level prediction as a function of the cable length is available based on the approximation function.

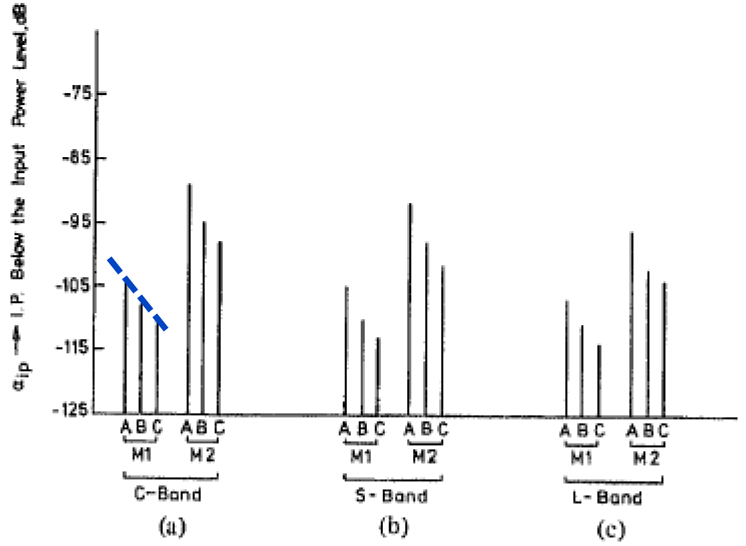


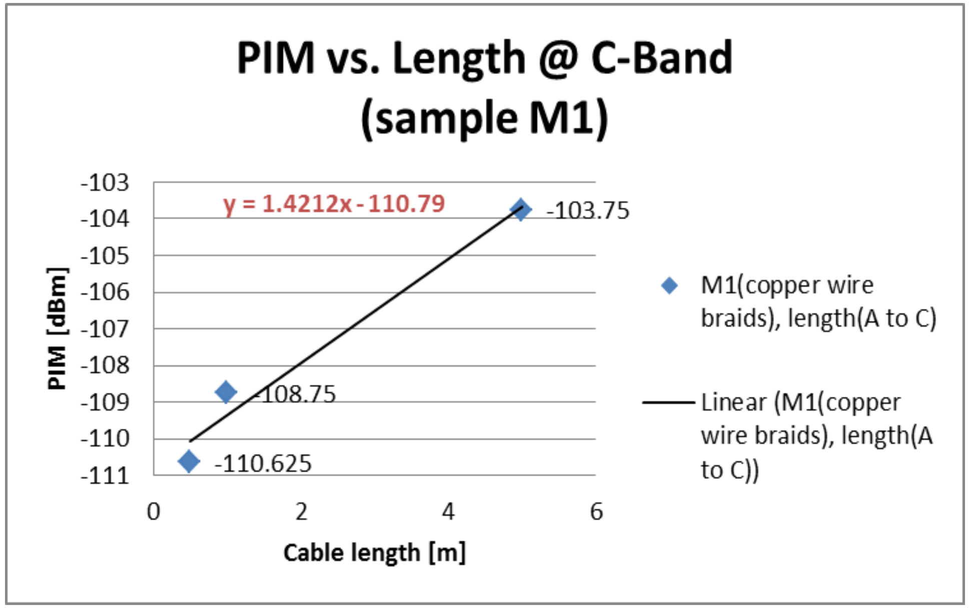

Fig. 4. Relationship between length and intermodulation products at L-, S-, and C-band frequencies for cables M1 and M2. A–Length of the cable sample = 5 m. B–Length of the cable sample = 1 m. C–Length of the cable sample = 0.5 m.

- A: 5 m
- B: 1 m
- C: 0.5 m

- L-Band (1.5 GHz)
- S-Band (3.0 GHz)
- C-Band (5.0 GHz)

- M1: copper wire braid
- M2: tin-plated copper wire braid

Typical length dependent PIM level of coaxial cable was reported in [RD37]



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# Scenario #6 study
# Multicarrier scenarios vs. PIM

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# Algorithm to determine the PIM frequency in multicarrier scenario

$$[\mathbf{f_{PIM}}]_{(\mathbf{n}\times 1)} = [\mathbf{K}]_{(\mathbf{n}\times \mathbf{m})} \cdot [\mathbf{f_{carriers}}]_{(\mathbf{m}\times 1)}$$

The matrix *[K]<sub></sub>*

$$\begin{bmatrix} f_{PIM_1} \\ \vdots \\ f_{PIM_n} \end{bmatrix} = \begin{bmatrix} K_{11} & \cdots & K_{1m} \\ \vdots & \ddots & \vdots \\ K_{n1} & \cdots & K_{nm} \end{bmatrix} \cdot \begin{bmatrix} f_{carrier_1} \\ \vdots \\ f_{carrier_m} \end{bmatrix}$$

$$n = \frac{m!}{k_1! \cdot k_2! \cdots k_i!}$$

***n*** different combination of multiplication coefficients in ***K***-matrix

**"first-zone"** product condition (in the near of carrier frequency)

$$K_{n,m} = \sum_{l=1}^{m} K_{nl} = 1$$

$$f_{Rx_1} \leq \begin{bmatrix} f_{PIM_1} \\ \vdots \\ f_{PIM_n} \end{bmatrix} \leq f_{Rx_2}$$



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# Example: 3rd order PIM using 3 carriers

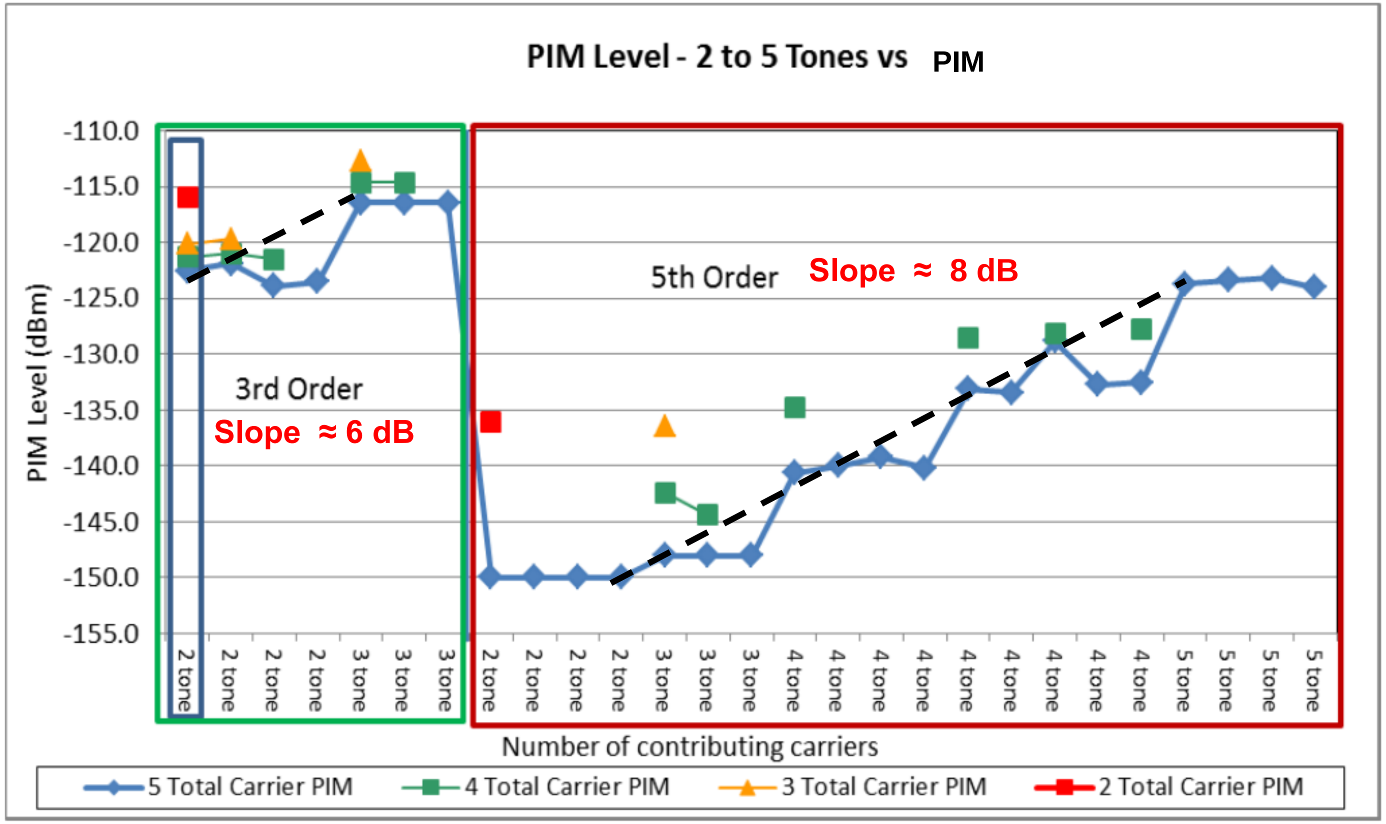
$$\boldsymbol{n} = \frac{\mathbf{3!}}{\mathbf{2!\cdot 1!}} = \mathbf{3}$$

***n*=3** different combination of multiplication coefficients in ***K***-matrix

$$\begin{bmatrix} f_{PIM_1} \\ f_{PIM_2} \\ f_{PIM_3} \end{bmatrix} = \begin{bmatrix} 1 & 1 & -1 \\ 1 & -1 & 1 \\ -1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} f_{c_1} \\ f_{c_2} \\ f_{c_3} \end{bmatrix} = \begin{bmatrix} 1\cdot f_{c_1} + 1\cdot f_{c_2} - 1\cdot f_{c_3} \\ 1\cdot f_{c_1} - 1\cdot f_{c_2} + 1\cdot f_{c_3} \\ -1\cdot f_{c_1} + 1\cdot f_{c_2} + 1\cdot f_{c_3} \end{bmatrix}$$

$$f_{Rx_1} \leq \begin{bmatrix} f_{PIM_1} \\ f_{PIM_2} \\ f_{PIM_3} \end{bmatrix} \leq f_{Rx_2}$$

# Extrapolation of the PIM level with multiple carriers using multi carrier test data




3rd order:

Using 2 carriers PIM test, 3 carriers PIM level can be estimated applying the slope value of 6 dB (for this particular example)

5th order:

Using 2 carriers PIM test, 5 carriers PIM level can be estimated applying the slope value of 8 dB (for this particular example)

**The slope values will be verified during phase 3 during scenario #6**

Reference: Satellite level PIM test from RD49
“*Multicarrier PIM Behaviour and Testing in Communications Satellites*”



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# Analytical investigation of multicarrier inter-modulation level variation (based on the power series expansion PIM model)

*Reference (RD 25): Investigation of multiple f.m./f.d.m. carriers through a satellite t.w.t. operating near to saturation !*

$$V_{in}(t) = \sum_{n=1}^{\infty} b_n \cos(\omega_n t) \longrightarrow \boxed{\text{PIM model (power series expansion)}} \longrightarrow V_{out}(t) = \sum_{r=1}^{\infty} a_r (V_{in}(t))^r$$

$$PIM_r = a_r \cdot \frac{r!}{2^{r-1}} \cdot \frac{1}{\alpha!\,\beta!\,\gamma!\cdots} \cdot (b_1{}^{\alpha} \cdot b_2{}^{\beta} \cdots) \cdot cos\{\alpha\omega_1 \pm \beta\omega_2 \pm \gamma\omega_3 \cdots\}$$

$a_r = coefficient\ of\ power\ term$

$b_1, b_2, \cdots = carrier\ amplitudes$

$r(order) = \alpha + \beta + \ ...$

$\alpha, \beta, \cdots = \{0, \in N\}$

$$\boldsymbol{\theta = \frac{1}{\alpha!\,\beta!\,\gamma!\cdots}}$$

- Assuming all the input carriers have the same amplitude, each product type for each order can be calculated.

- Within each order it is possible to choose a reference and calculate the relative amplitude of the other products, compared to the reference amplitude.



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# Example for relative PIM amplitude using active intermodulation model

$$\theta(normalised\ amplitude) = \frac{1}{\alpha!\,\beta!\,\gamma!\cdots}$$

| | Multiplication factor for carrier frequencies | | | | | | | Using active intermodulation mathematical model | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PIM order | α | β | γ | δ | ε | ζ | η | normalised amplitude for products (θ) | relative level to reference | relative level to reference (dB) | number of carriers | slope average (dB) | roll-off relative to $3^{rd}$ order(dB) |
| 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0.500 | 1 | Reference | 2 | 6.0 | 0 |
| 3 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1.000 | 2 | 6.02 | 3 | | |
| 5 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0.083 | 1 | Reference | 2 | 10.8 | 15.56 |
| 5 | 3 | 1 | 1 | 0 | 0 | 0 | 0 | 0.167 | 2 | 6.02 | 3 | | |
| 5 | 2 | 2 | 1 | 0 | 0 | 0 | 0 | 0.250 | 3 | 9.54 | 3 | | |
| 5 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0.500 | 6 | 15.56 | 4 | | |
| 5 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1.000 | 12 | 21.58 | 5 | | |
| 7 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 0.007 | 1 | Reference | 2 | 8.6 | 37.15 |
| 7 | 5 | 1 | 1 | 0 | 0 | 0 | 0 | 0.008 | 1.2 | 1.58 | 3 | | |
| 7 | 4 | 2 | 1 | 0 | 0 | 0 | 0 | 0.021 | 3 | 9.54 | 3 | | |
| 7 | 3 | 3 | 1 | 0 | 0 | 0 | 0 | 0.028 | 4 | 12.04 | 3 | | |
| 7 | 4 | 1 | 1 | 1 | 0 | 0 | 0 | 0.042 | 6 | 15.56 | 4 | | |
| 7 | 3 | 2 | 2 | 1 | 0 | 0 | 0 | 0.042 | 6 | 15.56 | 4 | | |
| 7 | 2 | 2 | 2 | 1 | 0 | 0 | 0 | 0.125 | 18 | 25.11 | 4 | | |
| 7 | 2 | 1 | 1 | 1 | 1 | 1 | 0 | 0.500 | 72 | 37.15 | 6 | | |
| 7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1.000 | 144 | 43.17 | 7 | | |

- For $3^{rd}$ order PIM:
  - ✓ 3 carrier PIM level is 6 dB higher than the two carrier PIM level
- For $5^{th}$ order:
  - ✓ 5 carrier PIM level is 21.5 dB higher than two carrier

**In this investigation for the PIM level variation, no phase information was included. Therefore, the straight forward increase of PIM level with increasing number of carrier need to be investigated using phase information based on a reliable PIM model instead power series model**

# Scenario #7 study
# Modulated schemes vs. PIM

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# Introduction

- There were not

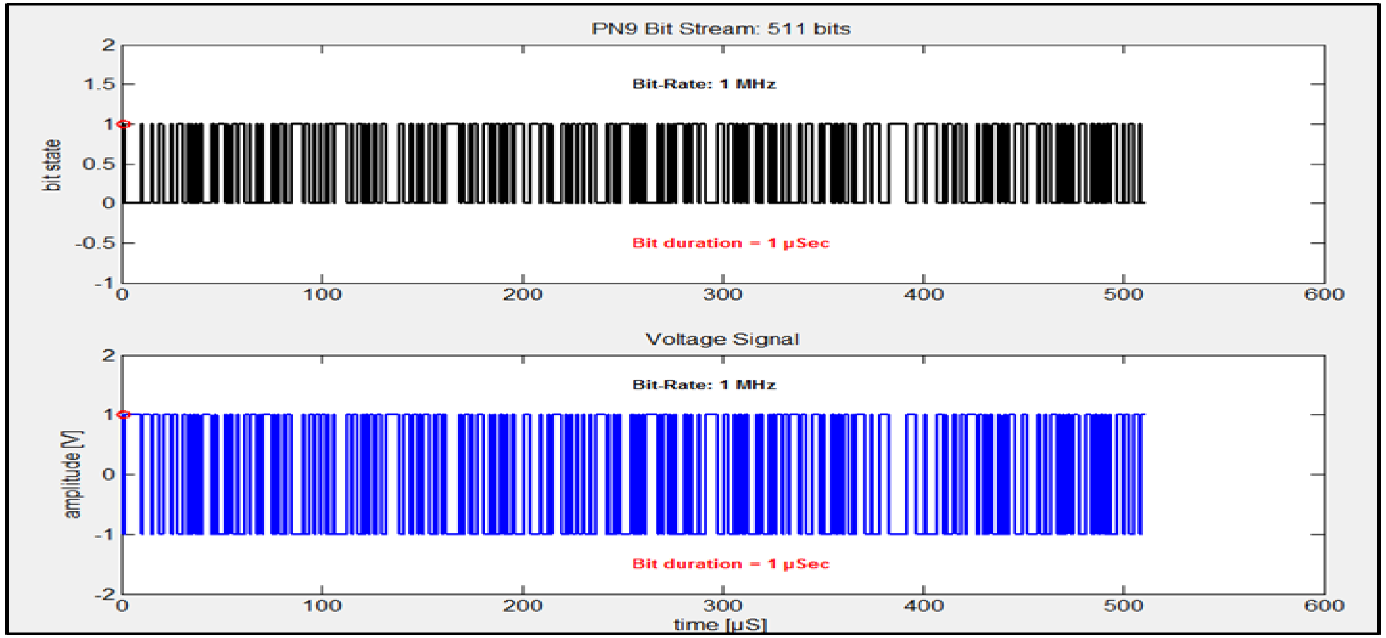
# Modulation signals for PIM investigation

- PN9 bit was proposed as data bit stream.
- A mapping between data bits and symbol is the fundamental step for each digital modulation scheme.
- Generally, the modulations can be applied for amplitude, frequency or phase changes.
- PSK-Modulation uses the phase as carrier of information coded by the data bits/symbols
- QAM utilises both the amplitude and phase of carrier based on the bit/symbol data signal.

- In the developed software from bit-stream generation to the PIM analysis with different modulation scheme will be implemented.

# PN9 data bit stream and up-sampling

- The PN9 sequence is required as input test digital data stream.
- The length of the sequence is $L = 2^9 - 1$
- The sequence is cyclic and has pseudo random characteristic





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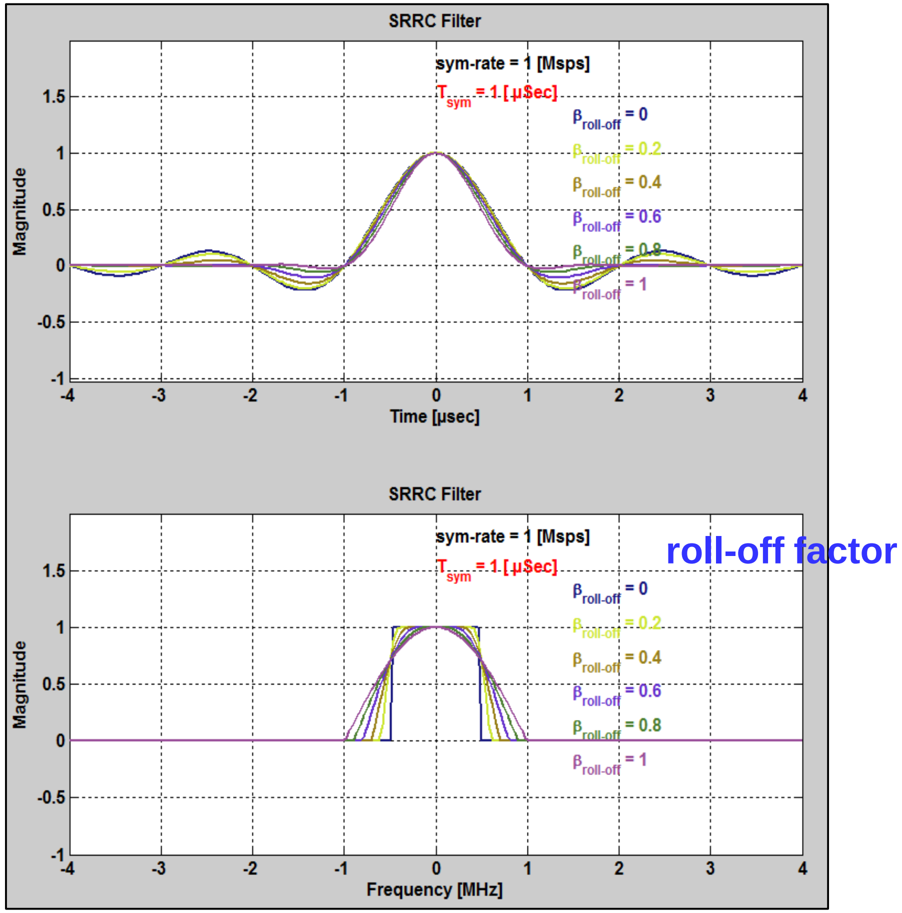
# Pulse-shaping rrc-filter (fundamental concept)



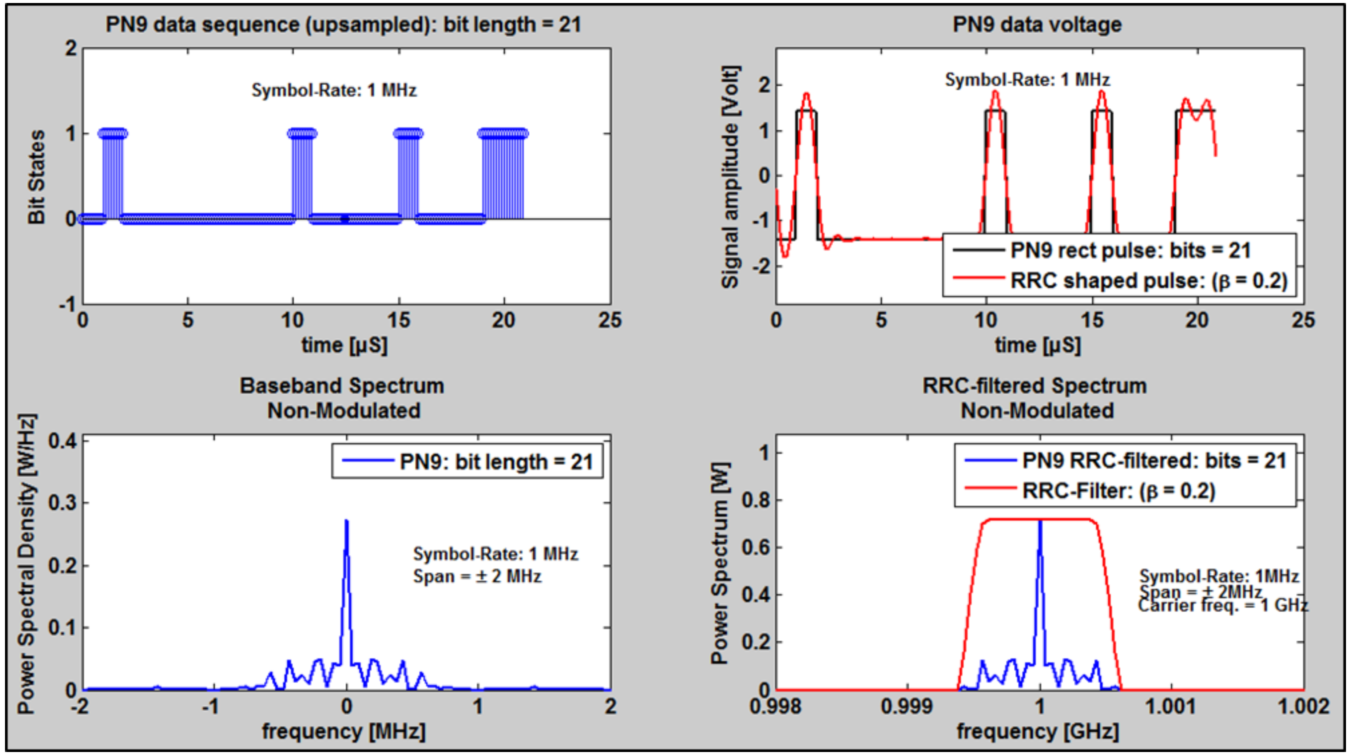

- Pulse shaping with RC(raised cosine) filter is often used for the digital modulated signal to limit the bandwidth.

- The bandwidth of the data is equal to the (1+roll-off)*symbol-rate.

  - ➢ The signal bandwidth with roll-off = 0.2 and 1 MHz symbol rate is 1,2 MHz.

# Pulse shaped up-sampled baseband signal (basic concept)

- Data bits are up-sampled in the bit duration time.
- The up-sampled rectangular pulse signal will be filtered with the specific bandwidth.
- Shaped-pulse contains the signal spectrum with the bandwidth of the filter including β(roll-off) values



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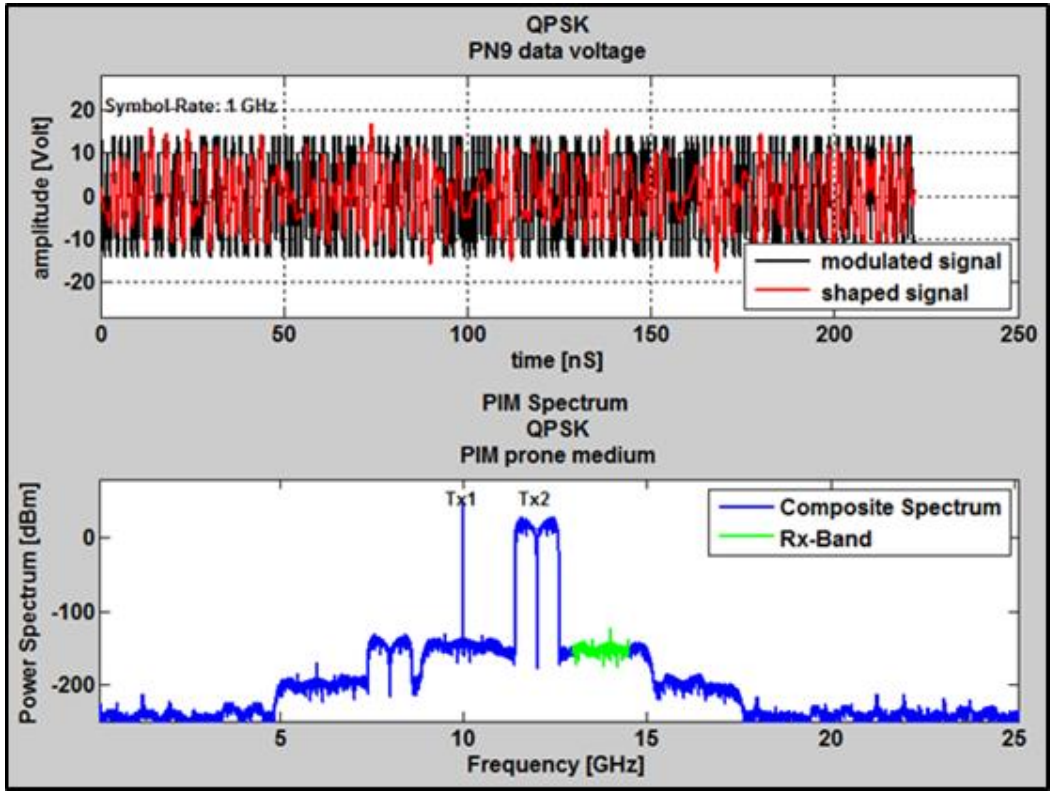
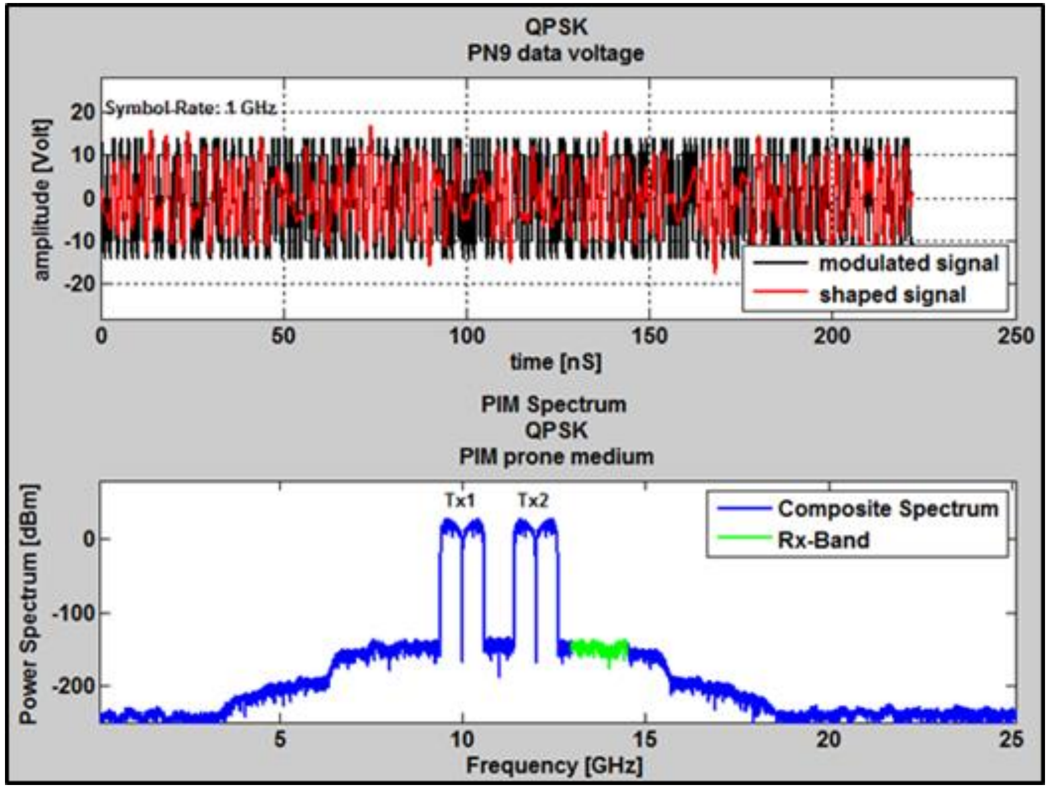
# Example of PIM spectrum with modulation (QPSK)

The signal spectrum will be spread with the digital modulation.
The PIM signal will be correspondingly convolved with each other.




Typical PIM behaviour of CW and Modulated signals




Typical PIM behaviour of two Modulated signals



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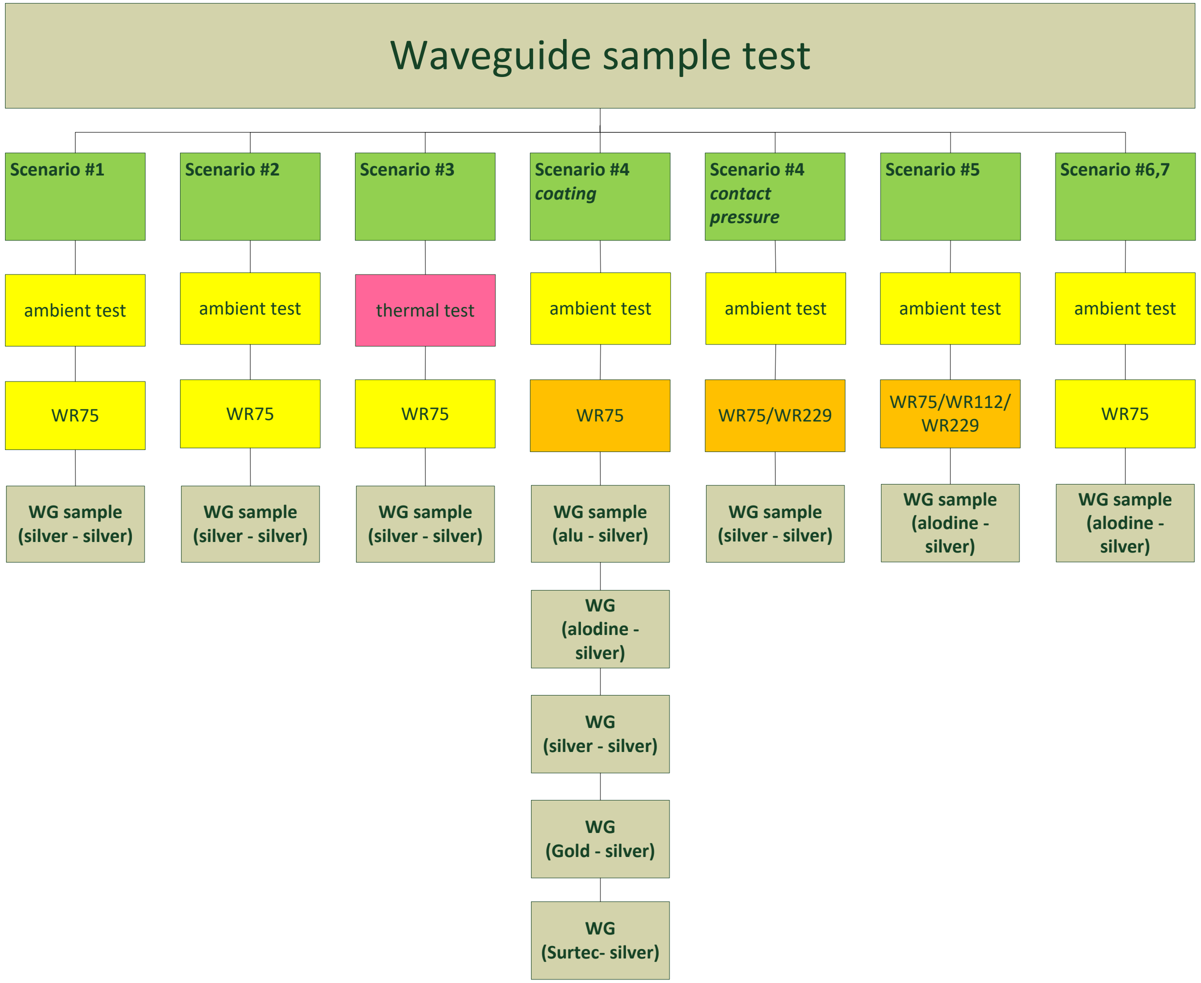
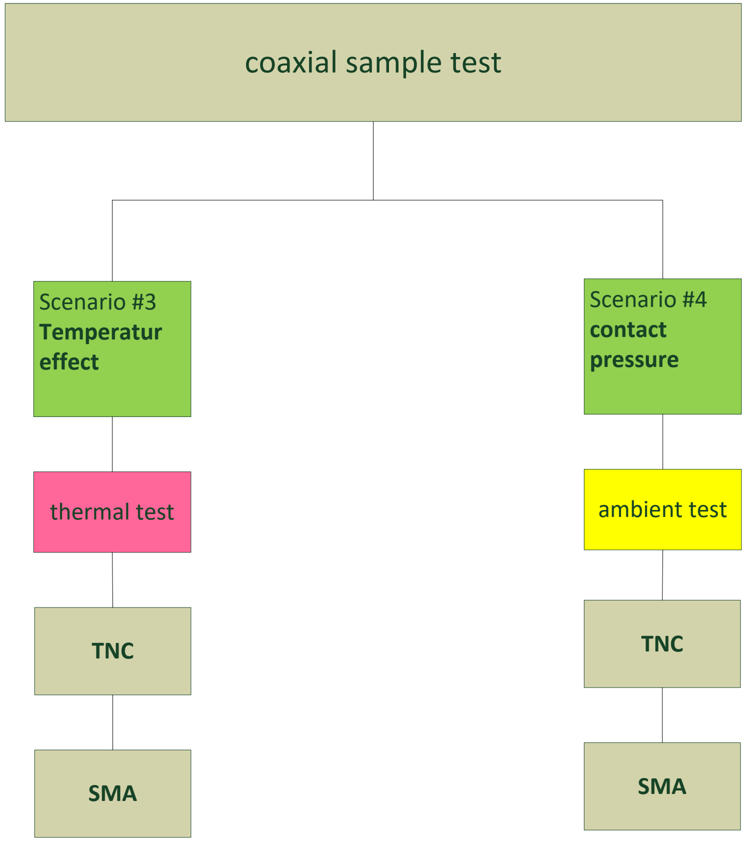
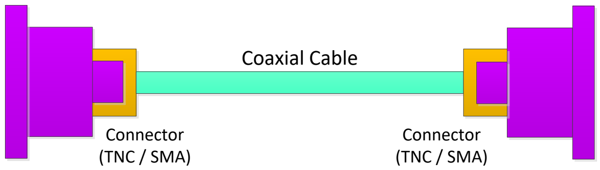
# Test plan

**Test plan was established for the proposed 7 scenarios for waveguide contact interface and coaxial cables.**




Waveguide-Coax Transtion

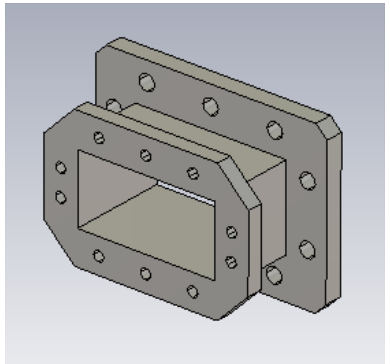


# Tests and test samples

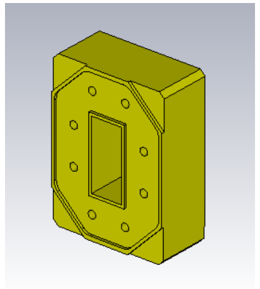
- The test campaign consists of 7 different scenarios.
- Detailed design of test samples.

$$P = (F)/(A_n),$$

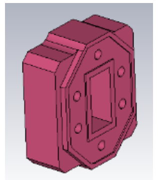
$$F = \frac{T_B}{K \cdot D_B}$$



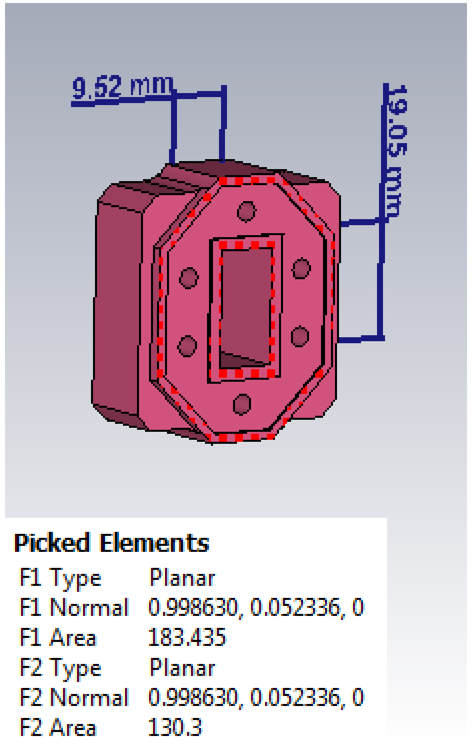
C-Band WG sample

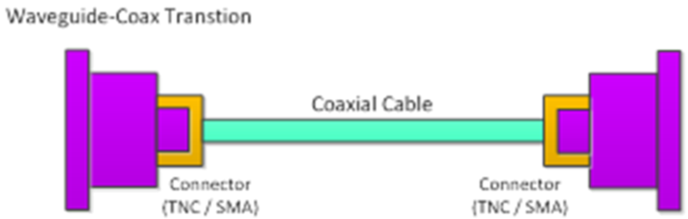


X-Band WG sample



Ku-Band WG sample



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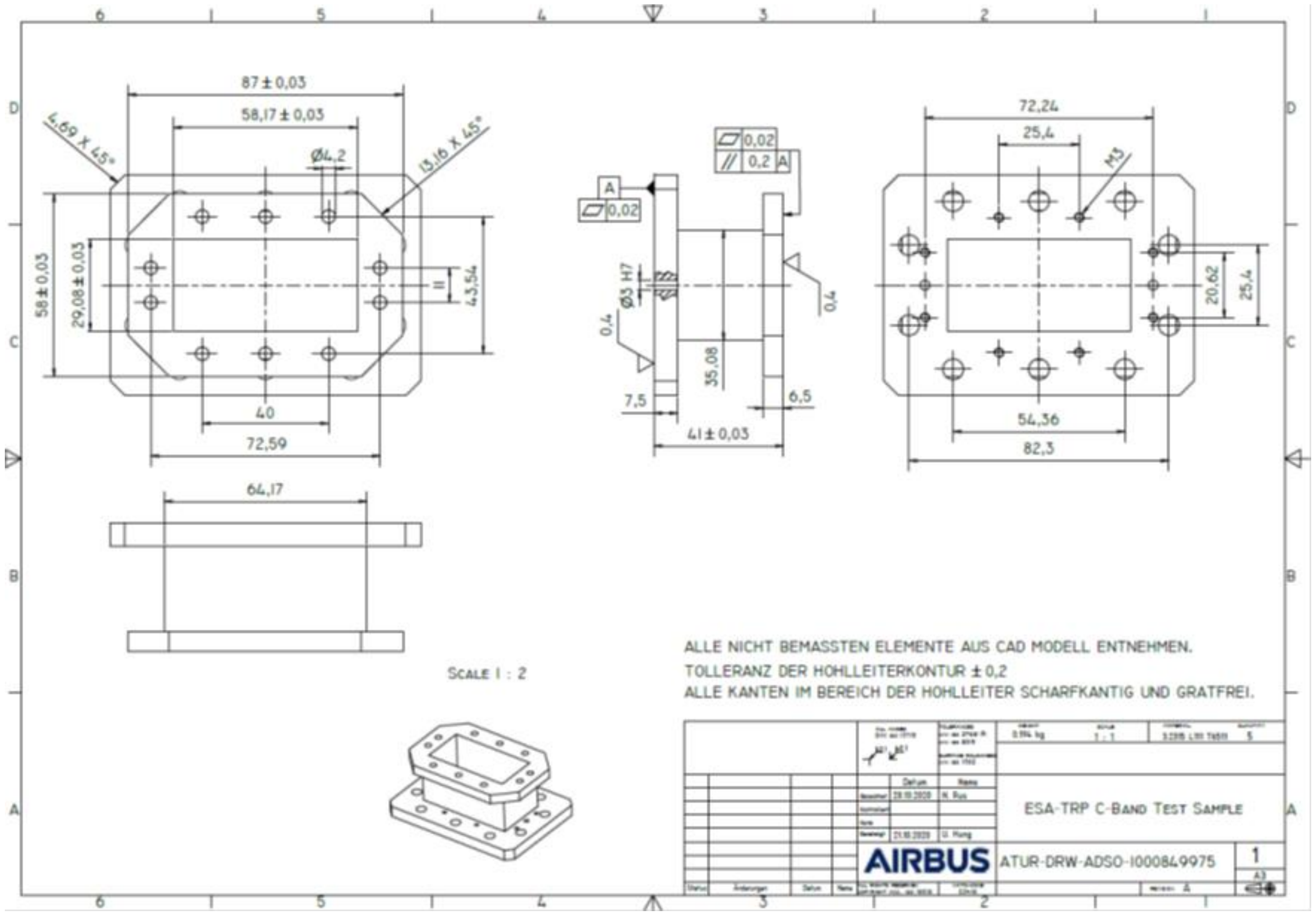
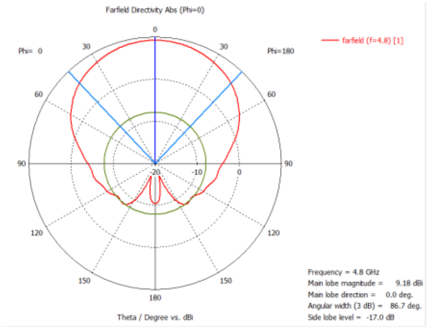
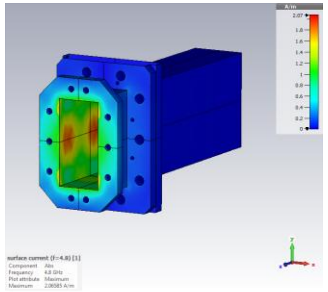
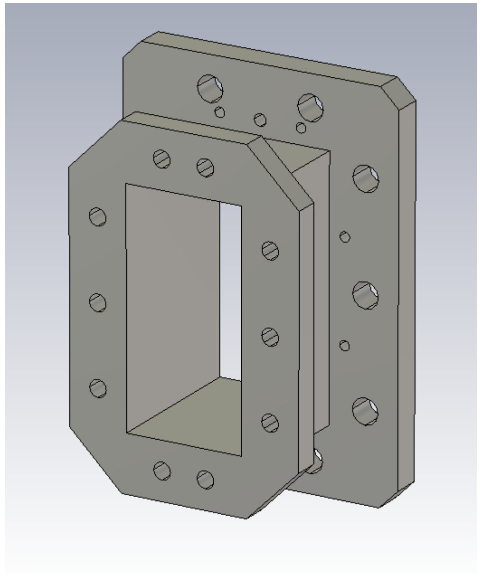
# C-Band waveguide test sample drawing & surface current distribution area

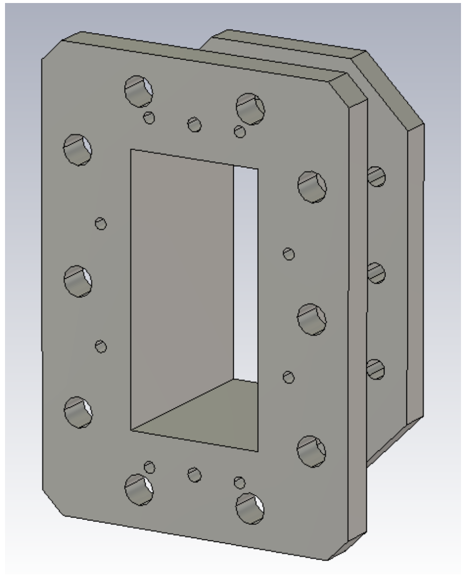




front side



Rear side



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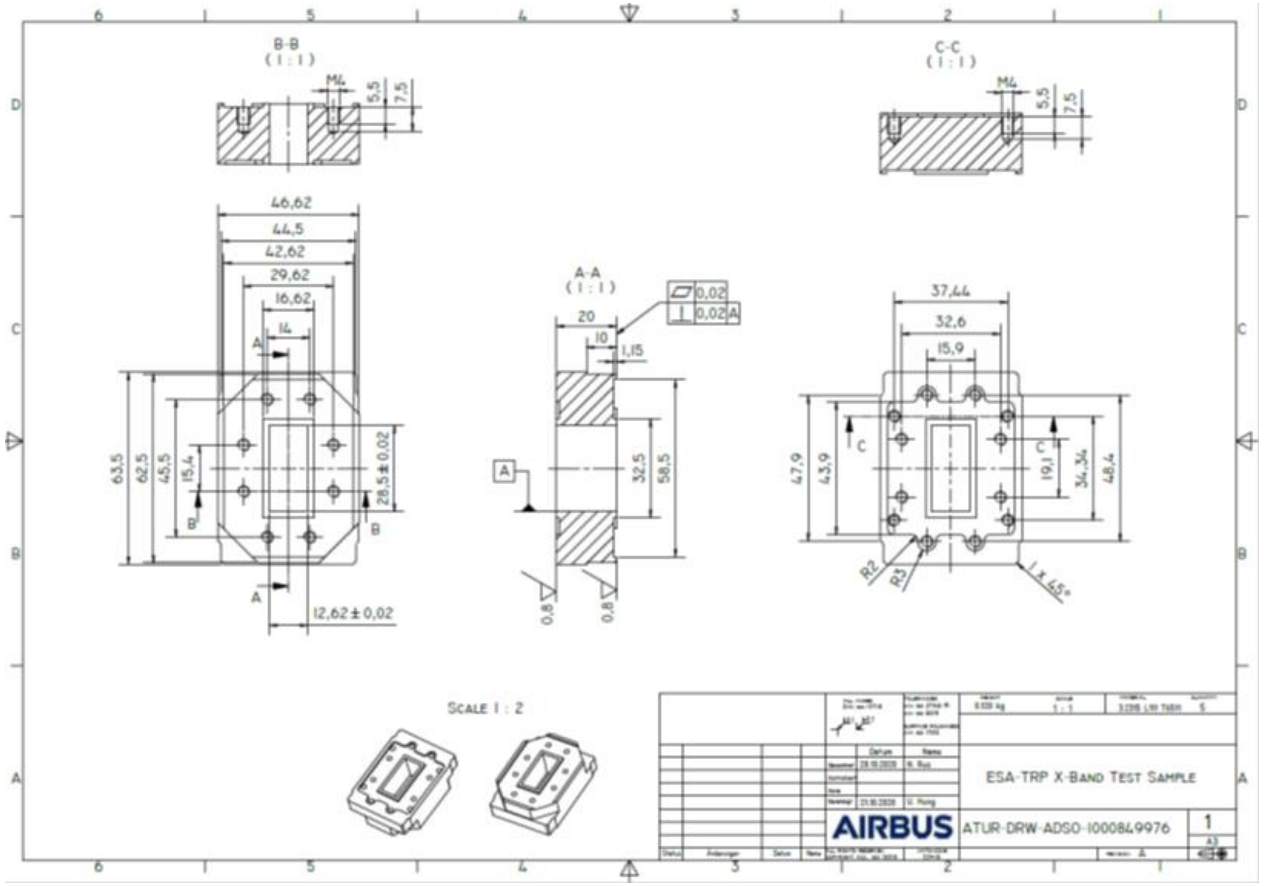
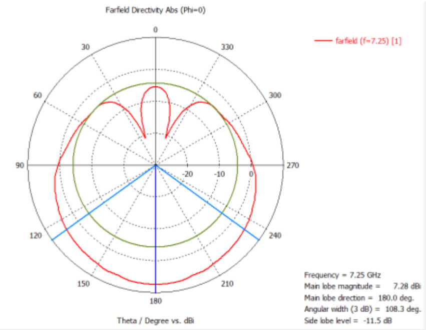
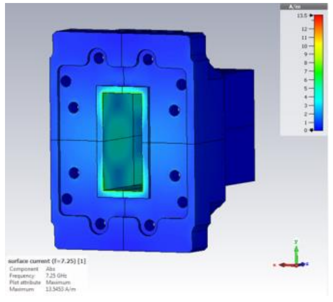
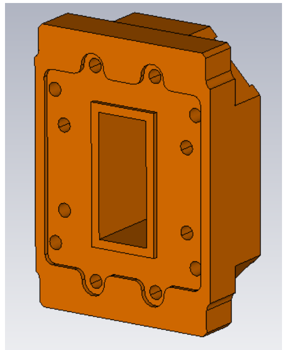
# X-Band waveguide test sample drawing & surface current distribution area

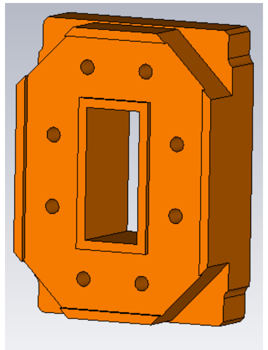




Front side



Rear side



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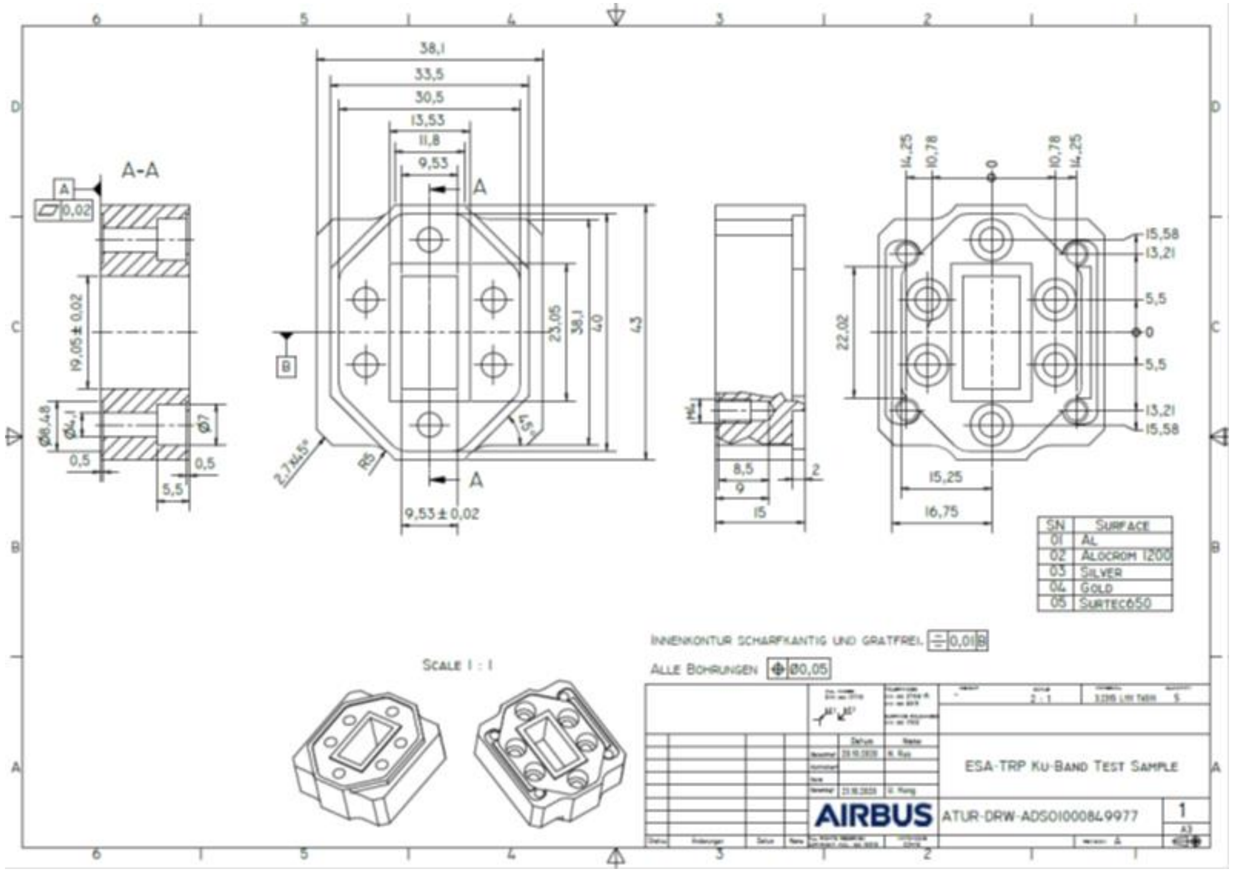
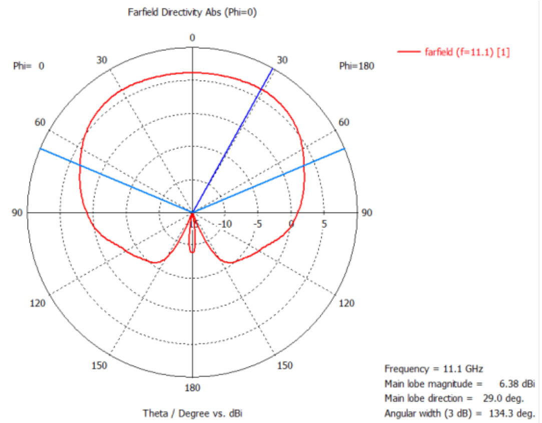
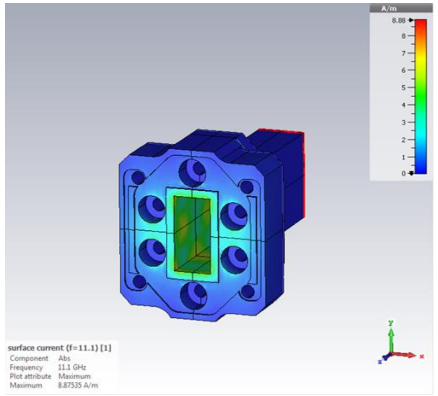
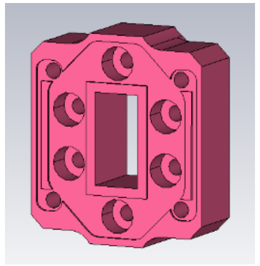
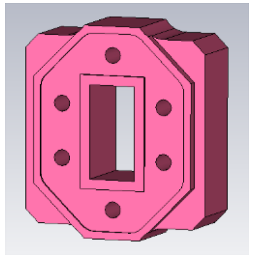
# Ku-Band waveguide test sample drawing & surface current distribution area



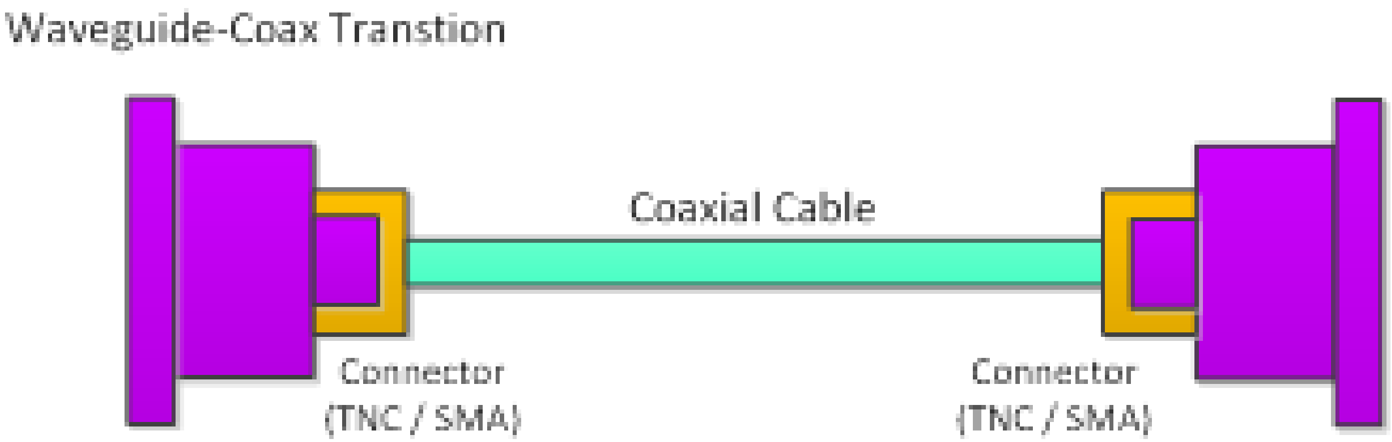



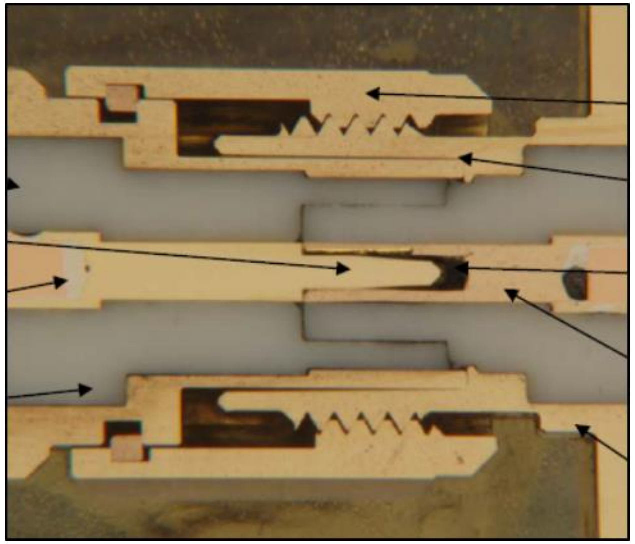



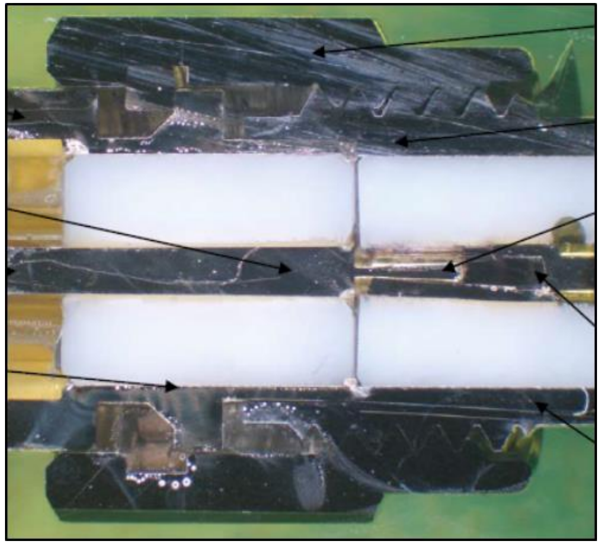


Front side


Rear side

# Coaxial test sample assembly





# Phase 3

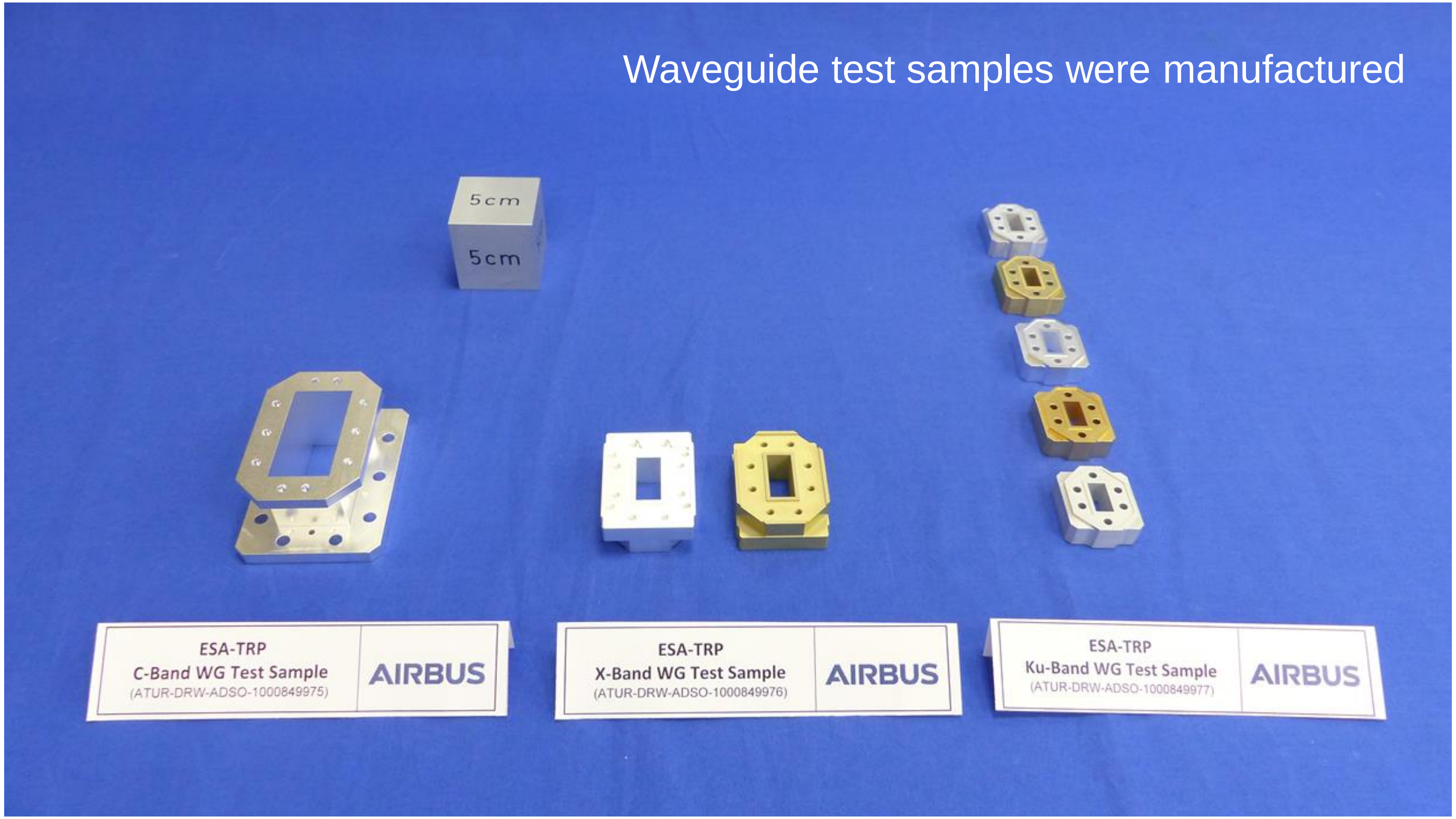
## Definition, manufacturing and testing

# Phase 3 overview

**Phase 3: Definition, manufacturing and testing**

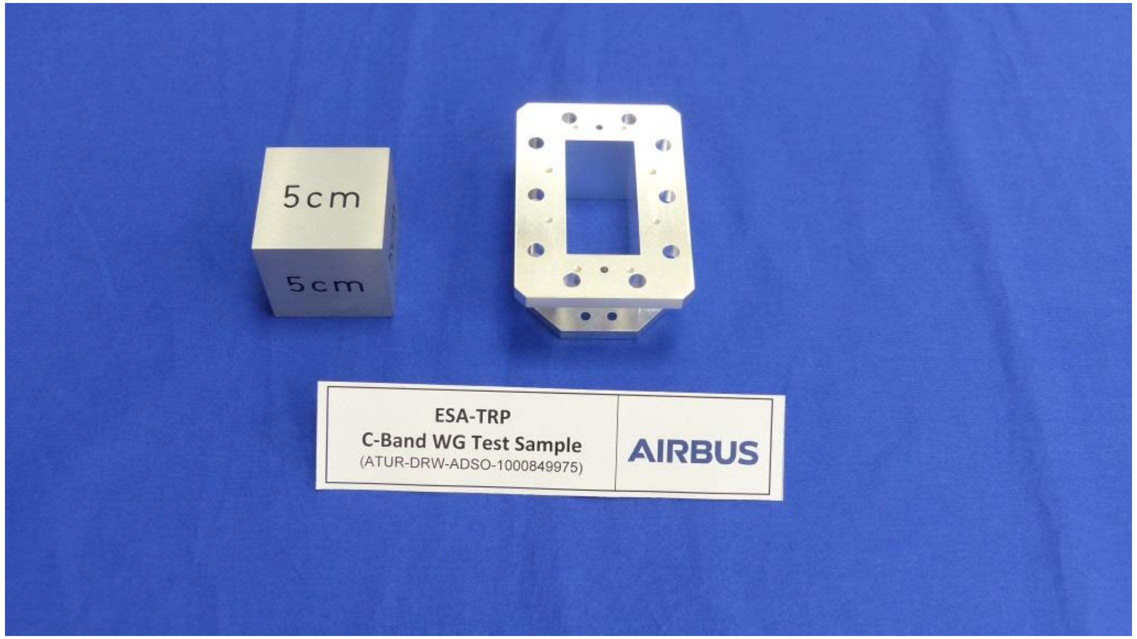
- **definition of hardware**
- **manufacturing**
- **test campaign**

# Waveguide test samples

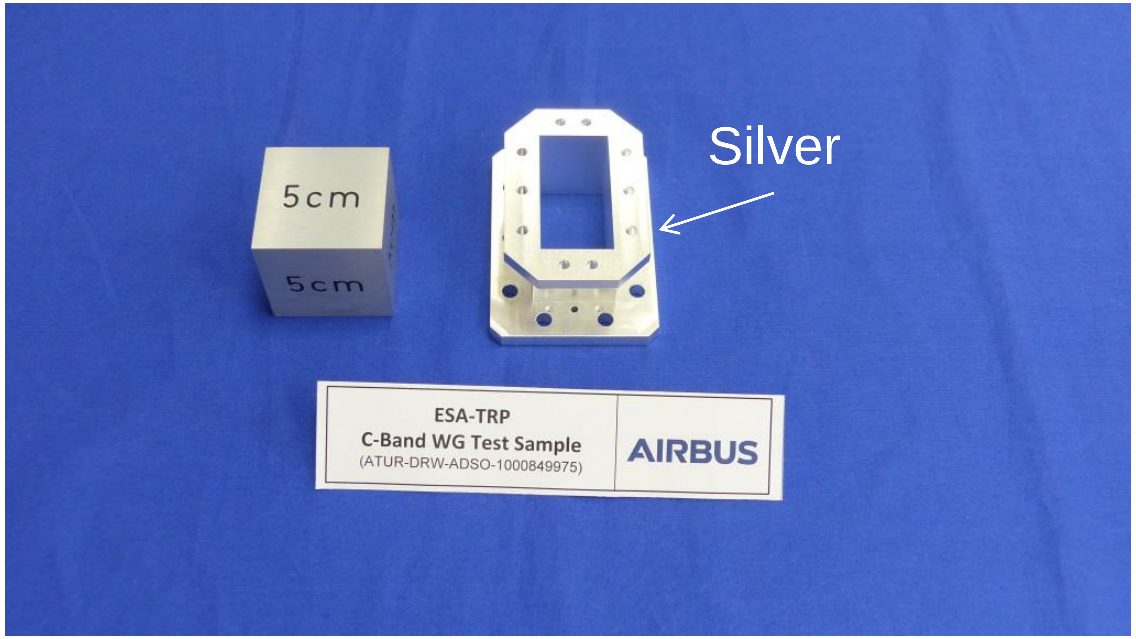


# C-Band waveguide test sample

Rear side (contacting side to the test setup)

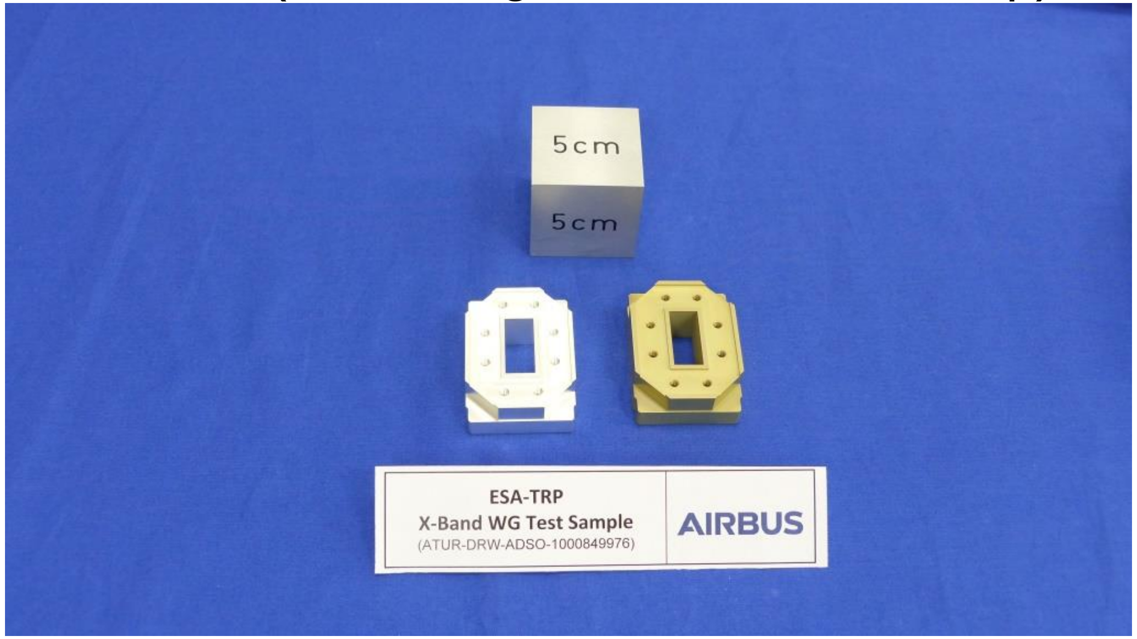



front side

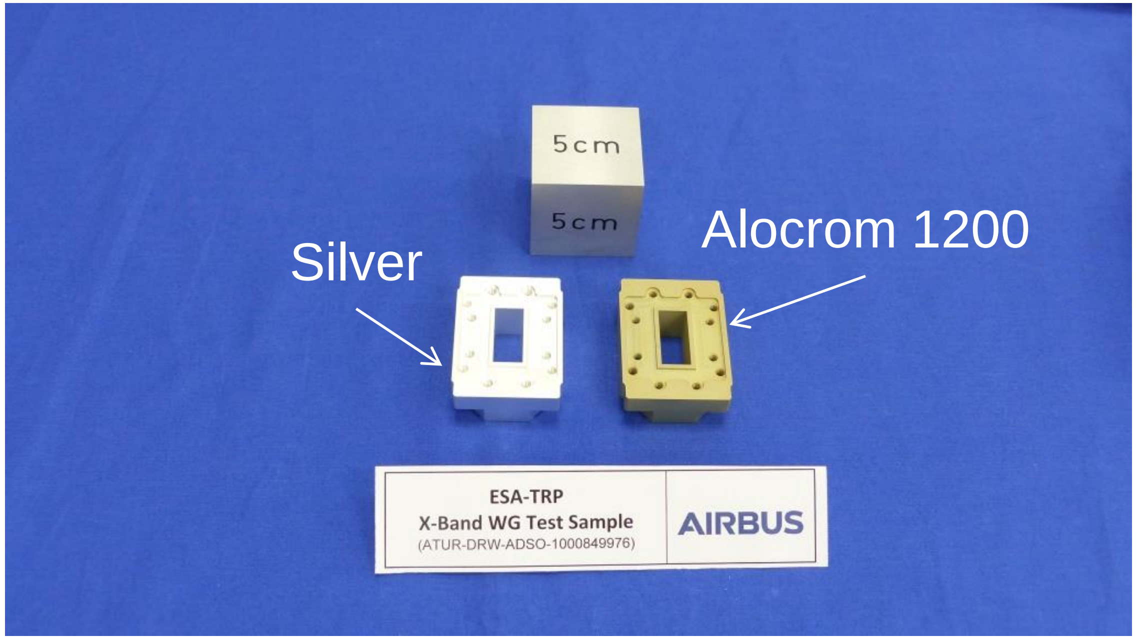


# X-band waveguide test samples

Rear side (contacting side to the test setup)



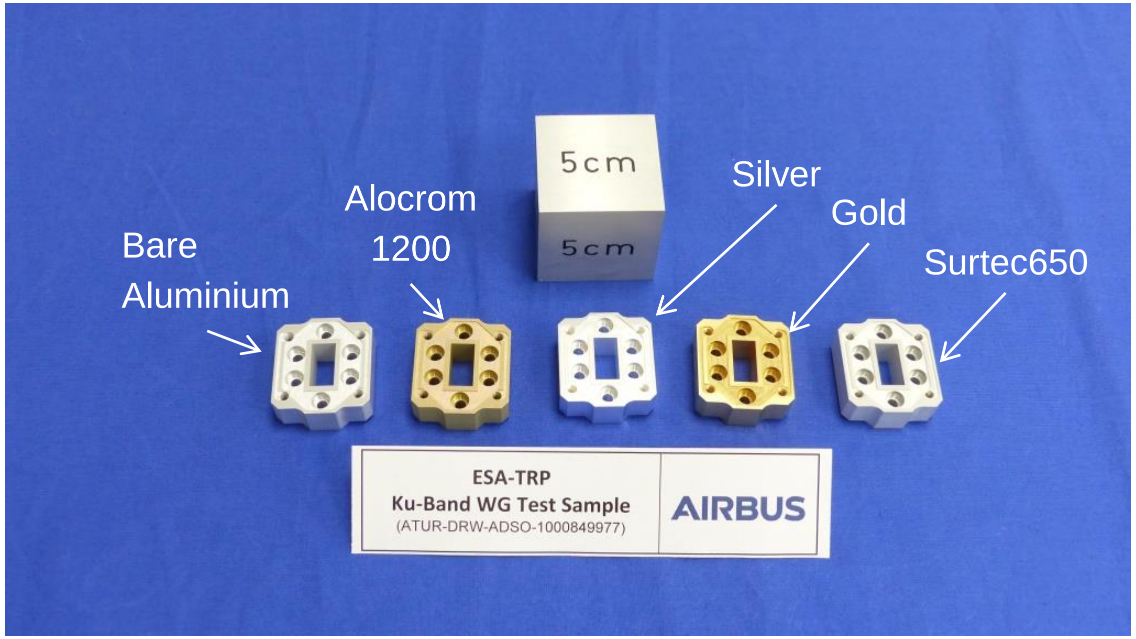

front side



# Ku-band waveguide test samples

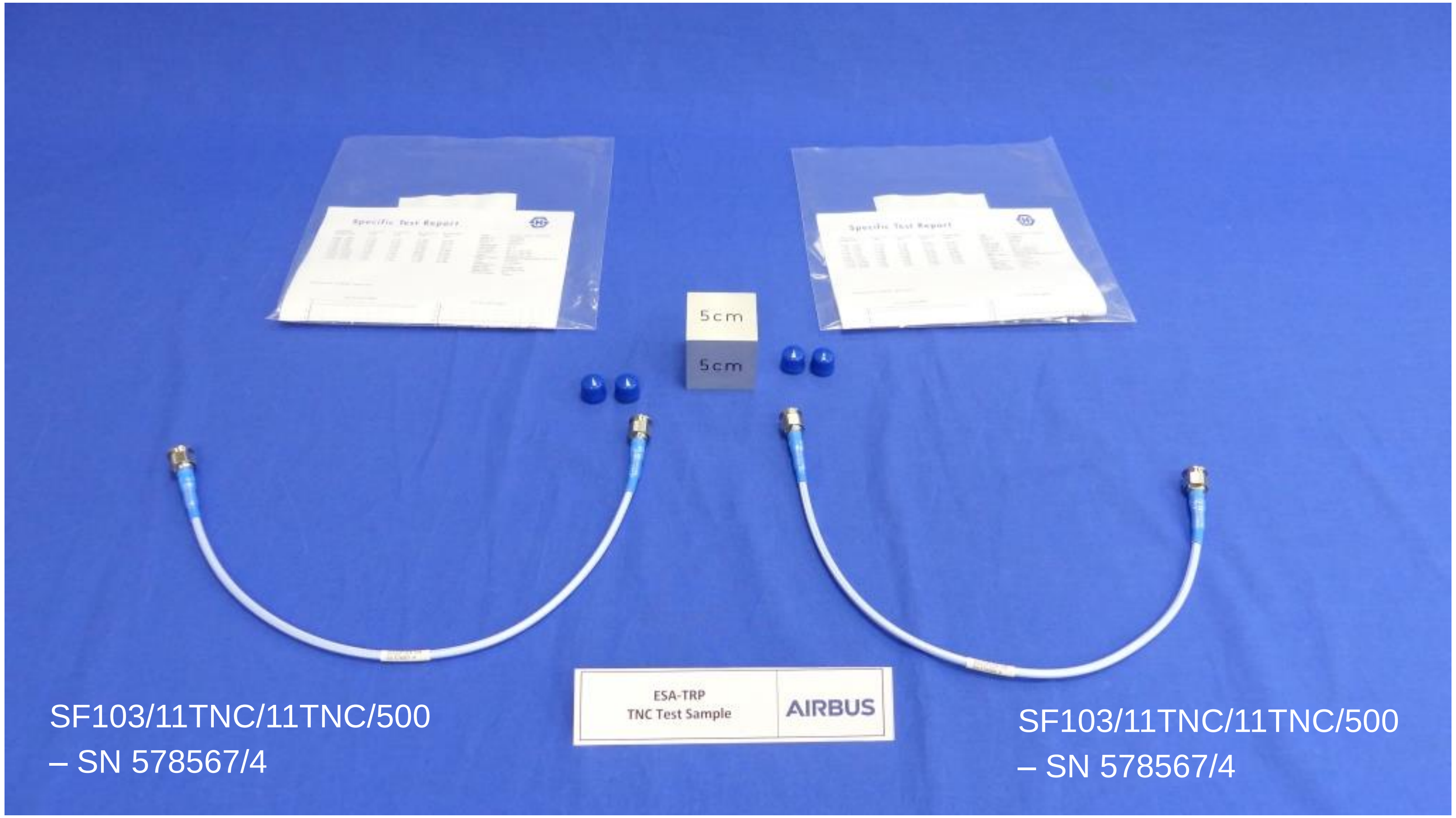
Rear side (contacting side to the test setup)

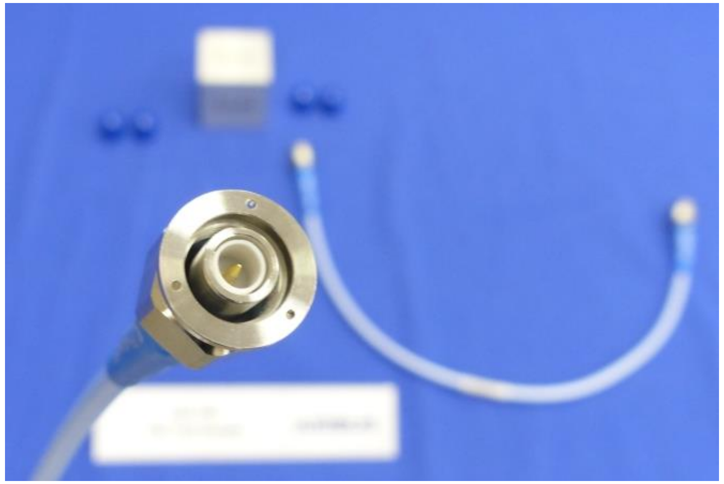

front side



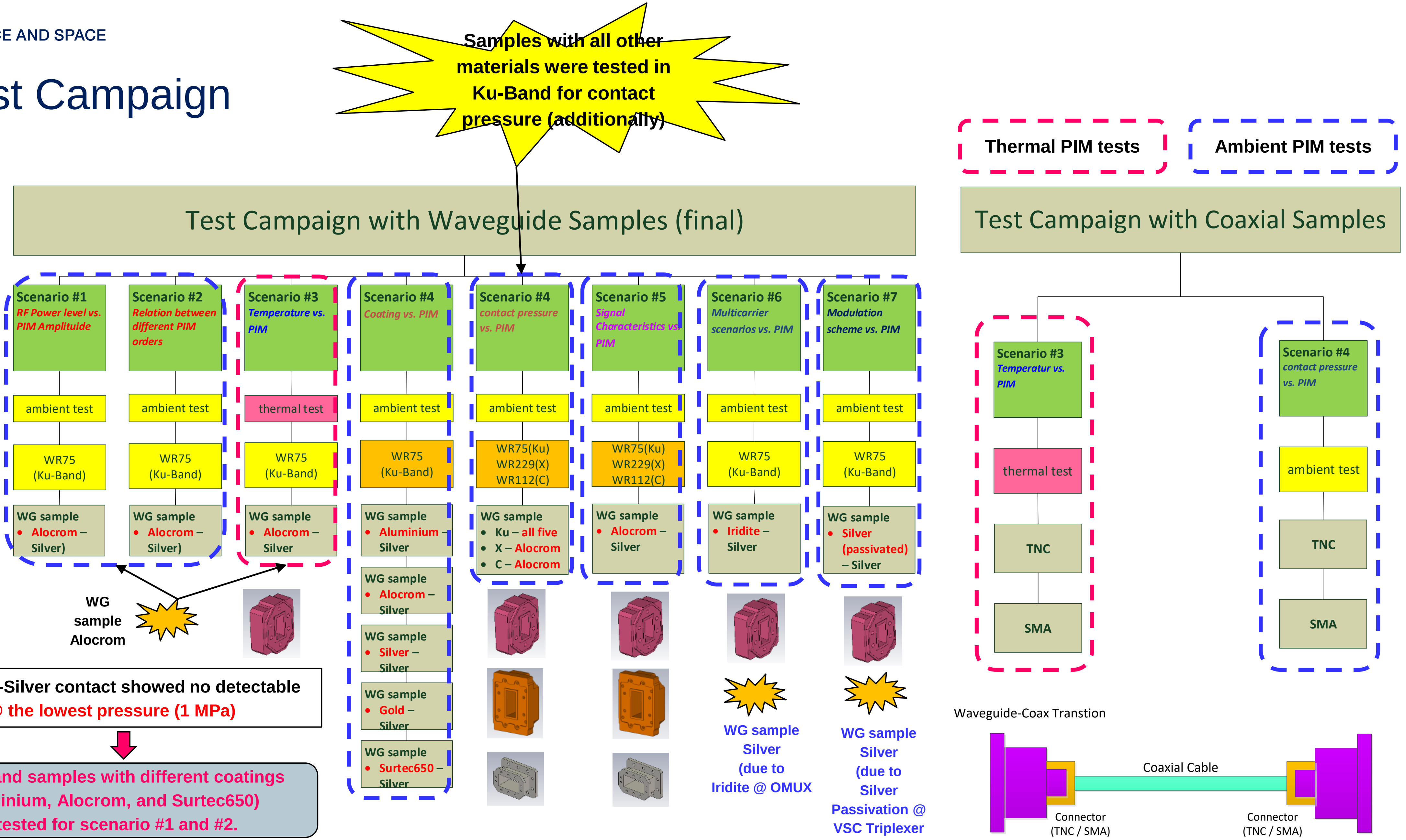
# SMA coaxial test samples

# TNC coaxial test samples



# Test Campaign




**Silver-Silver contact showed no detectable PIM @ the lowest pressure (1 MPa)**

**Ku-band samples with different coatings (Aluminium, Alocrom, and Surtec650) were tested for scenario #1 and #2.**

# General information

1. The most fundamental parameter for the PIM behaviour is the contact pressure.

2. The contact pressure can not be determined straight forward for many cases. (complex structure, unknown material, workmanship variation etc.)

3. Therefore the universal prediction for PIM behaviour is not possible.

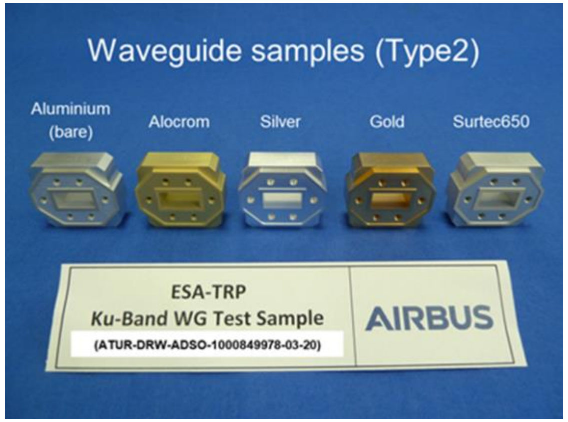
4. The prediction of the PIM behaviour is, therefore, related to the specific test case at every time.

5. The PIM test results is only valid for the specific test cases with following parameters,
   A. Contact pressure,
   B. Temperature,
   C. Material,
   D. Power,
   E. Signal characteristics (frequency, phase, multicarrier, modulation etc.)

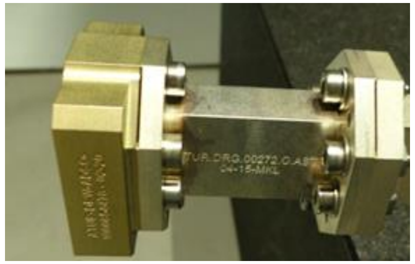
# Scenario #1 test
# RF power level vs. PIM amplitude

# Ku-Band waveguide test samples

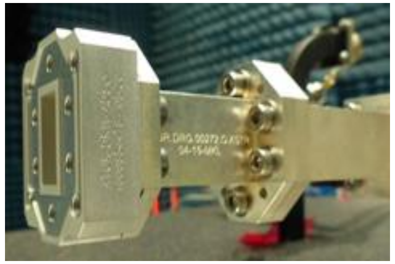
Waveguide test samples with five different coatings.











Aluminium

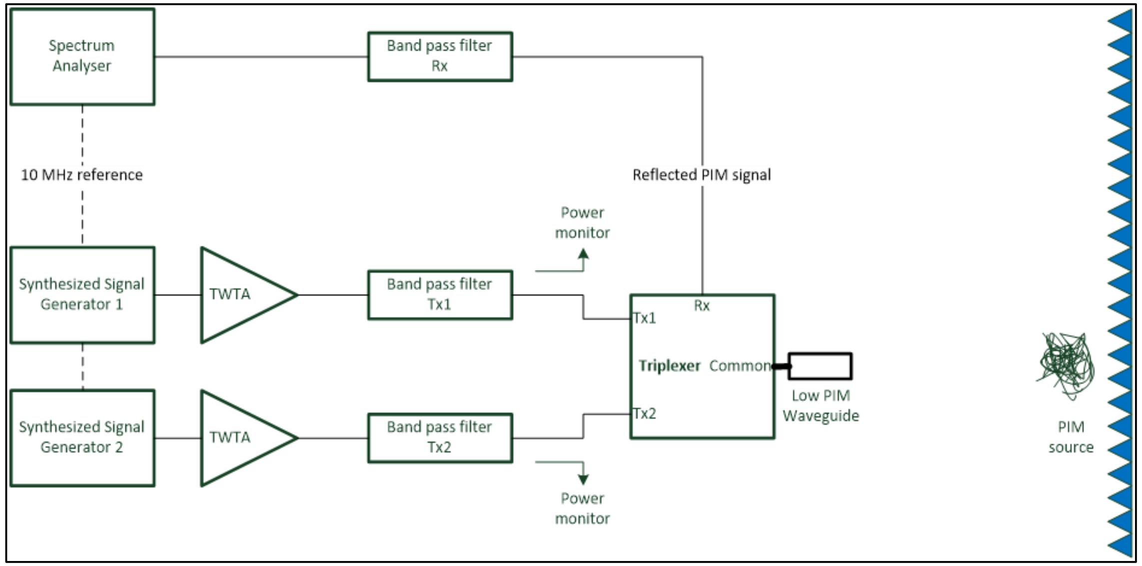
Alocrom

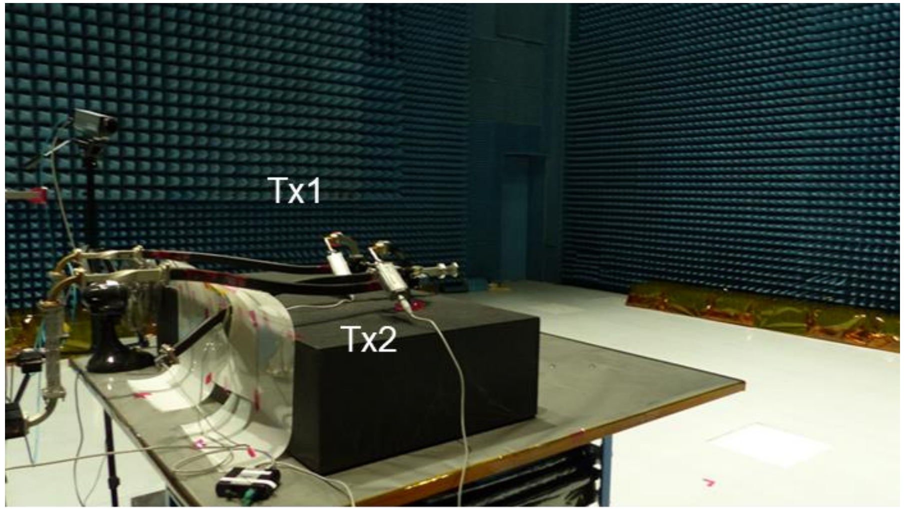
Silver

Gold

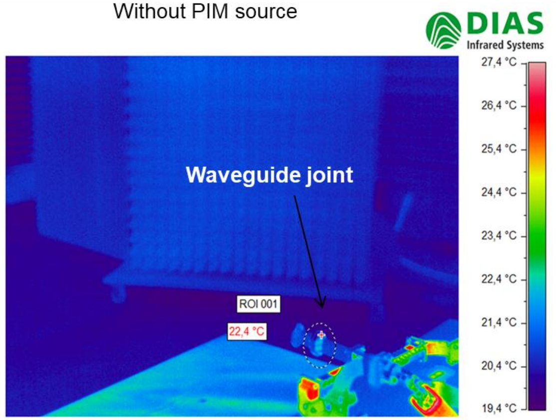
Surtec650

# General Test Setup Configuration in Ku-Band (Example)



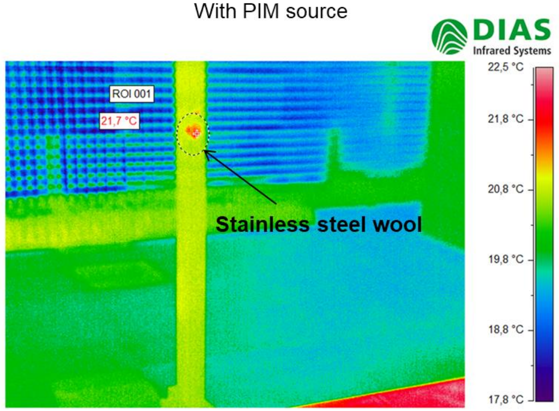




Without PIM source

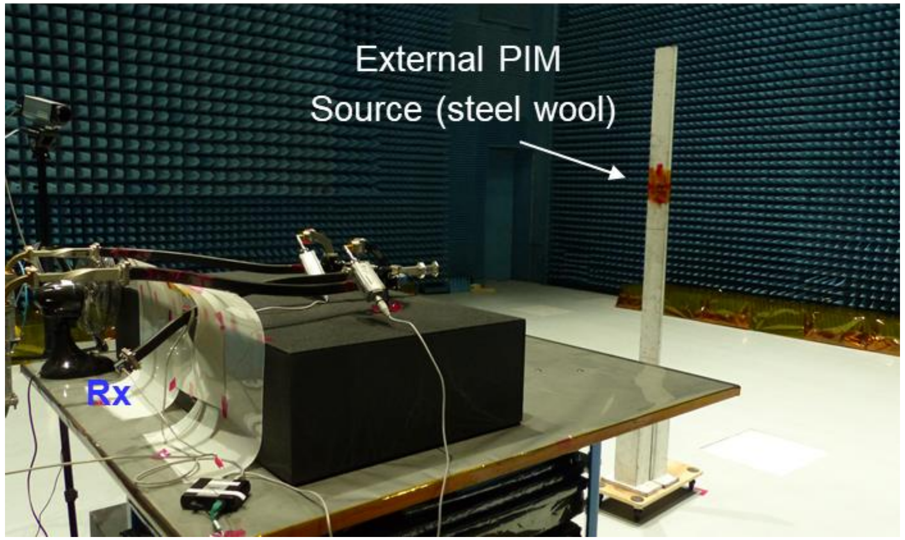



Temperature monitoring @ Test setup joint

With PIM source




Temperature monitoring @ PIM source (steel wool)



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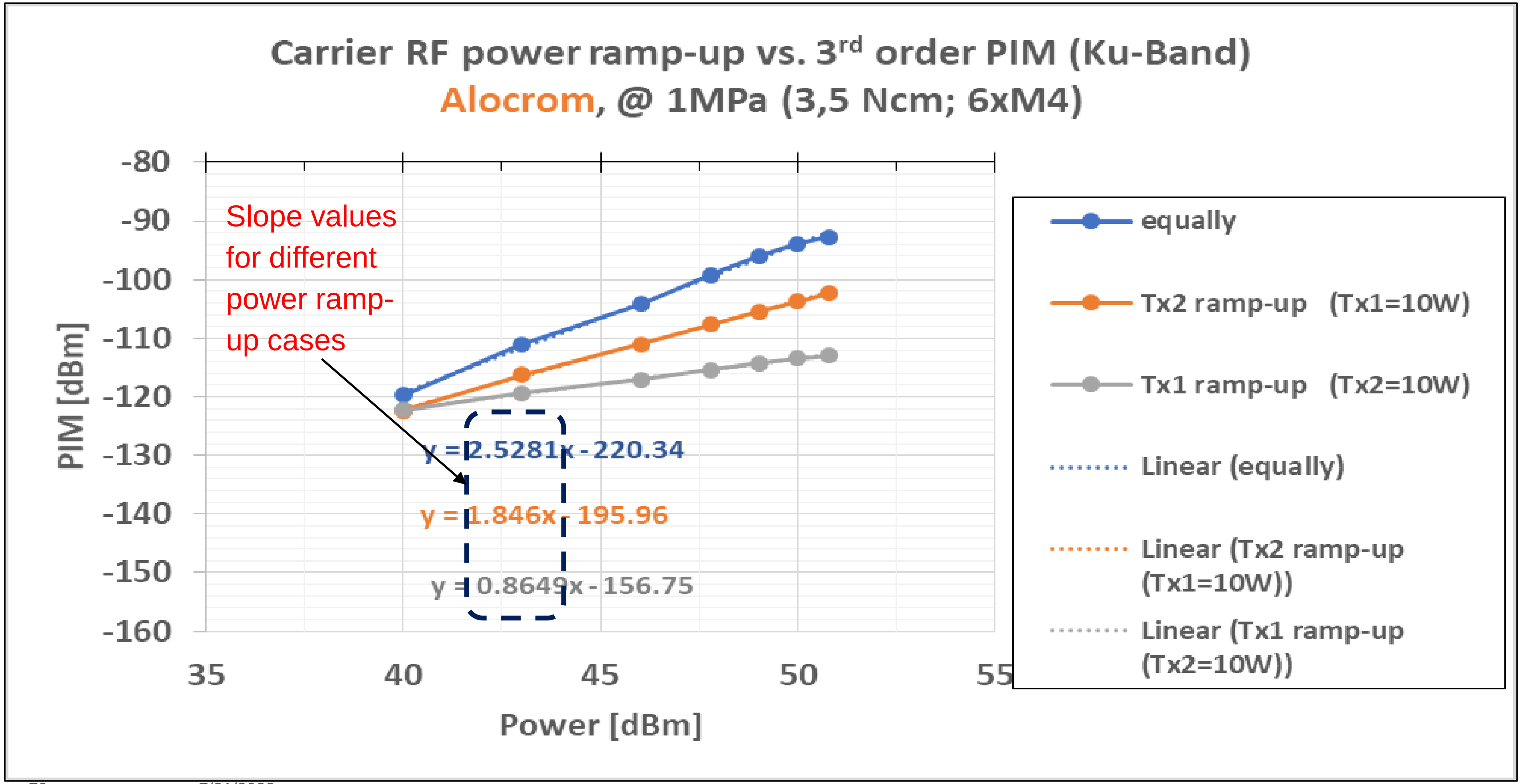
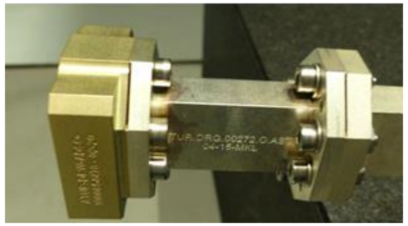
# Example: 3rd order PIM with power ramp-up Tx1 & Tx2 – Alocrom @ 1 MPa (3.5 Ncm, 6xM4 )

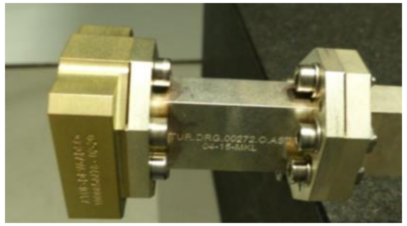


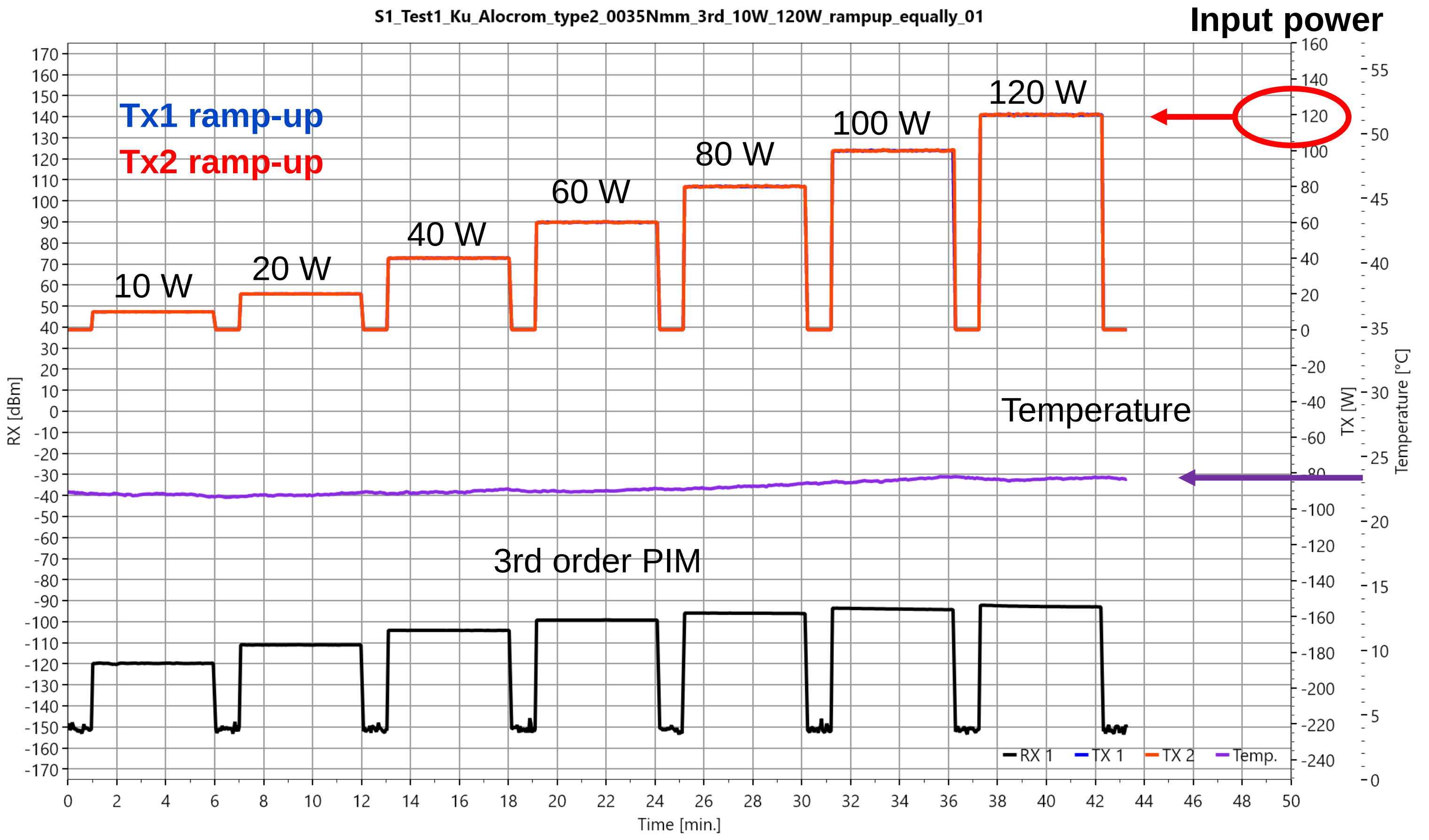




# 3rd order PIM: Power ramp-up equally – Alocrom @ 1 MPa (3.5 Ncm, 6xM4 )

PIM level increase with the increase of the carrier powers.



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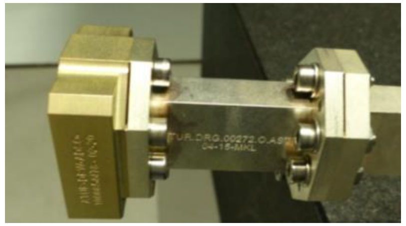
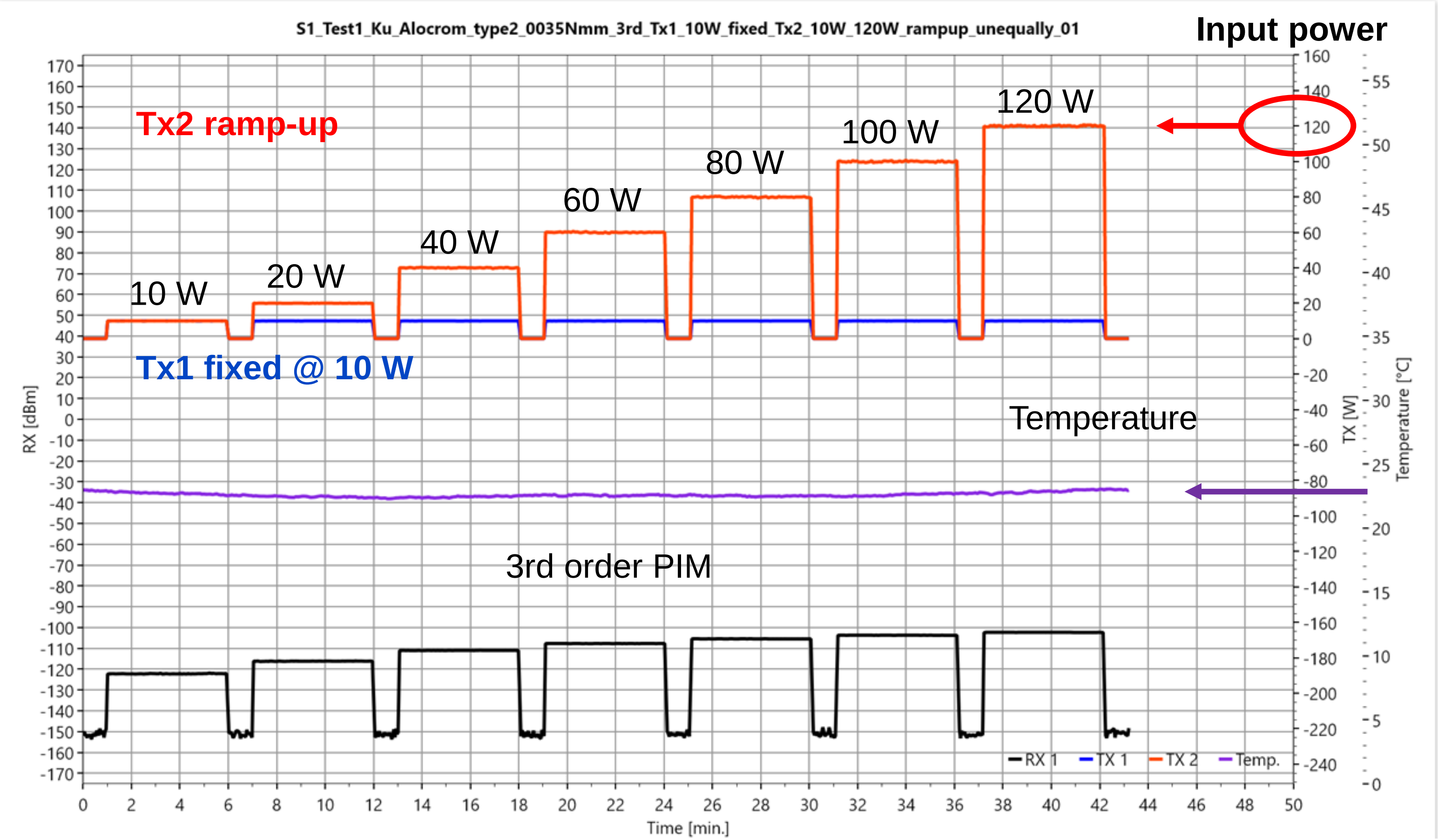
# Example: 3rd order PIM with power ramp-up only Tx2 – Alocrom @ 1 MPa (3.5 Ncm, 6xM4 )



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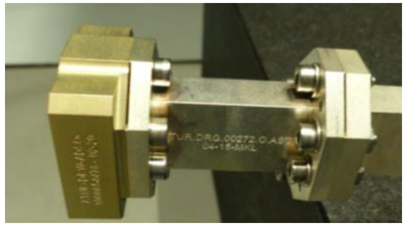
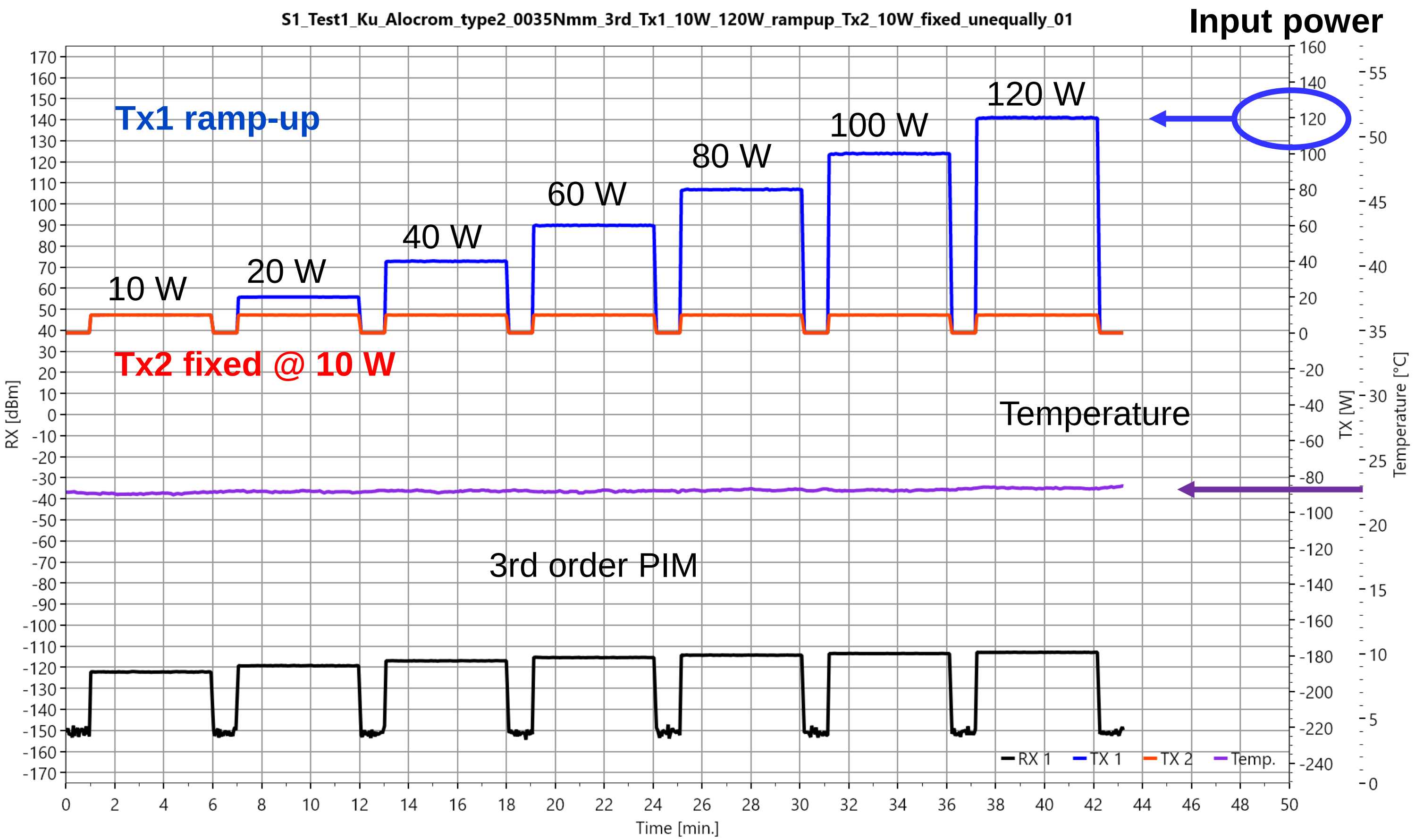
# Example: 3rd order PIM with power ramp-up only Tx1 – Alocrom @ 1 MPa (3.5 Ncm, 6xM4 )



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# Conclusions of scenario #1

- The test was performed at a specific conditions
  - 1 MPa contact pressure was used to get up to the 7th order PIM level beyond the noise level of the test setup.
  - The results are based on this specific test case.
  - The generalisation of the test results is not allowed.
- PIM amplitude increased with the RF power increase.
- The power of carrier 2 has more impact on the PIM amplitude than the carrier 1.
- The slope determination using power ramp-up tests is useful method for PIM level assessment for other power cases.

# Scenario #2 test
# Relation between different PIM orders

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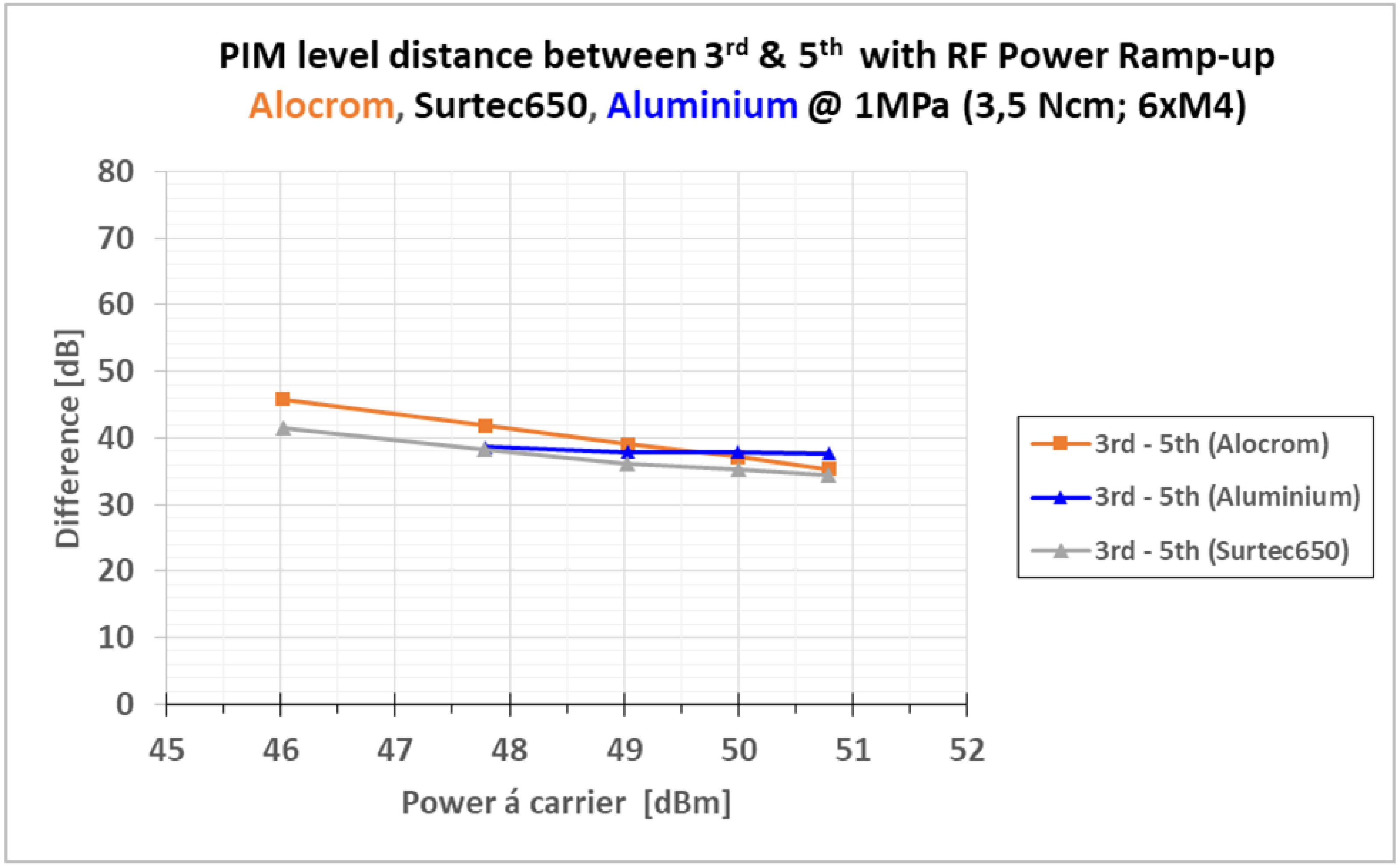
# Relation between different PIM orders




- Roll-off between 3rd and 5th order PIM for this specific contact condition showed about 40 dB.
- The roll-off between orders are dependent on the contact pressure and material.
- Derivation for the general roll-off value not possible.

# Conclusions of scenario #2

- The test was performed at a specific conditions

  - 1 MPa contact pressure was used to get up to the 7$^{th}$ order PIM level beyond the noise level of the test setup.
  - The results are based on this specific test case.
  - The generalisation of the test results is not allowed.

- PIM level distance between orders is contact pressure dependent.

- For the reliable prediction, PIM test shall be performed with a specific PIM test sample to get the test data for PIM model calibration.

# Scenario #3 test
# Temperature vs. PIM

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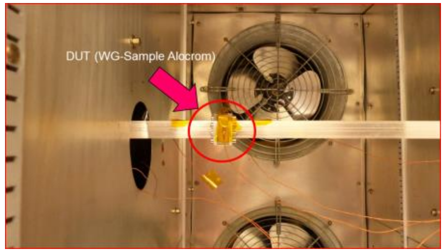
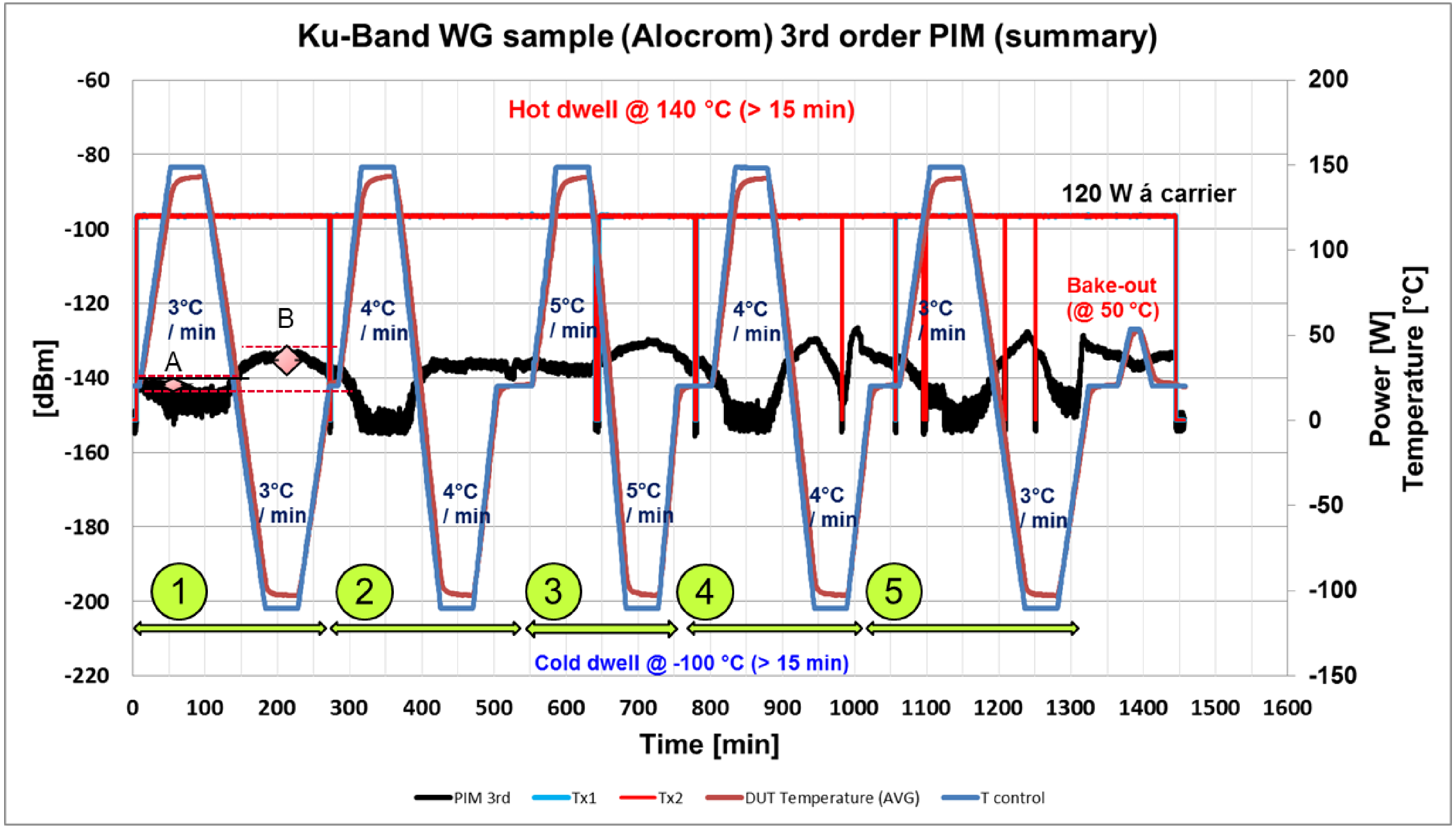
# Scenario #3: Temperature vs. PIM – Waveguide sample test result

20MPa (70 Ncm 6xM4) @ DUT Interface

5 cycles were applied with variation of the temperature slope values.



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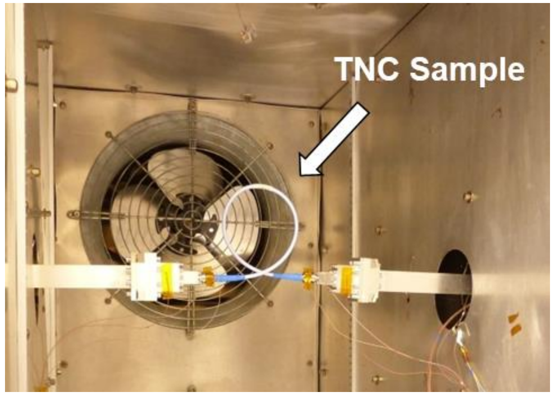
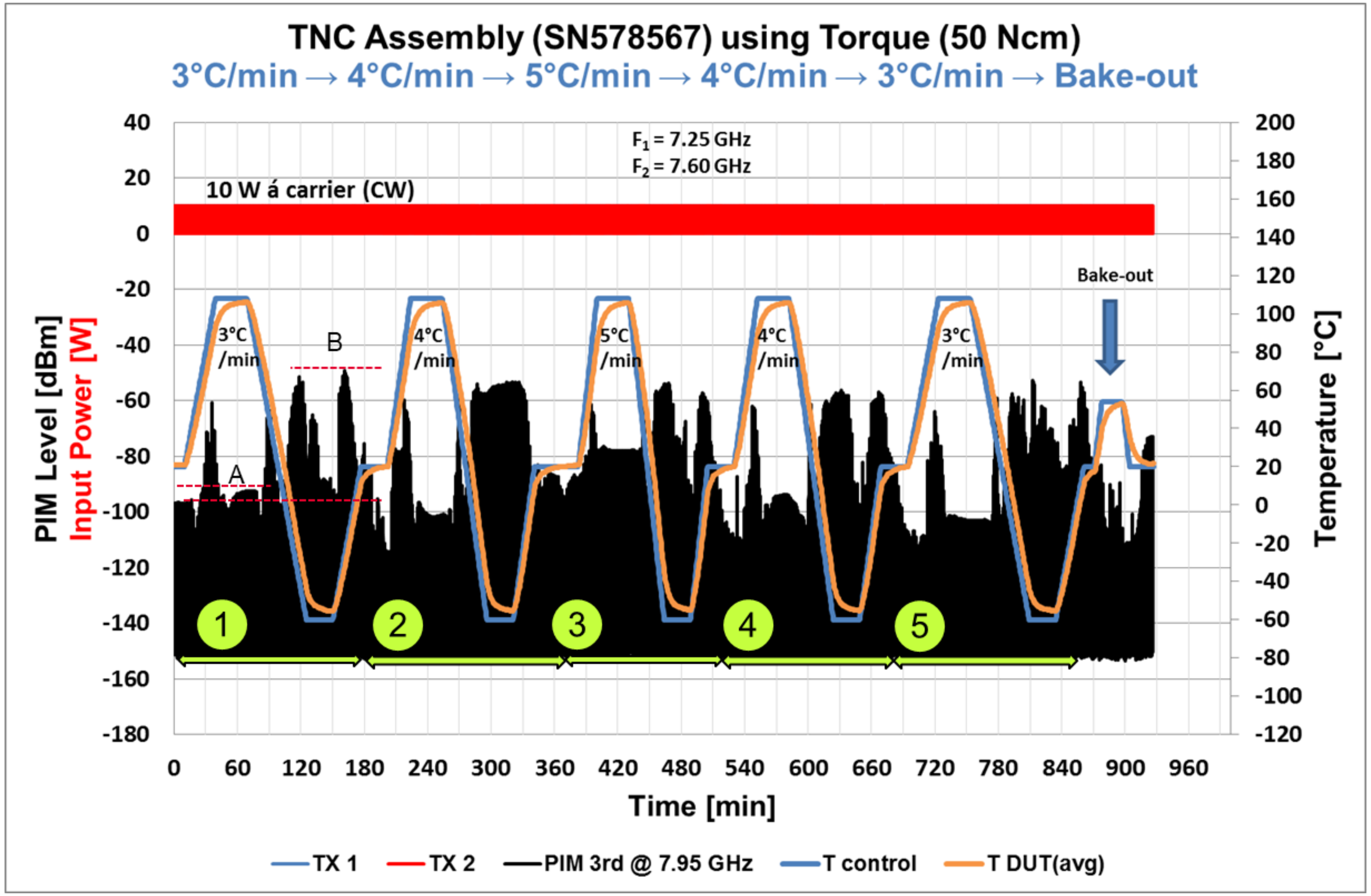
# Scenario #3: Temperature vs. PIM - Coaxial sample (TNC) test result

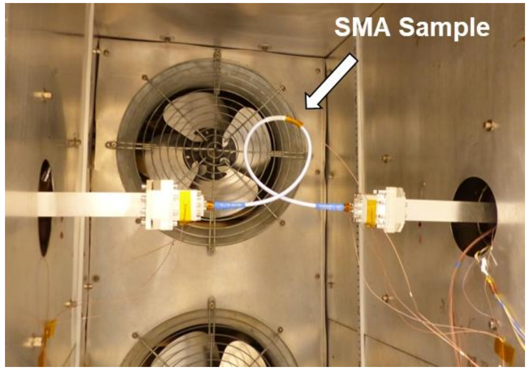


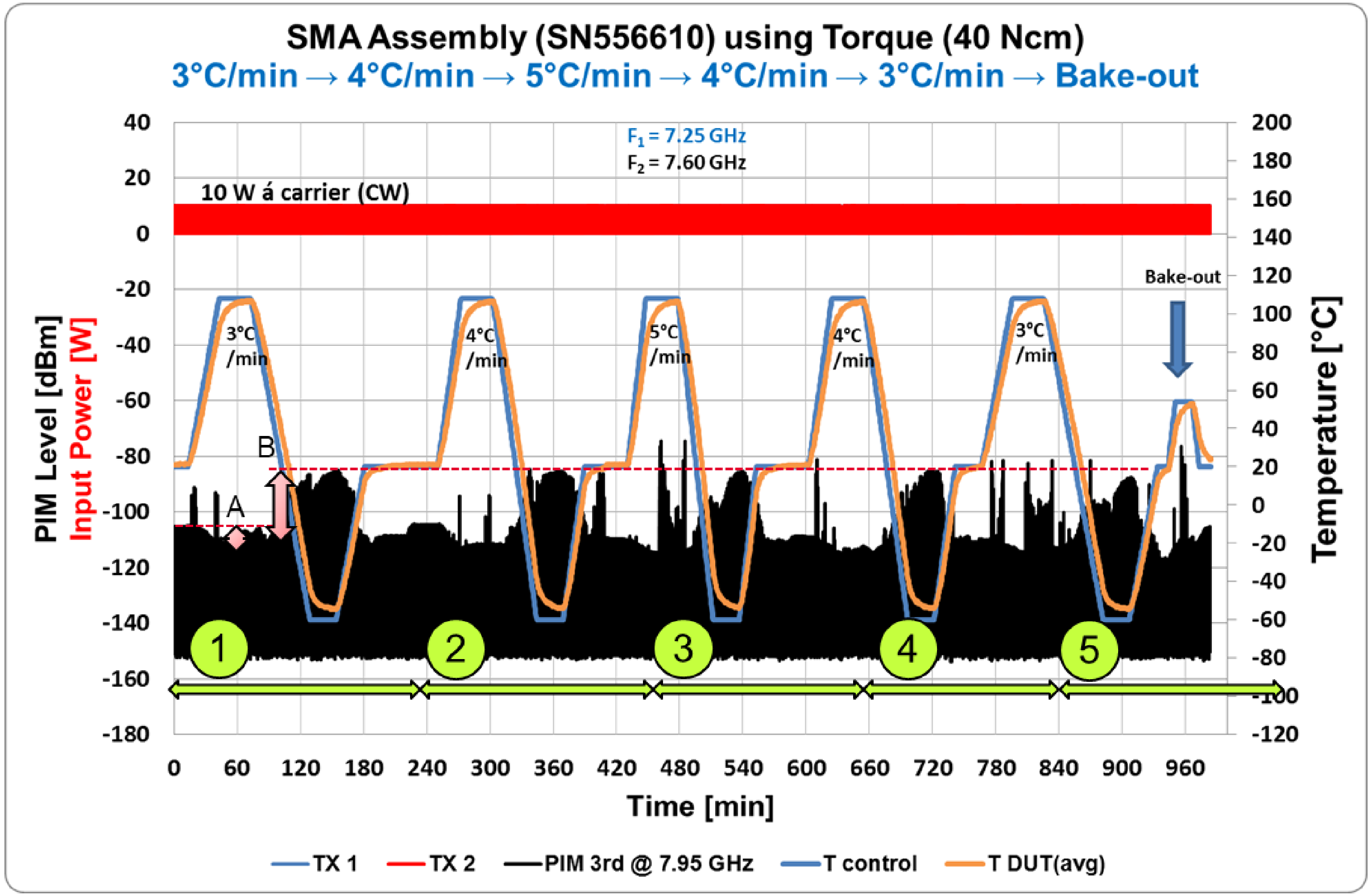




Instable PIM behaviour over the temperature variation observed.

Especially at the temperature transition area, the PIM level showd spike-like variation.

# Scenario #3: Temperature vs. PIM - Coaxial sample (SMA) test result




Instable PIM behaviour over the temperature variation observed.

Especially at the temperature transition area, the PIM level showd spike-like variation.



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# Conclusion of scenario #3

- The tests were performed at a specific conditions to characterise the 3rd order PIM variation.
  - Waveguide sample: 20 MPa contact pressure
  - TNC cable: 50 Ncm
  - SMA cable: 40 Ncm
- The results are based on this specific test case.
  - The generalisation of the test results is not allowed.
- Temperature impact on PIM level is dominant at cold case. (Worst case)
- Temperature transition phase provides burst-like PIM behaviour for the coaxial connectors dominantly.
- The speed of temperature gradient showed no significant difference for PIM level variation.
- For both waveguide contact and coaxial contact, the defined contact pressure using thermal compensation shall be applied.

# Scenario #4 test
# Coatings and Interface vs. PIM

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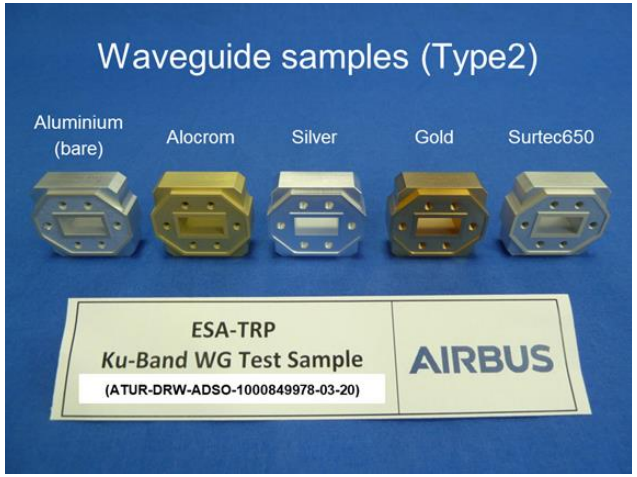
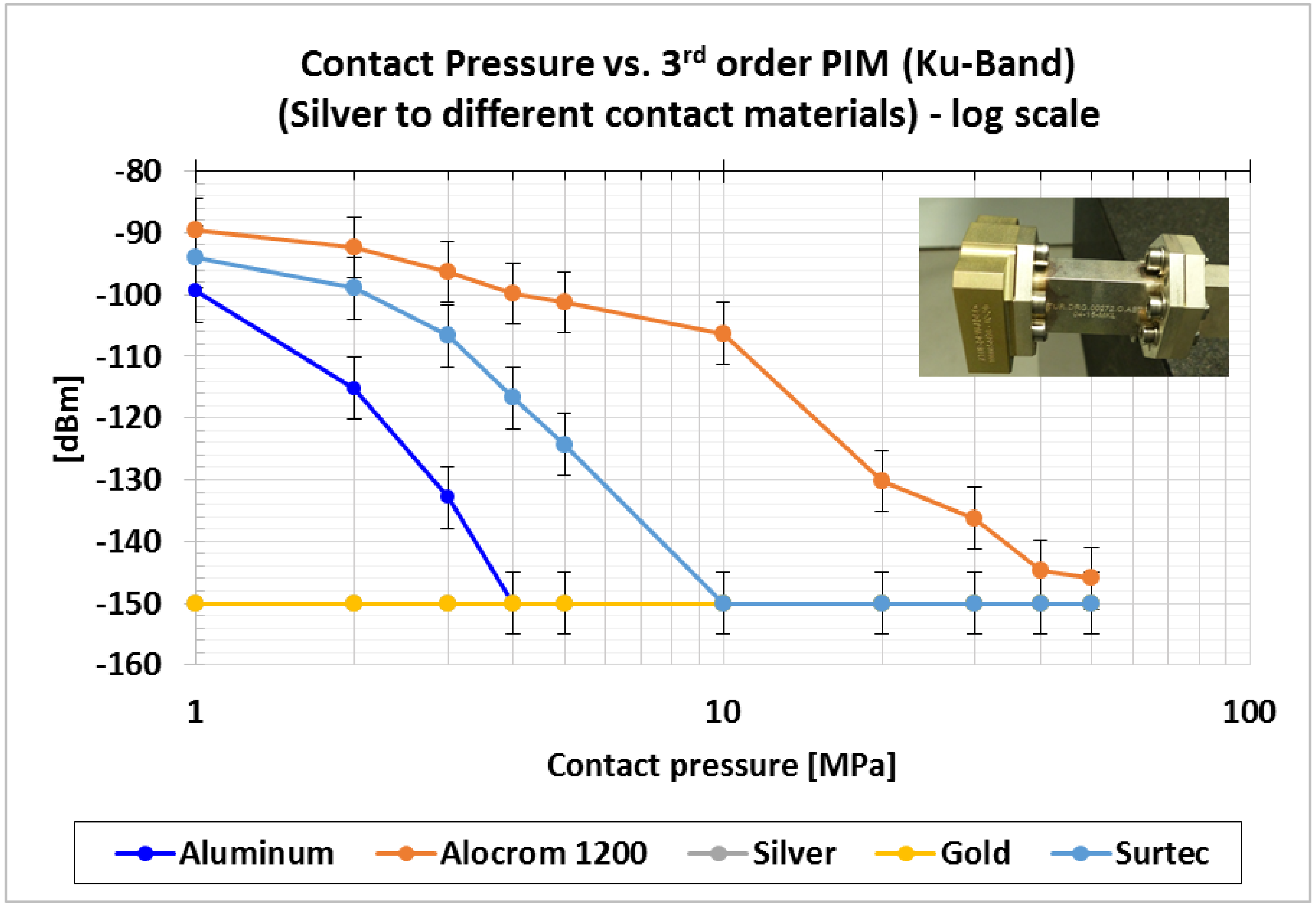
# Contact Pressure & Material Coatings vs. PIM (Ku-Band)




- 5 coating materials tested
- Silver and Gold showed very low PIM
- Alocrom showed highest PIM level at low contact pressure



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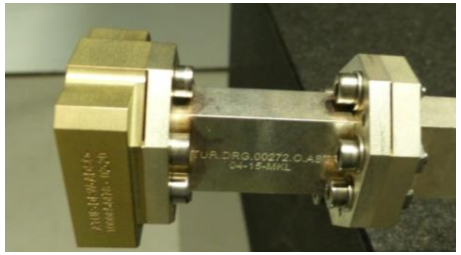
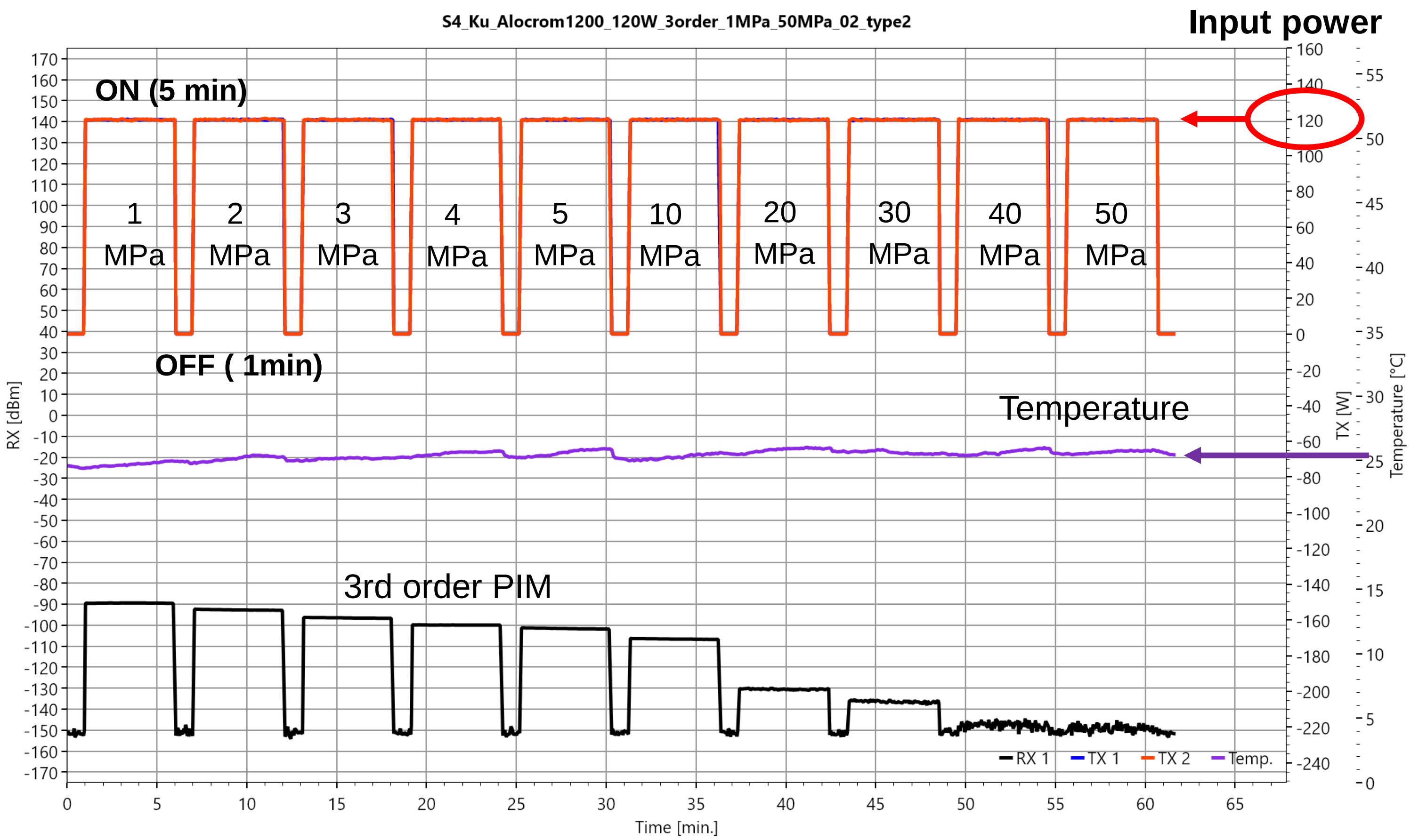
# Example: Contact pressure change from 1 MPa to 50 MPa - Alocrom

To keep the constant temperature at test interface and to minimise the contact pressure variation via self-heating, "off" times were introduced before every contact pressure step changes.



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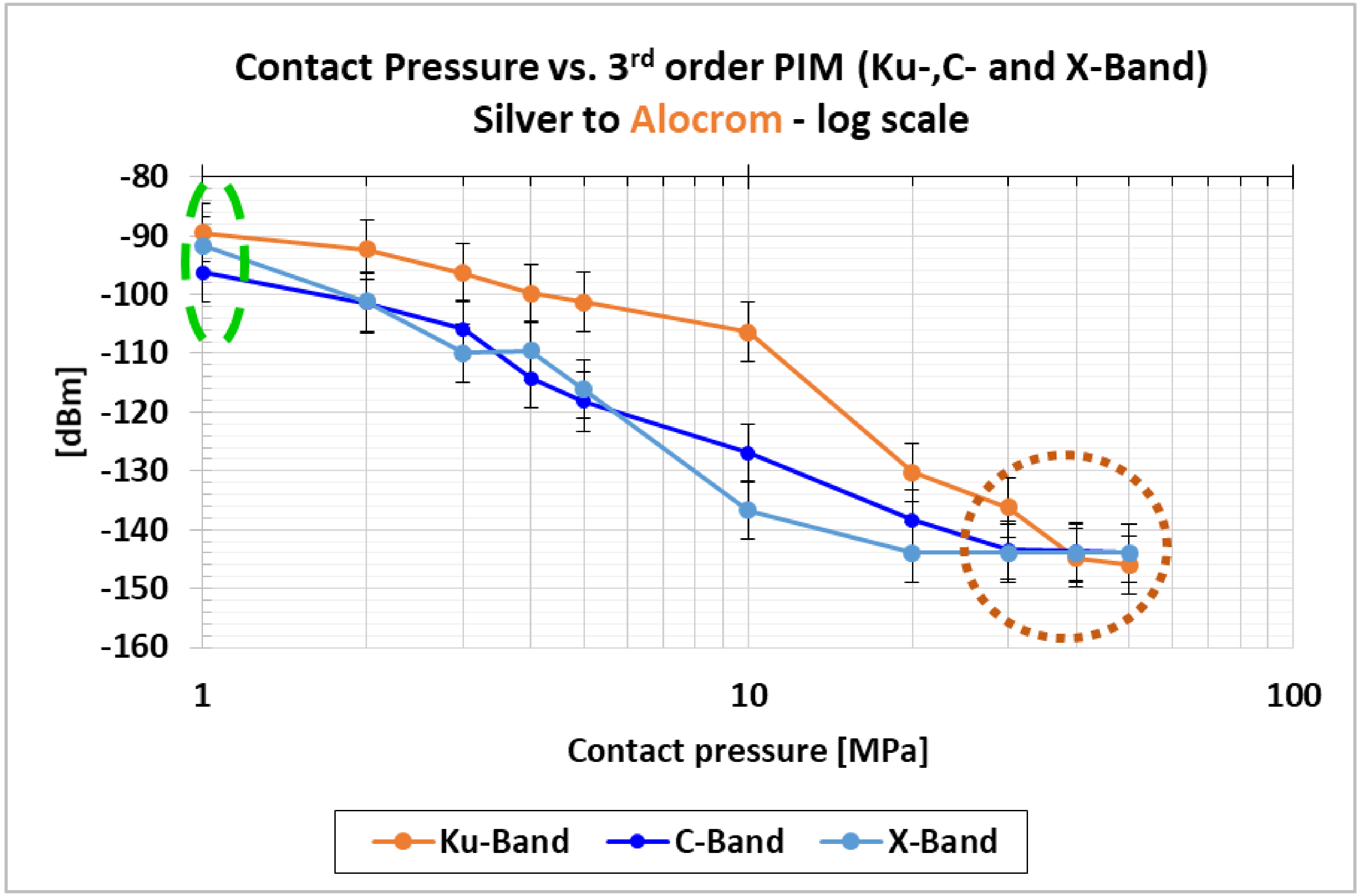
# Comparison: Contact Pressure & Material Coatings vs. PIM (C-X-/Ku-Band)

- The comparison shows exponentially reducing PIM behaviour with respect to the contact pressure.
- Tests with Alocrom waveguide PIM test sample showed nearly same PIM levels regardless of the frequency band (C-/X-/Ku-Band).



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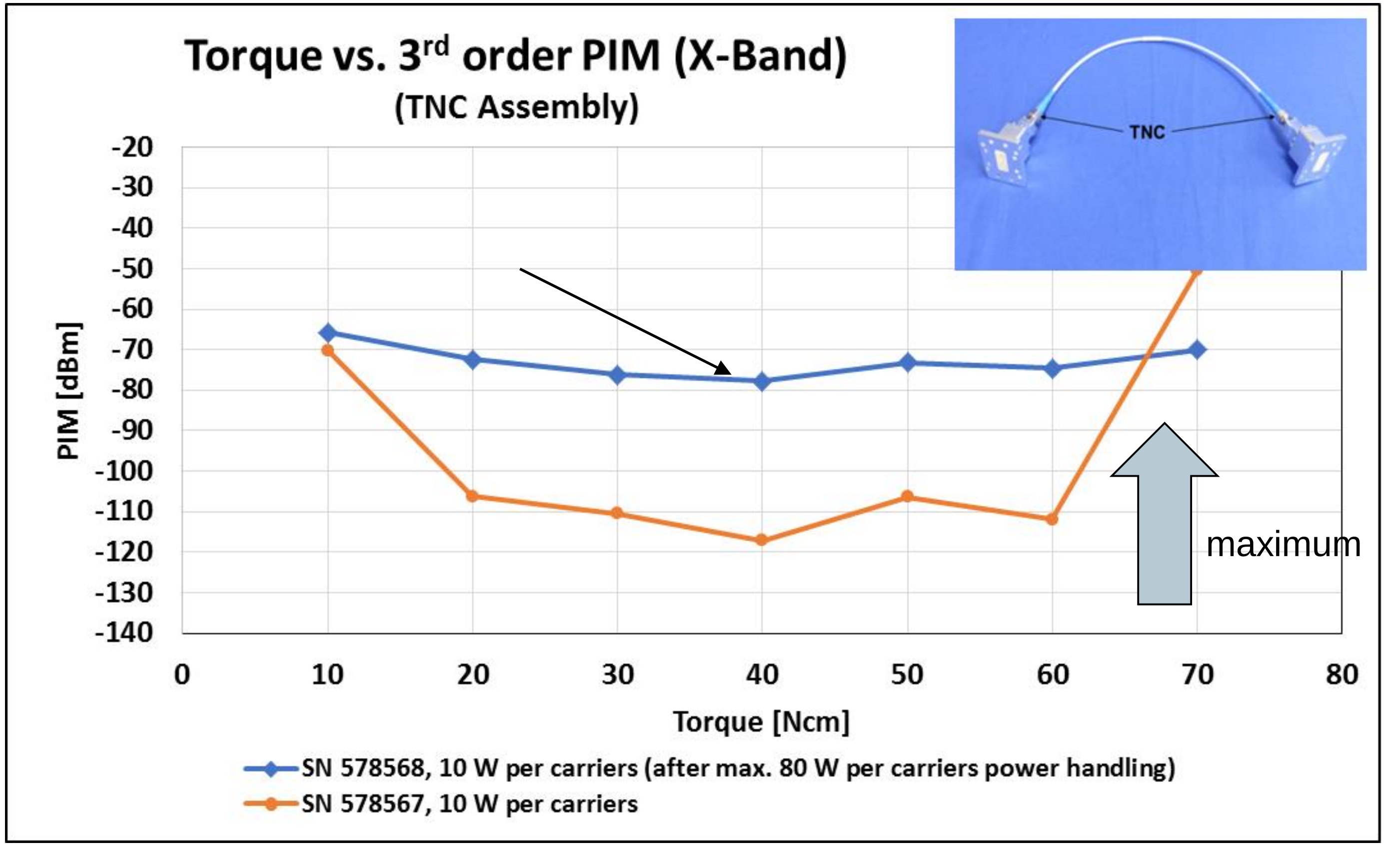
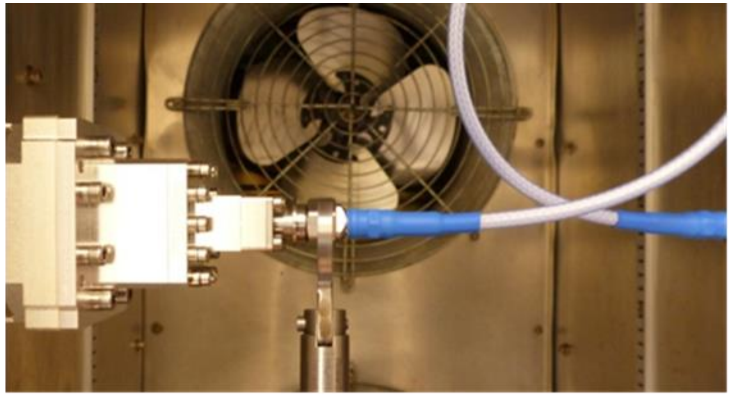
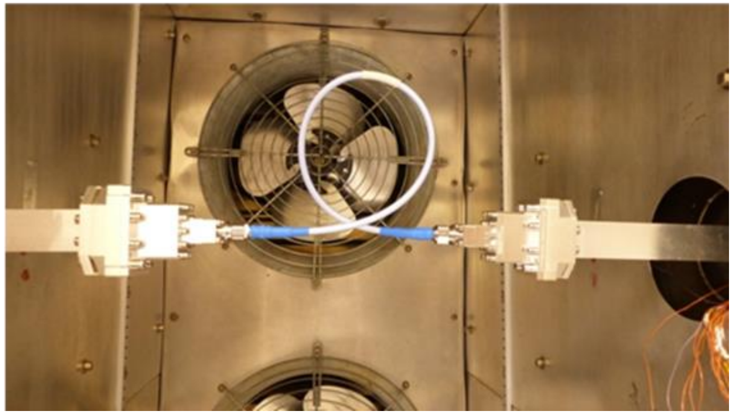
# Example: Contact pressure vs. PIM - coaxial sample test results TNC

High power (80W) pre-tested sample showed much higher PIM level.

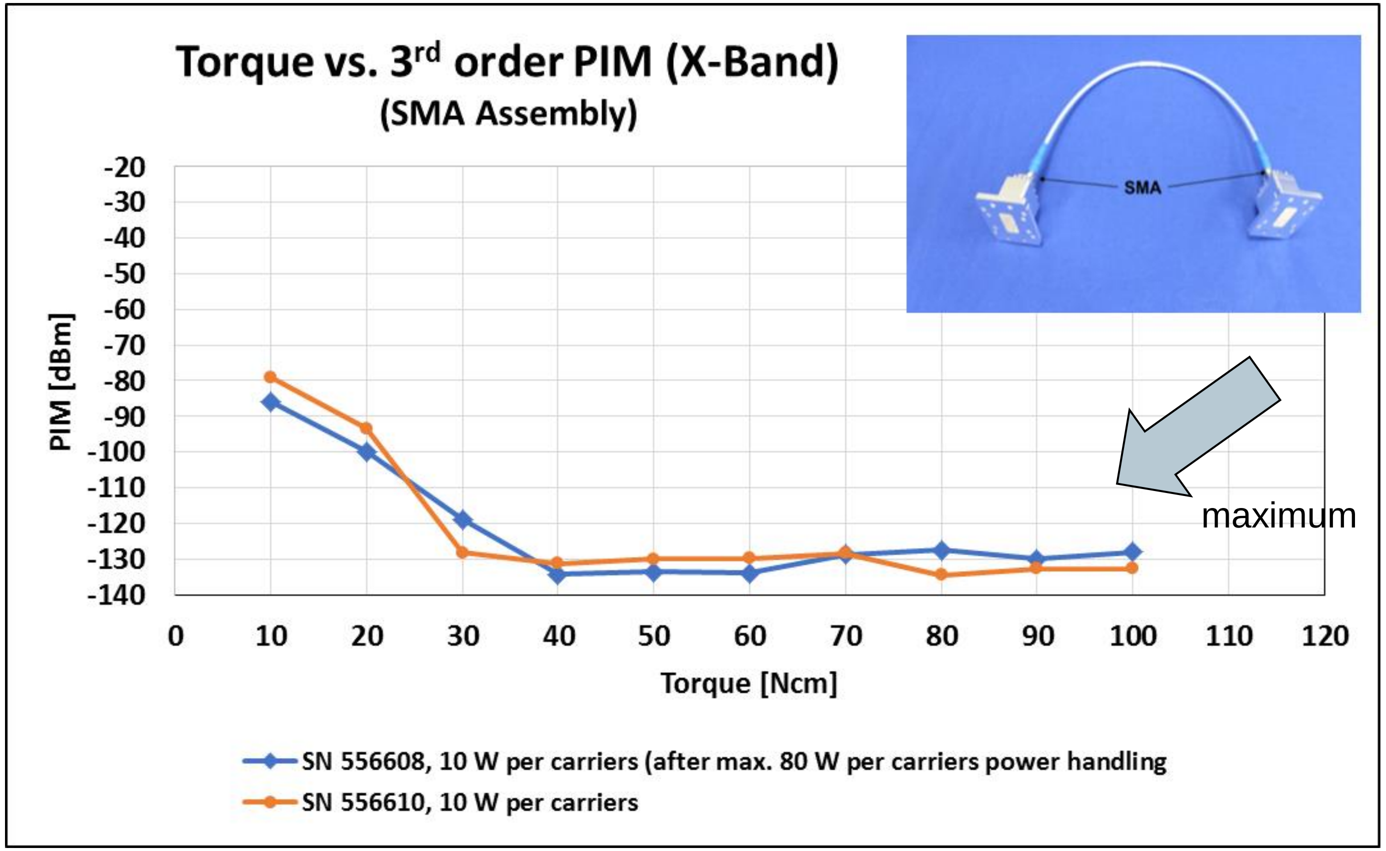


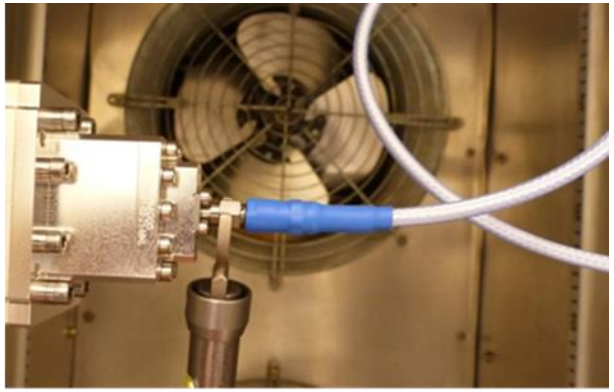



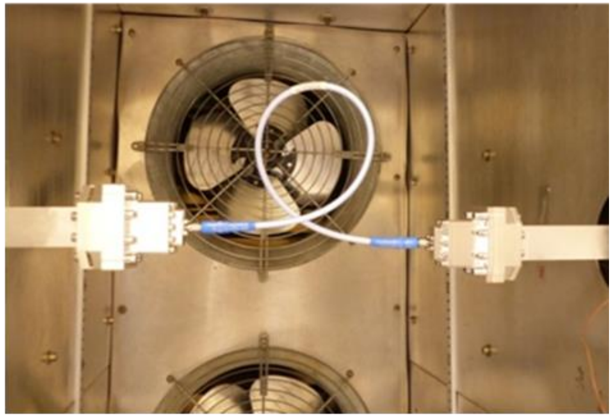


Supplier recommended torque value (46 Ncm – 69 Ncm)

# Example: Contact pressure vs. PIM - coaxial sample test results SMA





Supplier recommended torque value (80 Ncm - 100 Ncm)

# Conclusion of scenario #4

- With the increase of the contact pressure, the PIM level decreased exponentially.
- The PIM level reduction speed with the increasing contact pressure was slightly different for different materials.
- However, at about 50 MPa all test sample showed extreme PIM reduction below -140 dBm.
- This PIM levels are nearly same in C-/X-/Ku-Band.
- Recommendation for the contact pressure values is > 50 MPa regardless of the contact materials.
- For coaxial transmission line, the PIM behaviour was different.
- If the maximum allowable torque value is reached or even exuded the PIM level was increasing. (e.g. TNC connector)

# Scenario #5 test
# Signal characteristics vs. PIM

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# Example: Signal Characteristics vs. PIM (in Ku-Band)

**A** Carrier spacing change

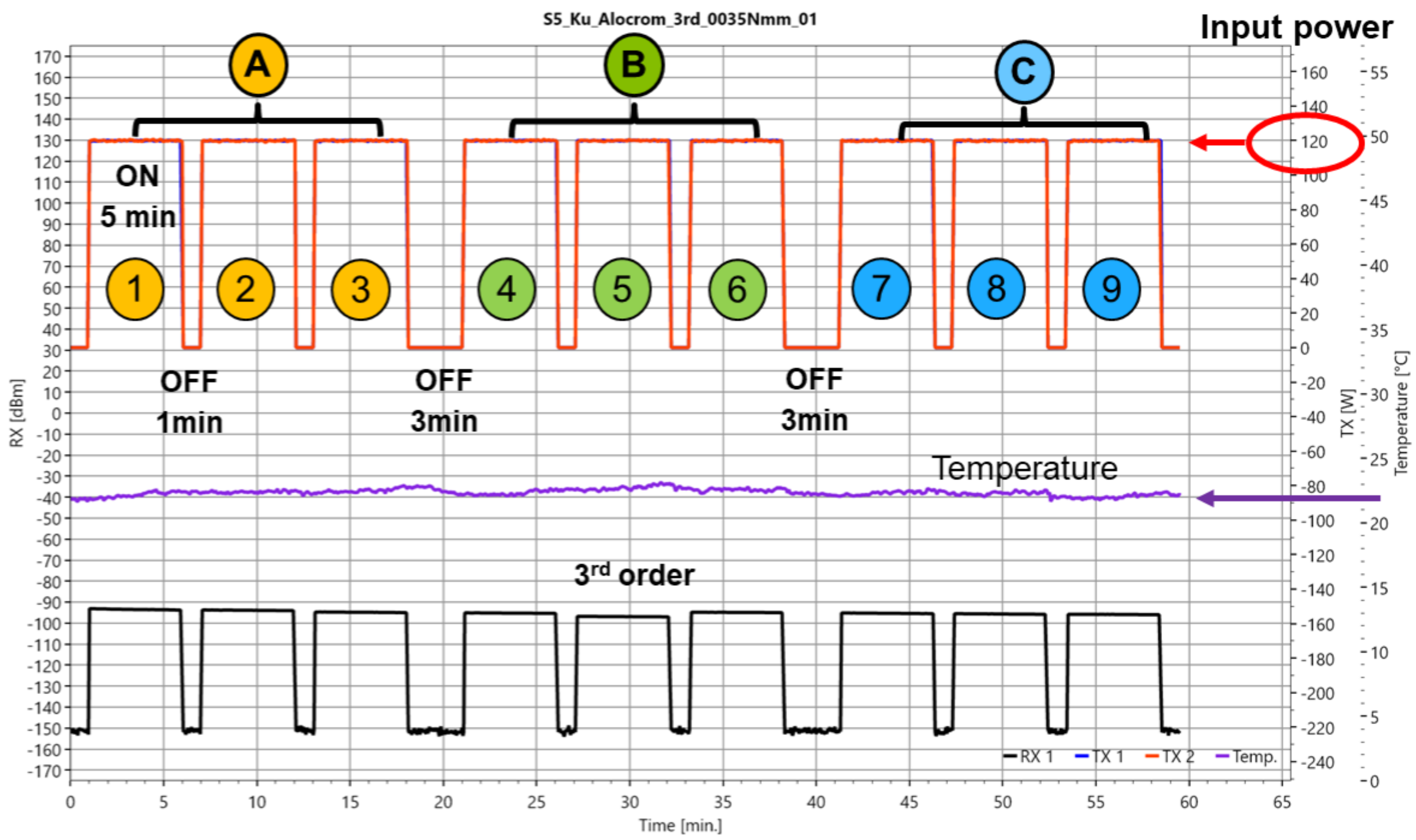
1. 11.10 / 12.60 / **14.10 GHz**
2. 11.10 / 12.55 / **14.00 GHz**
3. 11.10 / 12.50 / **13.90 GHz**

**B** Carrier frequency change

4. 11.00 / 12.60 / **14.20 GHz**
5. 10.95 / 12.65 / **14.35 GHz**
6. 11.10 / 12.50 / **14.50 GHz**

**C** Carrier phase change

7. 11.10 / 12.60 / 14.10 GHz ($\varphi_1$, $\varphi_2$)
8. 11.10 / 12.60 / 14.10 GHz ($\varphi_1$, $\varphi_2$-$\Delta\varphi$)
9. 11.10 / 12.60 / 14.10 GHz ($\varphi_1$ - $\Delta\varphi$, $\varphi_2$)



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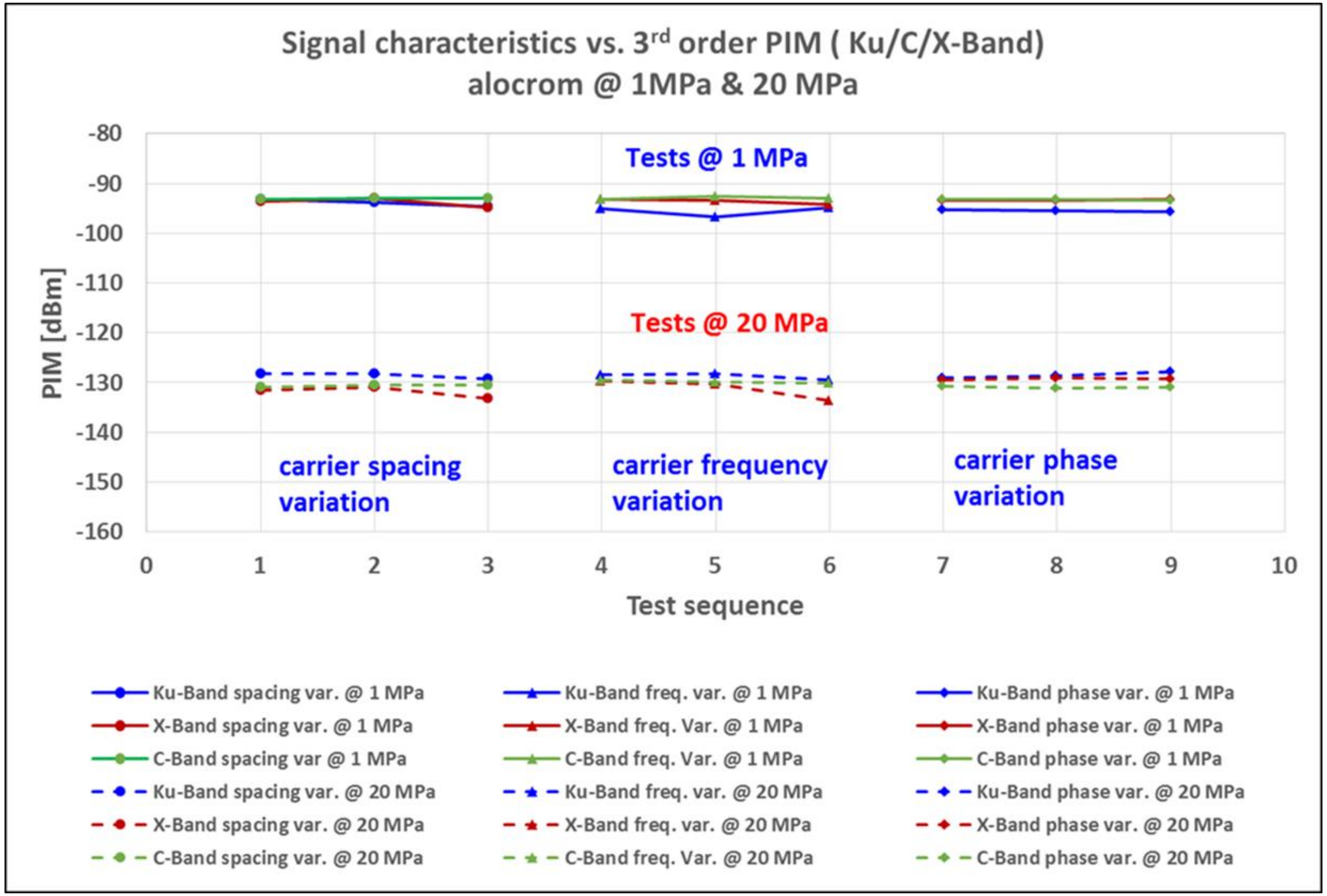
# Test results: signal characteristics vs. PIM (Ku, X, C-Band)

| seq | Variation | Tx1 Freq. [GHz] | Tx2 Freq. [GHz] | PIM Freq. [GHz] | PIM 3rd [dBm] @ 13 Ncm (1MPa) | PIM 3rd [dBm] @ 260 Ncm (20MPa) |
|---|---|---|---|---|---|---|
| 1 | carrier spacing | 3,65 | 4,80 | 5,95 | -93,26 | -130,87 |
| 2 | | 3,70 | 4,80 | 5,90 | -93,01 | -130,55 |
| 3 | | 3,95 | 4,80 | 5,85 | -92,94 | -130,59 |
| 4 | carrier frequencies | 3,65 | 4,75 | 5,85 | -93,14 | -129,53 |
| 5 | | 3,64 | 4,77 | 5,90 | -92,67 | -130,00 |
| 6 | | 3,63 | 4,76 | 5,95 | -92,94 | -130,10 |
| 7 | carrier phase | 3,65 | 4,80 | 5,95 | -93,21 | -130,78 |
| 8 | | 3,65 | 4,80 | 5,95 | -93,23 | -131,07 |
| 9 | | 3,65 | 4,80 | 5,95 | -93,33 | -130,90 |

| seq | Variation | Tx1 Freq. [GHz] | Tx2 Freq. [GHz] | PIM Freq. [GHz] | PIM 3rd [dBm] @ 4,2 Ncm (1MPa) | PIM 3rd [dBm] @ 84 Ncm (20MPa) |
|---|---|---|---|---|---|---|
| 1 | carrier spacing | 7,25 | 7,60 | 7,95 | -93,61 | -131,62 |
| 2 | | 7,25 | 7,64 | 8,03 | -92,97 | -130,97 |
| 3 | | 7,25 | 7,68 | 8,11 | -94,8 | -133,26 |
| 4 | carrier frequencies | 7,26 | 7,62 | 7,98 | -93,31 | -129,63 |
| 5 | | 7,28 | 7,65 | 8,02 | -93,40 | -130,41 |
| 6 | | 7,30 | 7,67 | 8,04 | -94,18 | -133,57 |
| 7 | carrier phase | 7,25 | 7,60 | 7,95 | -93,50 | -129,58 |
| 8 | | 7,25 | 7,60 | 7,95 | -93,39 | -129,19 |
| 9 | | 7,25 | 7,60 | 7,95 | -93,13 | -129,21 |

| seq | Variation | Tx1 Freq. [GHz] | Tx2 Freq. [GHz] | Freq. [GHz] | PIM 3rd [dBm] @ 3,5 Ncm (1MPa) | PIM 3rd [dBm] @ 70 Ncm (20MPa) |
|---|---|---|---|---|---|---|
| 1 | carrier spacing | 11,10 | 12,60 | 14,10 | -93,12 | -128,20 |
| 2 | | 11,10 | 12,55 | 14,00 | -93,73 | -128,30 |
| 3 | | 11,10 | 12,50 | 13,90 | -94,75 | -129,20 |
| 4 | carrier frequencies | 11,00 | 12,60 | 14,20 | -95,12 | -128,40 |
| 5 | | 10,95 | 12,65 | 14,35 | -96,83 | -128,30 |
| 6 | | 10,90 | 12,70 | 14,50 | -94,85 | -129,40 |
| 7 | carrier phase | 11,10 | 12,60 | 14,10 | -95,19 | -129,03 |
| 8 | | 11,10 | 12,60 | 14,10 | -95,56 | -128,57 |
| 9 | | 11,10 | 12,60 | 14,10 | -95,8 | -127,93 |



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# Conclusion of scenario #5

- The tests were performed at a specific conditions to characterise the 3rd order PIM variation.
  - ➢ Waveguide sample were used for C-/X-/Ku-Band tests
  - ➢ Contact pressure was defined at 1 MPa and 20 MPa to observe the difference of the PIM level variation over the contact pressure.

- The variation of the carrier frequencies, carrier spacing and carrier phase showed no impact on the PIM level.

- The frequency band variation from C-Band to Ku-Band, which were possible for test, showed that the PIM levels were nearly in dependent on the frequency band.

## Scenario #6 test
## Multicarrier scenarios vs. PIM

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# Multicarrier PIM Test @ ESA-VSC Test setup block diagram and setup

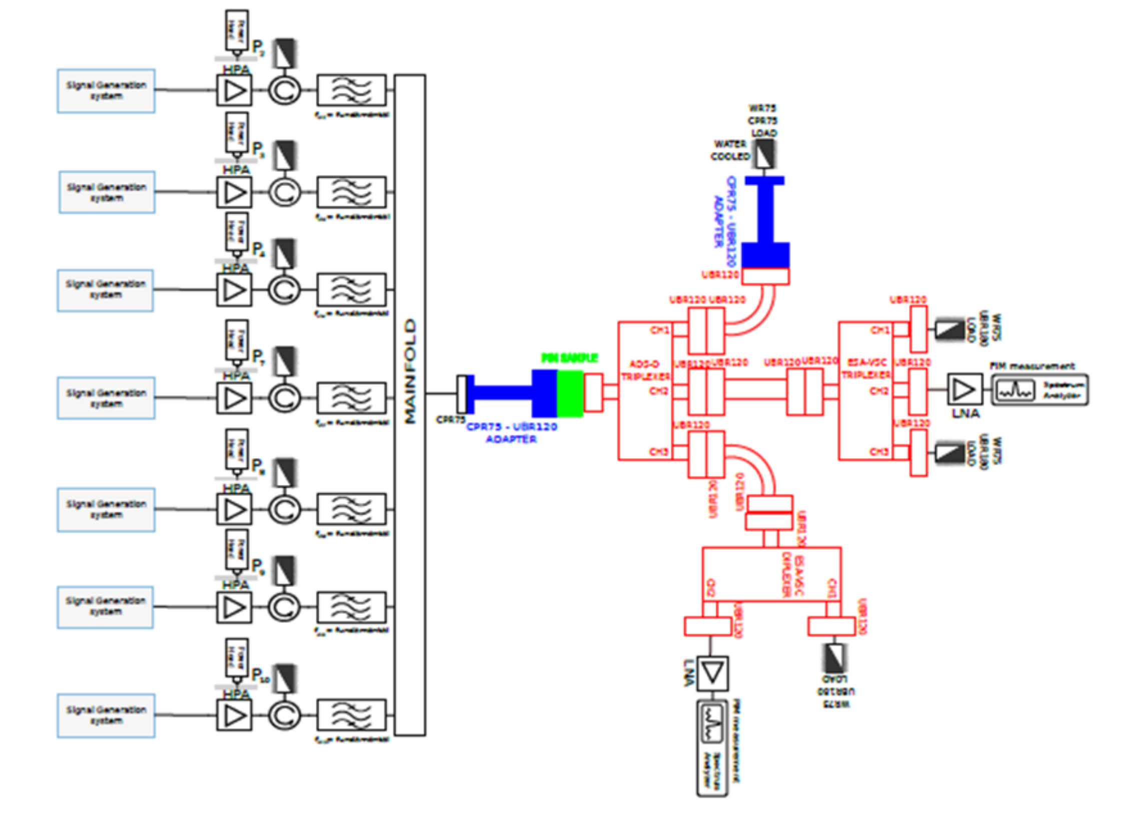
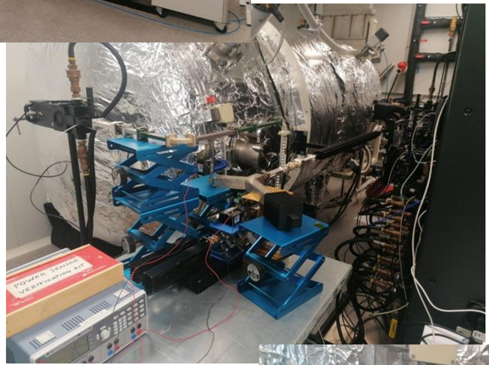
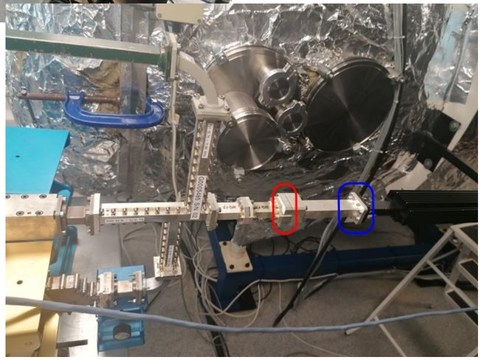



Figure 3: PIM tests with Multicarrier signals - basic test bed.



DUT



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# Test Frequencies and PIM results (20 W per carrier)

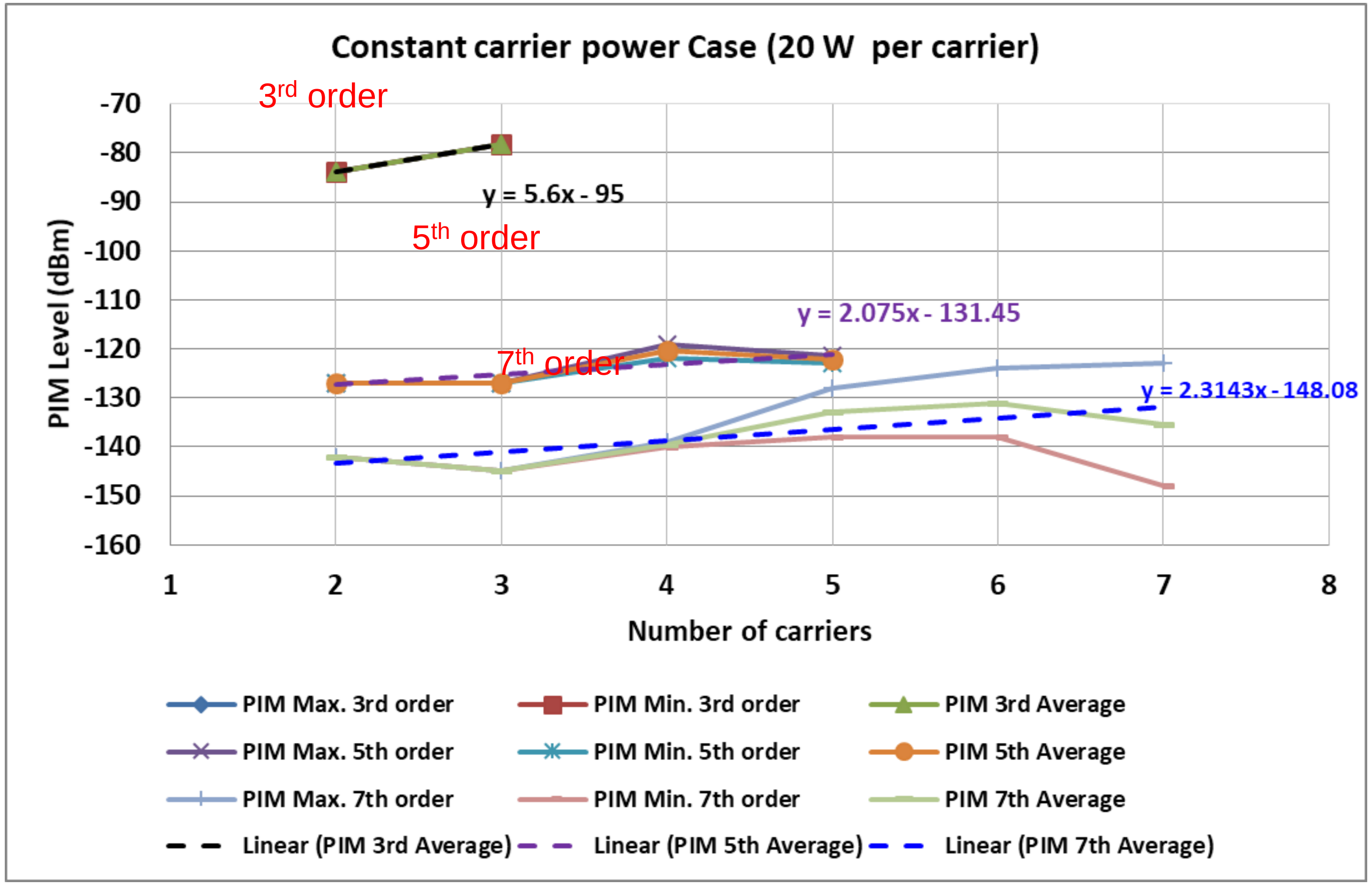
PIM orders | Measured PIM levels | Active channels & factors | frequencies | Number of used channels

| Test No. | PIM Order | PIM Frequency [GHz] | Measured PIM Level [dBm] (Maximum) | Measured PIM Level [dBm] (Minimum) | Measured PIM Level [dBm] (Average) | Ch_#02 factor | Ch_#03 factor | Ch_04 factor | Ch_#07 factor | Ch_#08 factor | Ch_#09 factor | Ch_#10 factor | Ch_#02 frequency [GHz] | Ch_#03 frequency [GHz] | Ch_#04 frequency [GHz] | Ch_#07 frequency [GHz] | Ch_#08 frequency [GHz] | Ch_#09 frequency [GHz] | Ch_#10 frequency [GHz] | Used # of OMUX channels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3,00 | 12,39 | -83,80 | -83,80 | -83,80 | -1 | 0 | 0 | 0 | 0 | 0 | 2 | 10,810 | 10,920 | 11,010 | 11,310 | 11,420 | 11,510 | 11,600 | 2,00 |
| 2 | 3,00 | 12,35 | -78,20 | -78,20 | -78,20 | -1 | 0 | 0 | 0 | 0 | 1 | 1 | 10,790 | 10,920 | 11,010 | 11,310 | 11,420 | 11,510 | 11,630 | 3,00 |
| 3 | 5,00 | 12,71 | -127,00 | -127,00 | -127,00 | 0 | -2 | 0 | 0 | 0 | 3 | 0 | 10,830 | 10,910 | 11,010 | 11,310 | 11,420 | 11,510 | 11,620 | 2,00 |
| 4 | 5,00 | 12,73 | -127,00 | -127,00 | -127,00 | 0 | -2 | 0 | 1 | 0 | 0 | 2 | 10,830 | 10,910 | 11,010 | 11,310 | 11,420 | 11,510 | 11,620 | 3,00 |
| 5 | 5,00 | 12,74 | -119,00 | -122,00 | -120,50 | -1 | -1 | 0 | 0 | 2 | 0 | 1 | 10,810 | 10,910 | 11,010 | 11,310 | 11,420 | 11,510 | 11,620 | 4,00 |
| 6 | 5,00 | 12,78 | -121,50 | -123,00 | -122,25 | -1 | -1 | 0 | 0 | 1 | 1 | 1 | 10,810 | 10,910 | 11,010 | 11,310 | 11,400 | 11,510 | 11,590 | 5,00 |
| 7 | 7,00 | 12,75 | -142,00 | -142,00 | -142,00 | -3 | 0 | 0 | 4 | 0 | 0 | 0 | 10,830 | 10,920 | 11,010 | 11,310 | 11,420 | 11,510 | 11,620 | 2,00 |
| 8 | 7,00 | 12,72 | -145,00 | -145,00 | -145,00 | 1 | 0 | -3 | 0 | 0 | 0 | 3 | 10,830 | 10,910 | 10,990 | 11,300 | 11,390 | 11,500 | 11,620 | 3,00 |
| 9 | 7,00 | 12,61 | -139,00 | -140,00 | -139,50 | 1 | 0 | -3 | 0 | 0 | 1 | 2 | 10,830 | 10,910 | 10,990 | 11,320 | 11,440 | 11,510 | 11,620 | 4,00 |
| 10 | 7,00 | 12,55 | -128,00 | -138,00 | -133,00 | -1 | -1 | 0 | 1 | 0 | 3 | -1 | 10,790 | 10,910 | 11,010 | 11,310 | 11,380 | 11,510 | 11,590 | 5,00 |
| 11 | 7,00 | 12,44 | -124,00 | -138,00 | -131,00 | 1 | -2 | -1 | 1 | 0 | 1 | 1 | 10,830 | 10,920 | 10,990 | 11,310 | 11,440 | 11,510 | 11,620 | 6,00 |
| 12 | 7,00 | 12,47 | -123,00 | -148,00 | -135,50 | -1 | -1 | 1 | -1 | 1 | 1 | 1 | 10,780 | 10,910 | 10,990 | 11,310 | 11,380 | 11,500 | 11,600 | 7,00 |
| 13 | 9,00 | 14,31 | n.a. | n.a. | n.a. | -4 | 0 | 0 | 0 | 0 | 5 | 0 | 10,810 | 10,900 | 11,010 | 11,300 | 11,380 | 11,510 | 11,570 | 2,00 |
| 14 | 9,00 | 14,10 | n.a. | n.a. | n.a. | -3 | 0 | 0 | 0 | 0 | -1 | 5 | 10,830 | 10,920 | 11,010 | 11,310 | 11,420 | 11,510 | 11,620 | 3,00 |
| 15 | 9,00 | 14,10 | n.a. | n.a. | n.a. | -3 | 0 | 0 | 0 | -1 | 1 | 4 | 10,820 | 10,910 | 11,010 | 11,310 | 11,420 | 11,500 | 11,620 | 4,00 |
| 16 | 9,00 | 13,85 | n.a. | n.a. | n.a. | -3 | 0 | 0 | 1 | -1 | 1 | 3 | 10,810 | 10,920 | 11,010 | 11,310 | 11,420 | 11,500 | 11,630 | 5,00 |
| 17 | 9,00 | 13,87 | n.a. | n.a. | n.a. | -1 | -2 | 0 | -1 | 1 | 1 | 3 | 10,780 | 10,910 | 11,010 | 11,310 | 11,420 | 11,500 | 11,620 | 6,00 |
| 18 | 9,00 | 13,89 | n.a. | n.a. | n.a. | -2 | -1 | -1 | 1 | 1 | 2 | 1 | 10,780 | 10,910 | 10,990 | 11,310 | 11,430 | 11,500 | 11,610 | 7,00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Case 1 | 20 Watt | constacnt | per carrier | Ref. | ESA-TECEFE-LAB-TR-2022-001746 | Iss1 | Rev1 |

# Summary of test results

**Carrier power kept constant → Total power increases with the increasing number of carriers.**




- PIM level increases with the growing number of carriers up to the number of carriers equals to the order.
- The fluctuation at 7th order PIM level observed as the number of carriers were increased.
- The overlaying PIM orders resulted from other carrier frequency combinations resulted in the PIM level variation.
- Destructive superimposing lead to the minimum PIM level, while the constructive superimposing affected the maximum PIM level.

# Summary of test results (cont'd)

- When only one PIM term was present at the specified PIM frequency, the PIM level was constant despite a phase variation on one of the Tx carriers.
- Conversely, when more PIM tones were appearing at the same PIM frequency, this caused a fluctuation in the PIM level.
- The fluctuation was observed to be little when the overlapping PIM order is higher than the one of interest.
- However, when the overlapping PIM term belongs to an equivalent or lower order than the one of interest, huge fluctuations in the range of 11 dB or more were observed.

# Conclusions of scenario #6

- The tests were performed to characterise the 3rd order PIM variation at a specific conditions. (different interface contact material)

  - ➢ VSC 10 channel Ku-Band OMUX was used with Iridite surface treatment.
  - ➢ Silver plated waveguide.

- PIM level increases with the growing number of carriers up to the number of carriers equals to the order number.
  - ➢ The slope of PIM for 3rd order with increasing carrier number showed about 5.6 dB

- With the increasing number of the carrier beyond of the order number, there was no contribution to the PIM levels.

# Scenario #7 test
# Modulated schemes vs. PIM

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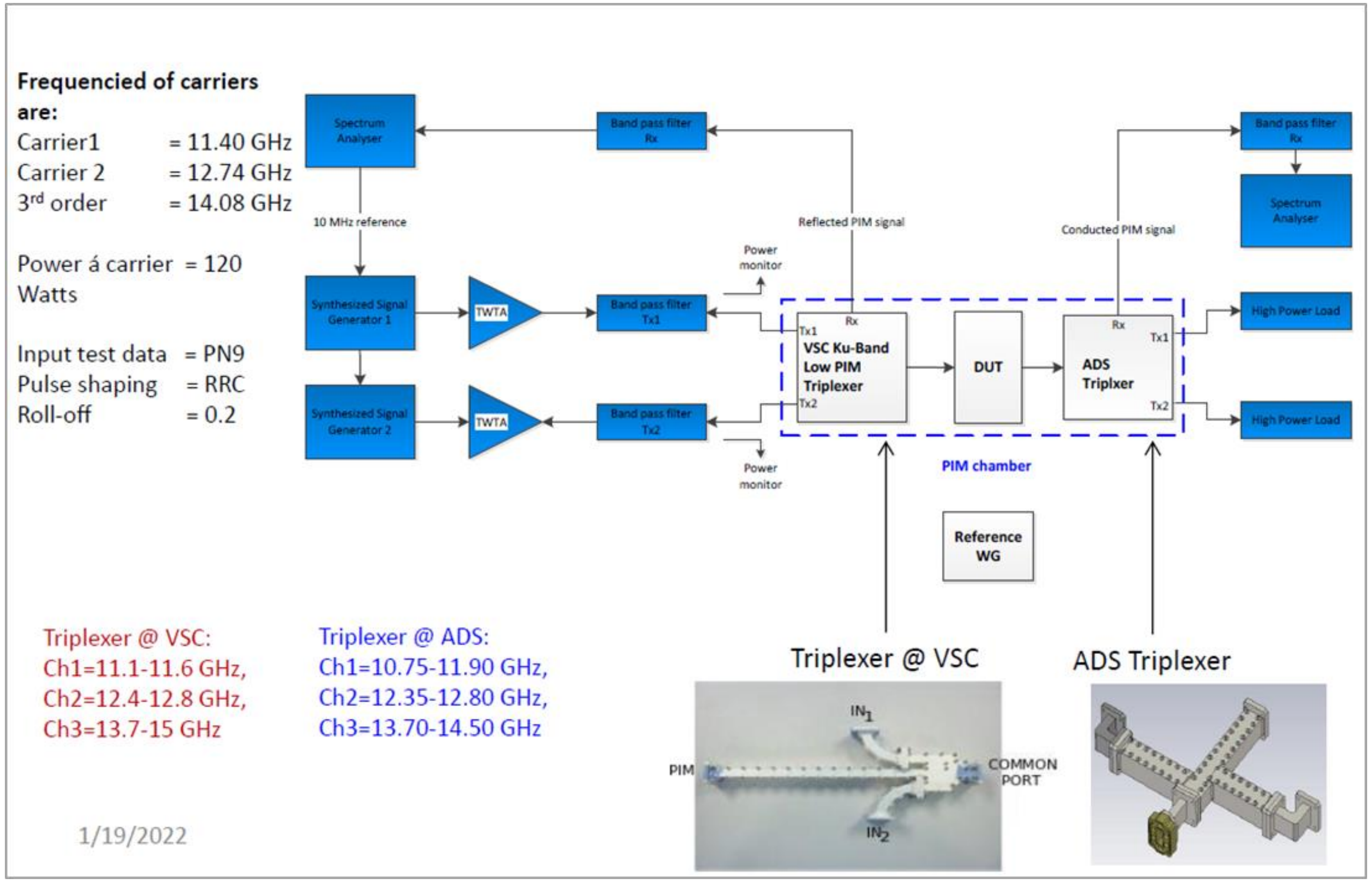
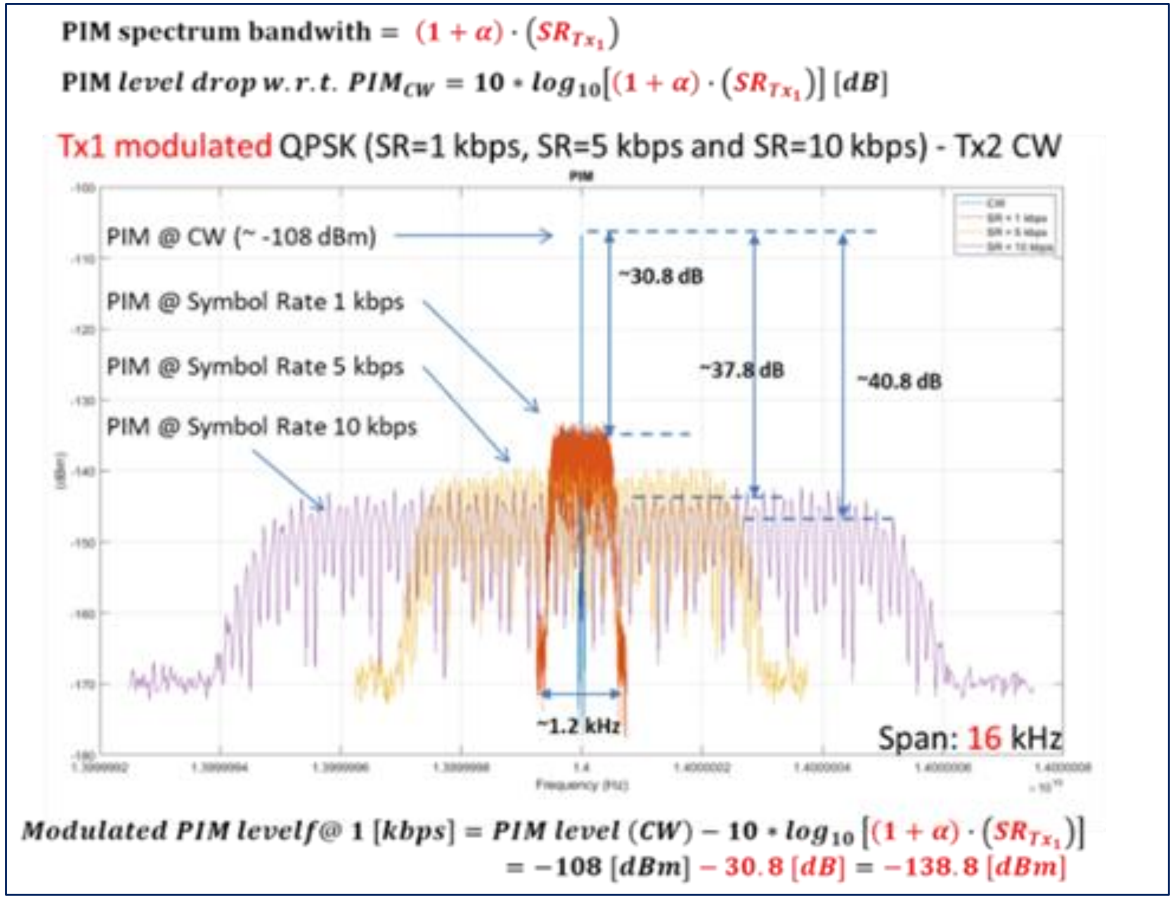
# Test setup configuration (ambient temperature)




Test facility and setup @ VSC

# 3rd order CW PIM spectrum & PIM spectrum spreading (with Tx1 signal modulation)




- PIM signal bandwidth is equal to the Tx1 modulated signal bandwidth itself.
- PIM signal spreading is proportional to the signal bandwidth (symbol rate)



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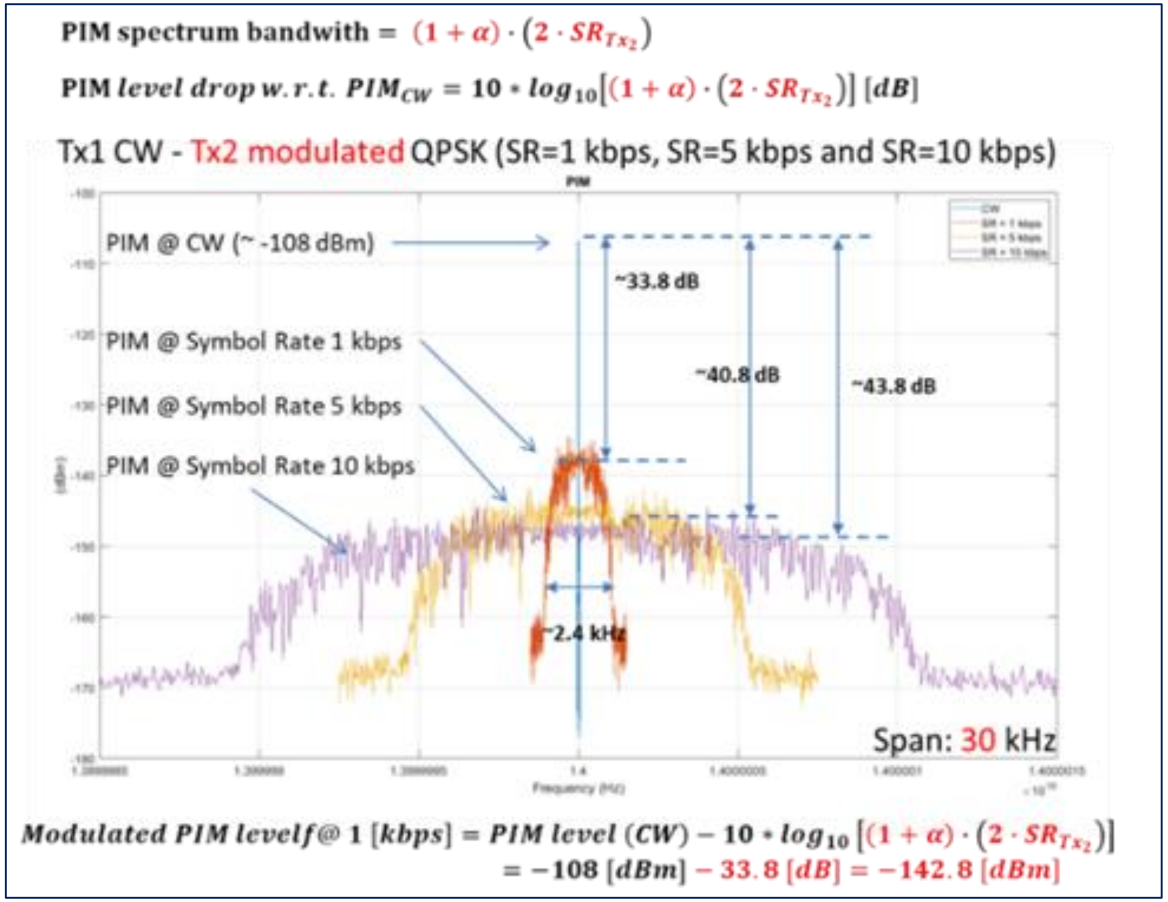
# $3^{rd}$ order CW PIM spectrum & PIM spectrum spreading (with Tx2 signal modulation)




- PIM signal bandwidth is equal to the two times of the Tx2 modulated signal bandwidth
- PIM signal spreading is proportional to the signal bandwidth (symbol rate)



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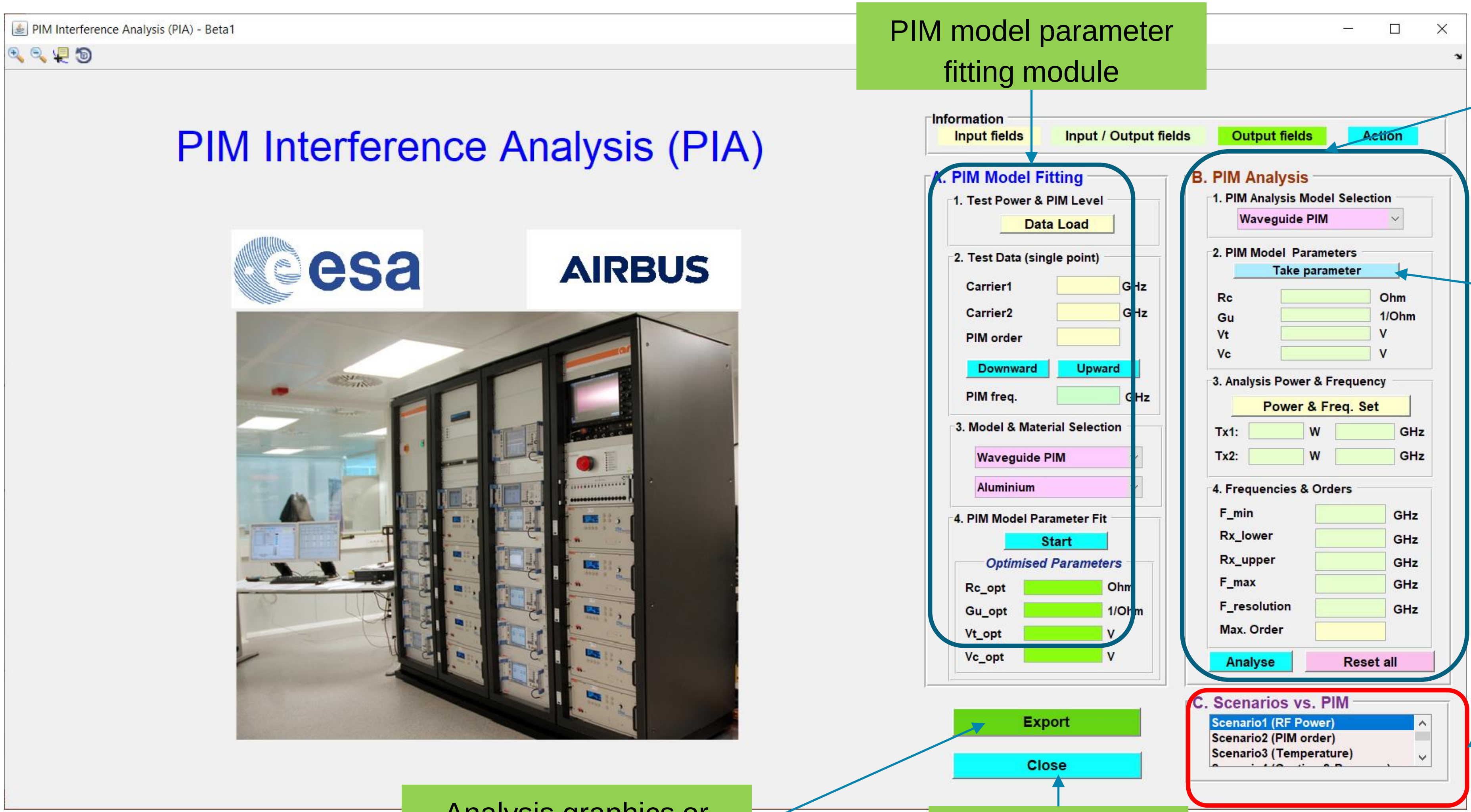
# Conclusion of scenario #7

- PIM test with modulates signal showed that the CW PIM level and modulated signal PIM level is mainly related over the spectrum spreading.
- The CW PIM spectrum of a specific PIM order is spread over the modulated signal bandwidth.
- This spreading factor is independent on the modulation scheme. (QPSK, 8PSK, QAM, 16QAM)
- Using spreading factor, modulated single PIM level can be estimated based on the two-tone CW PIM test.

# Phase 4 - Conclusions and recommendations

1. Evaluation of the test results and software parameter optimisation
2. Methodology to transpose complex scenarios to simple ones
3. General guidelines and margins

# Developed PIM analysis tool for results evaluation and prediction




PIM model parameter fitting module

PIM analysis module based on the model parameters

Parameter taking from optimisation

Analysis module for TRP specific scenarios

Analysis graphics or data export module

Termination of analysis tool



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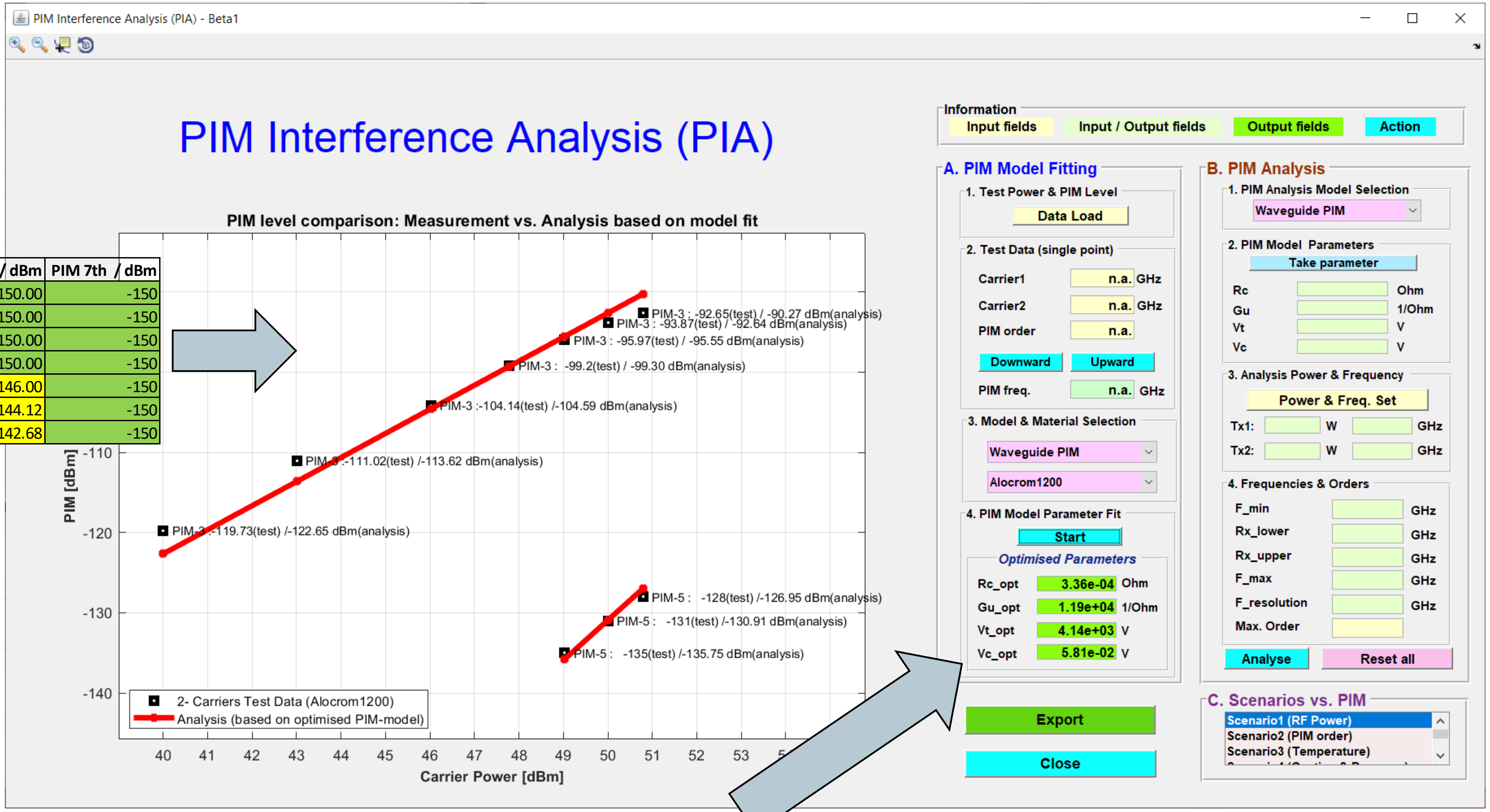
# Evaluation for scenario #1 (RF power levels vs. PIM amplitude)
# PIM analysis model “calibration”

Test data for PIM model “calibration” import

| Power | Steps | Tx1 / W | Tx2 / W | Tx1 / dBm | Tx2 /dBm | PIM 3rd / dBm | PIM 5th / dBm | PIM 7th / dBm |
|---|---|---|---|---|---|---|---|---|
| ramp-up equally Tx1 = Tx2 | 1 | 10 | 10 | 40.00 | 40.00 | -132.50 | -150.00 | -150 |
| | 2 | 20 | 20 | 43.01 | 43.01 | -123.50 | -150.00 | -150 |
| | 3 | 40 | 40 | 46.02 | 46.02 | -115.74 | -150.00 | -150 |
| | 4 | 60 | 60 | 47.78 | 47.78 | -111.34 | -150.00 | -150 |
| | 5 | 80 | 80 | 49.03 | 49.03 | -108.12 | -146.00 | -150 |
| | 6 | 100 | 100 | 50.00 | 50.00 | -106.20 | -144.12 | -150 |
| | 7 | 120 | 120 | 50.79 | 50.79 | -104.97 | -142.68 | -150 |

- Test data is imported
- PIM model parameters have been optimised (PIM model parameter calibrated)




PIM analysis model parameter optimisation



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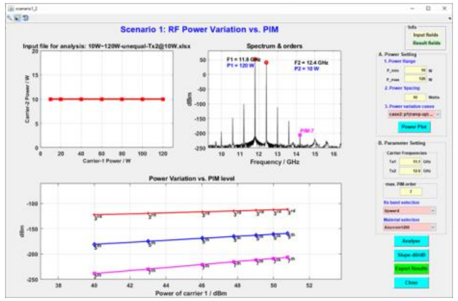
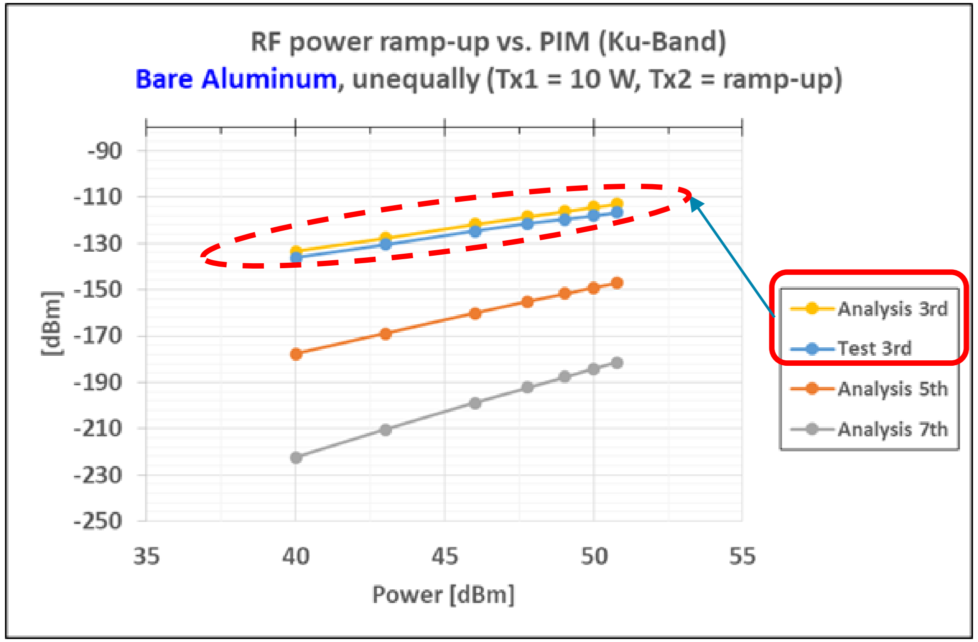
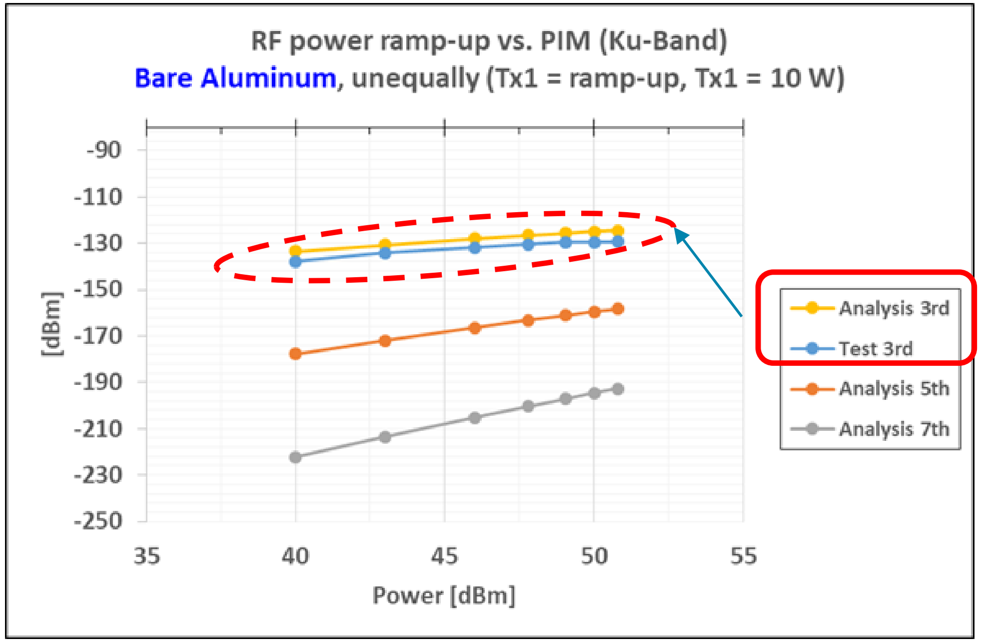
# Unequally power ramp-up analysis & comparison with test results - Aluminium (Example)



- Analysed PIM level using the obtained PIM model shows good agreement to the test values.
- Analysis for 5th and 7th using the same PIM model give prediction possibility.




Demonstrate for other cases!



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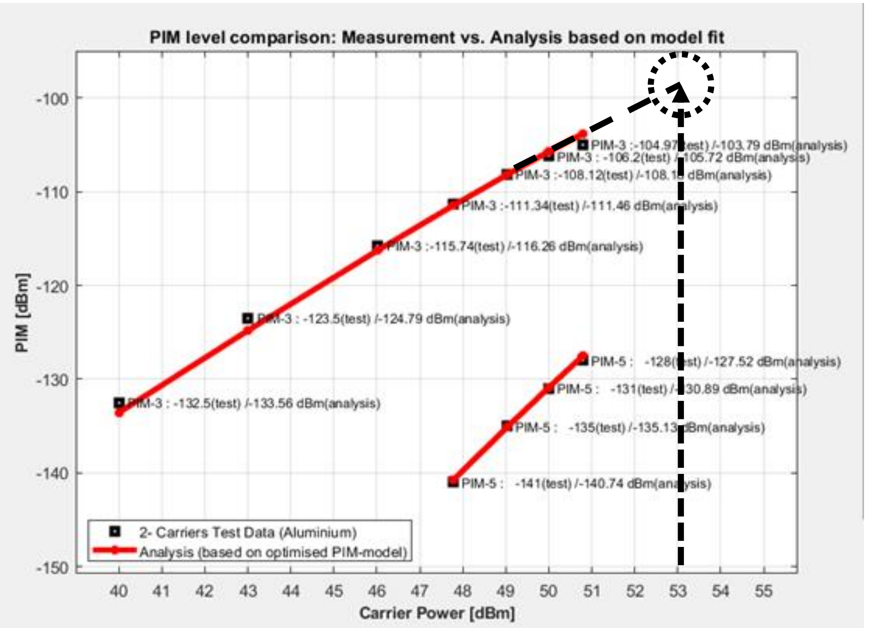
# Recommendations and guidelines for PIM related to RF Power variation

| | Slope dB/dB | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Aluminium | | | Alocrom | | | Surtec650 | | |
| | 3rd | 5th | 7th | 3rd | 5th | 7th | 3rd | 5th | 7th |
| equall ramp-up | 2.68 | 4.57 | 6.41 | 3 | 5 | 7 | 2.99 | 4.99 | 6.99 |
| Tx2 ramp-up | 1.86 | 2.8 | 3.72 | 2 | 3 | 4 | 2 | 3 | 4 |
| Tx1 ramp-up | 0.79 | 1.73 | 2.64 | 1 | 2 | 3 | 1 | 2 | 3 |




$$PIM\ level_{Estimated} = slope * \Delta P + reference_{level} + margin$$

$\Delta P$: $10*\log_{10}$((Power of interest)/ (Power_tested)) dB
Reference value: Tested PIM value

Using calibrated slope value, PIM level can be estimated for other power values.

Example:

| | |
|---|---|
| Test PIM order | = 3rd |
| Reference PIM level | = -108 dBm |
| @ Test power | = 2 x 100 W |
| Material | = Aluminium |

Estimation of 3rd order PIM level at 2 x 200 W for aluminium?

$$PIM\ level_{Estimated}$$
$$= 2.68 * 10 * \log_{10}\left(\frac{200\ \mathrm{W}}{100\ \mathrm{W}}\right) - 108\ \mathrm{dBm}$$
$$= -99.9\ \mathrm{dBm}$$



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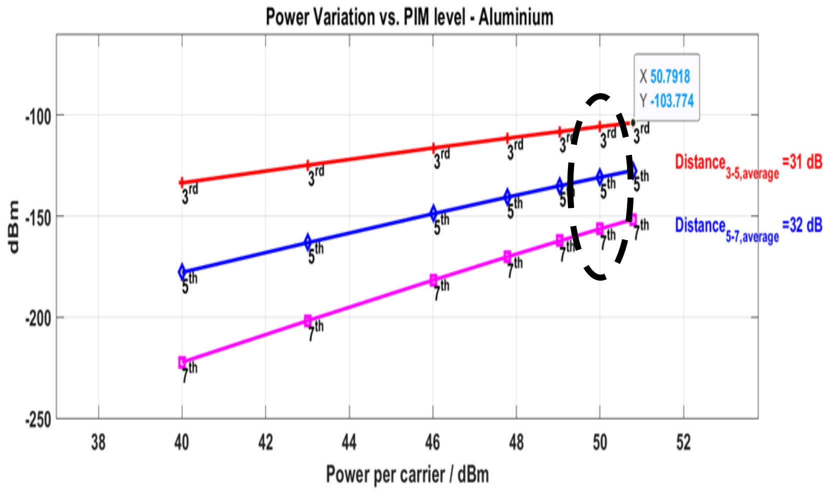
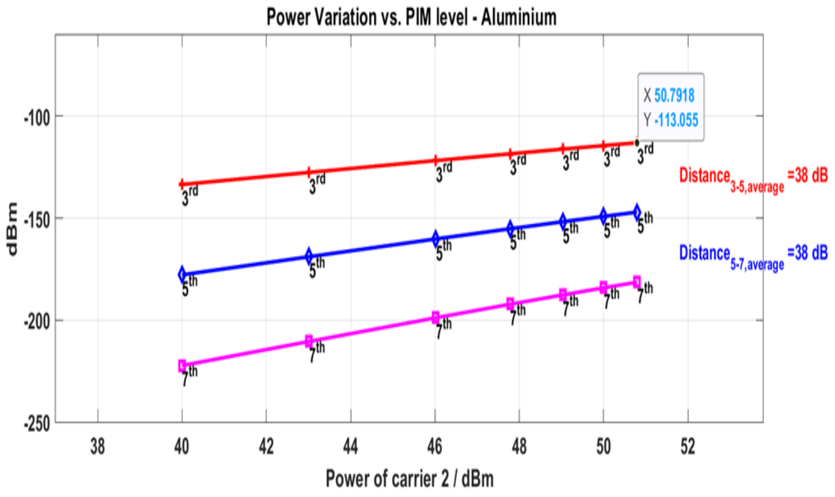
# Evaluation for scenario #2 (RF power variation vs. PIM order relations)
# Analysis of PIM level difference between orders using calibrated PIM model

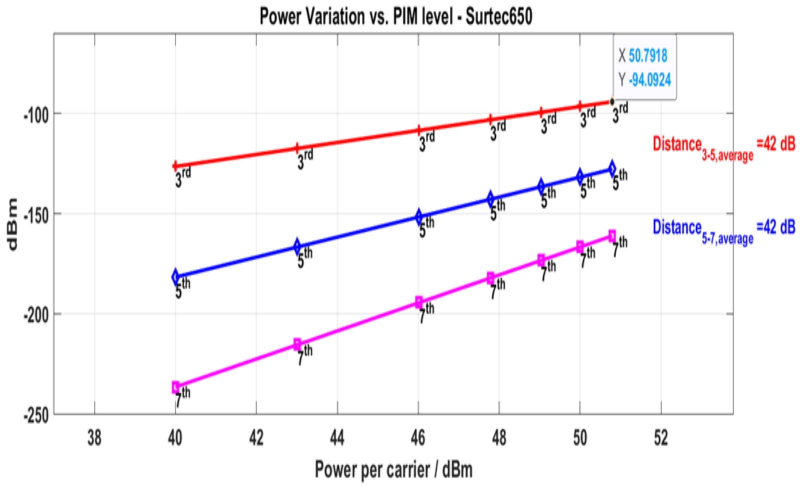
| | average distance between orders / dB | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminium | | | | Alocrom | | | | Surtec650 | | | |
| | Analysis | | Test | | Analysis | | Test | | Analysis | | Test | |
| | 3rd to 5th | 5th-7th | 3rd to 5th | 5th-7th | 3rd to 5th | 5th to 7th | 3rd to 5th | 5th to 7th | 3rd to 5th | 5th to 7th | 3rd to 5th | 5th to 7th |
| **equall ramp-up** | 31 | 32 | 38 | note 1 | 45 | 45 | 40 | note 1 | 42 | 42 | 37 | note 1 |
| **Tx2 ramp-up** | 38 | 38 | note 2 | | 52 | 51 | note 2 | | 49 | 48 | note 2 | |
| **Tx1 ramp-up** | 38 | 38 | | | 52 | 51 | | | 49 | 48 | | |

note 1: 7th order were not measurable (< -150 dBm, setup residual level)

note 2: 5th order were not measurable (< -150 dBm, setup residual level)



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# Recommendations using an example of aluminium

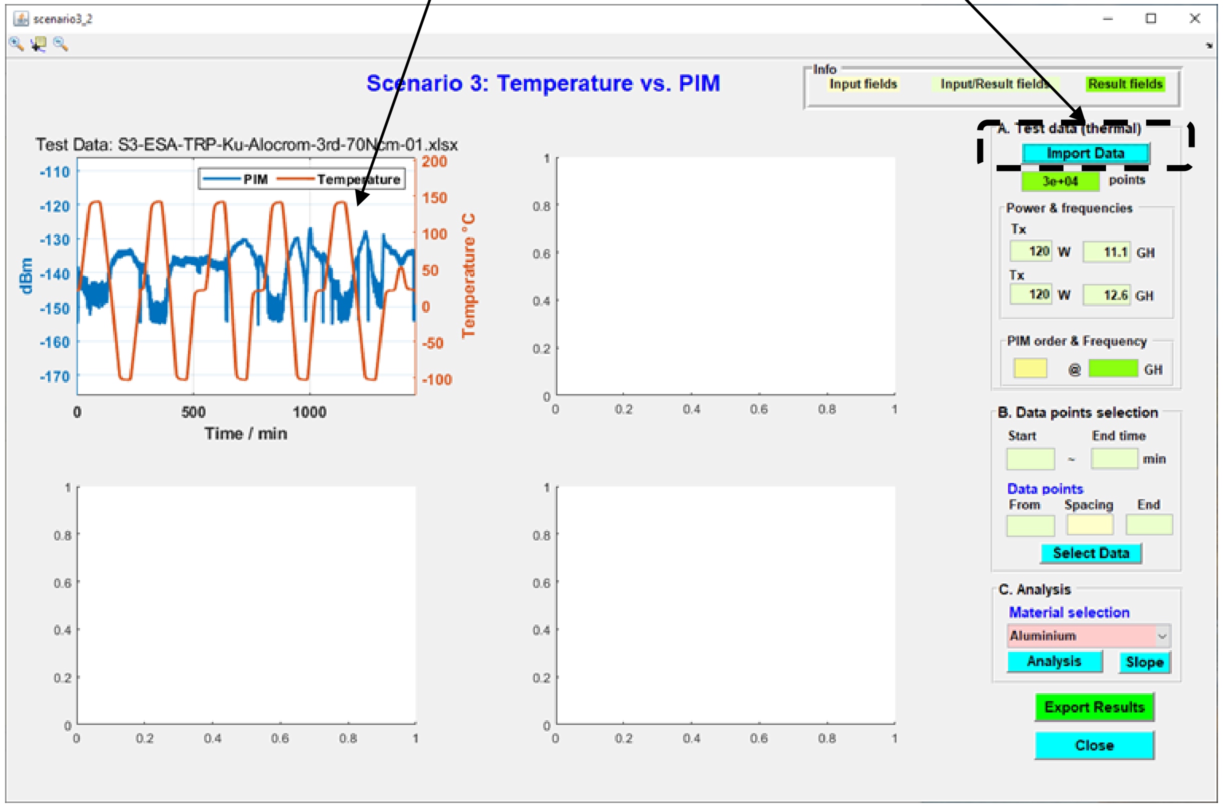
- PIM level distance between 3$^{rd}$ and 5$^{th}$
- 3$^{rd}$ order at 100 W per carrier = -110 dBm
- **Average distance of between 3$^{rd}$ and 5$^{th}$ order = 31 dB**
- Estimated 5$^{th}$ order PIM = -141 dBm
- The distance between orders is called also “roll-off”
- The roll-off values are contact pressure dependent.
- PIM test on sample level with the particular conditions (pressure, material, temperature) shall be available for the PIM model calibration.

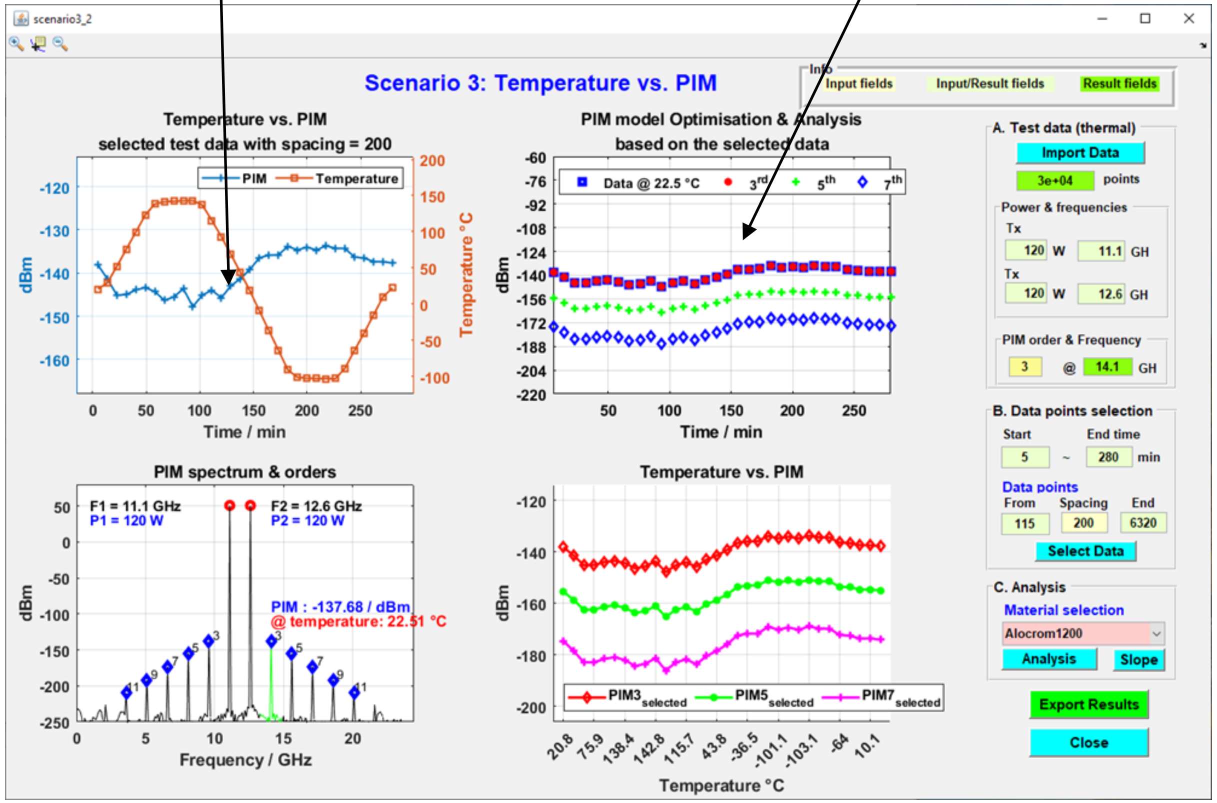
# Test data import, selection of temperature area and analysis

Test data are imported

Test data are selected

PIM model obtained and PIM analysed



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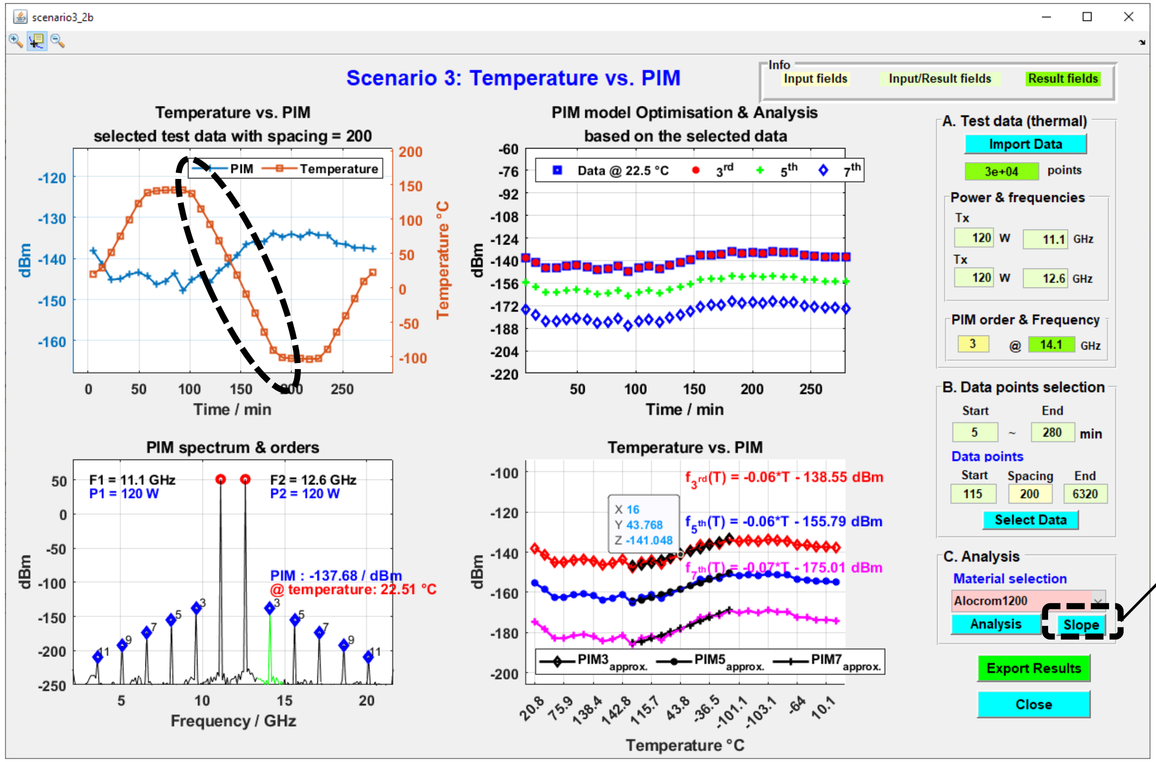
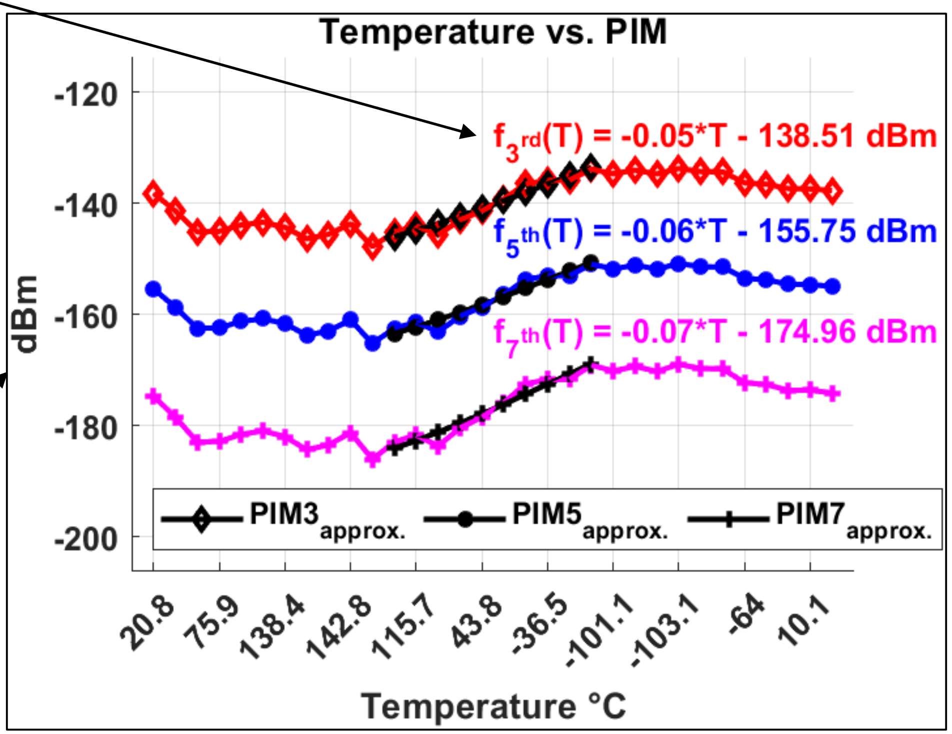
# scenario #3 (Temperature vs. PIM)
# Slope over temperature calculation (Example)

Specific temperature area selected and the approximation function obtained.



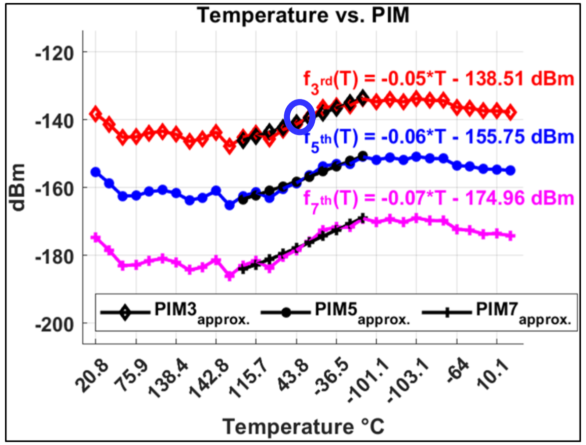



# PIM slope / Temperature and orders and PIM level estimation (Example)

| | PIM Slope - dB/Temperature | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1st (3 °C/min) | | | 2nd (4 °C/min) | | | 3rd (5 °C/min) | | | 4th (4 °C/min) | | | 5th (3 °C/min) | | |
| PIM Order | ambient - hot | hot - cold | cold - ambient | ambient - hot | hot - cold | cold - ambient | ambient - hot | hot - cold | cold - ambient | ambient - hot | hot - cold | cold - ambient (Note 1) | ambient - hot | hot - cold | cold - ambient (Note 1) |
| 3rd | -0.01 | -0.05 | -0.03 | -0.15 | -0.07 | 0 | -0.01 | -0.02 | -0.04 | -0.11 | -0.08 | 0.33 | -0.14 | -0.10 | 0.13 |
| 5th | -0.01 | -0.06 | -0.03 | -0.15 | -0.08 | 0 | -0.01 | -0.02 | -0.04 | -0.11 | -0.08 | 0.34 | -0.14 | -0.10 | 0.13 |
| 7th | -0.01 | -0.07 | -0.04 | -0.17 | -0.09 | 0 | -0.01 | -0.03 | -0.05 | -0.13 | -0.10 | 0.43 | -0.16 | -0.12 | 0.13 |

Note 1: At 4th and 5th cycle the contact was gradually instable due to the cycles before. Therefor the sign of the gradient changed.

Reference PIM level




$$PIM\ level_{Estimated} = slope * \Delta T + reference_{value} + margin$$

ΔT: (Temperature of interest – reference temperature )°C
Reference_value: PIM level at reference temperature

Using calibrated slope value, PIM level can be estimated for other power values.

Example:
Tested PIM level = -141 dBm
Test power = 2 x 120 W
Temperature = 43.7 °C
Material = Alocrom

Estimated PIM level at -150 °C for aluminium?
Slope = -0.05 dB / °C
ΔT = (-150 – 43.6 °C) = -193.6 °C
$PIM_{\_level@200\ W}$ = -0.05*(-193.6) – 141 dBm
≈ -131.32 dBm



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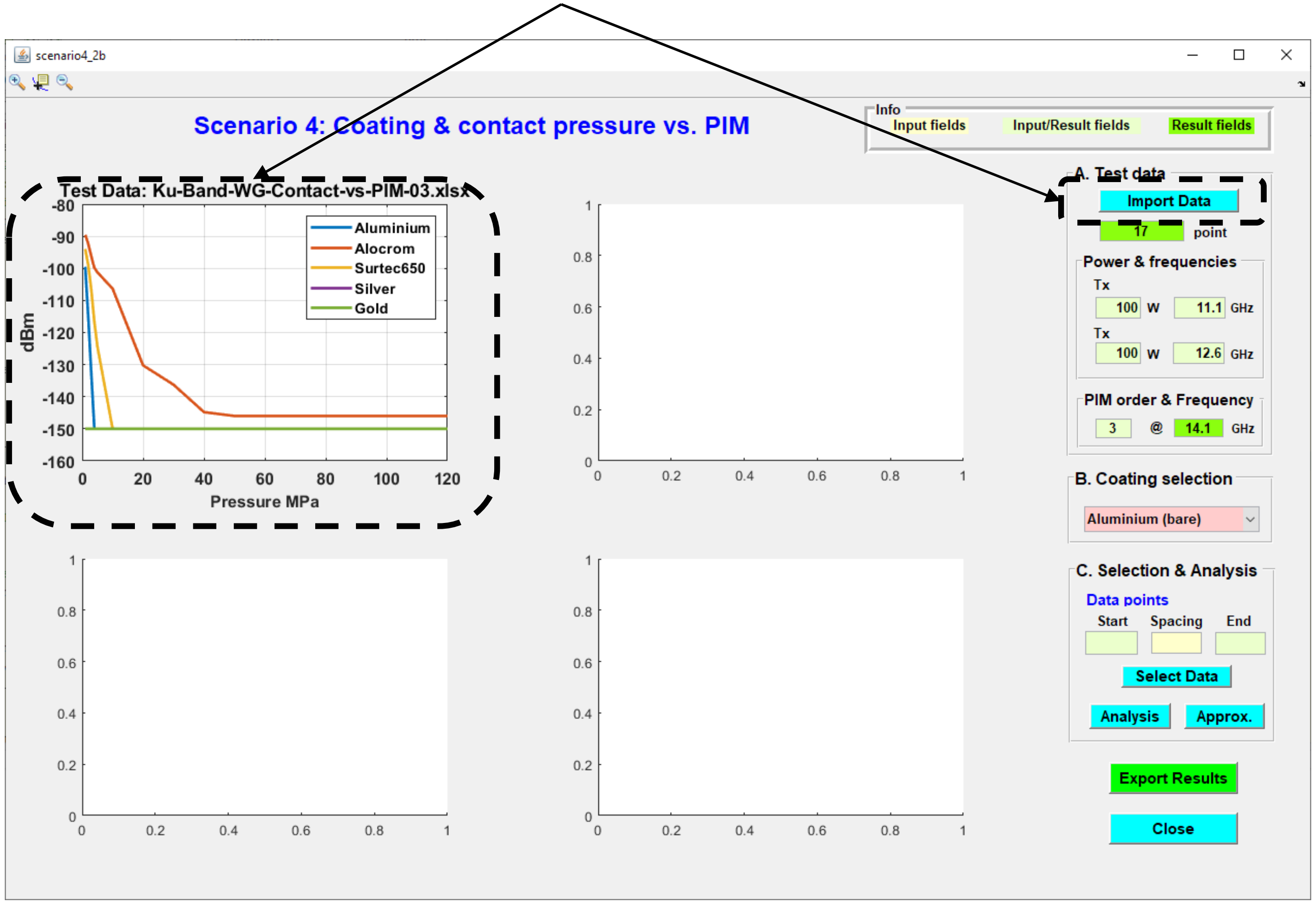
# Analysis tool: scenario #4 (Coating & contact pressure vs. PIM)

Test data are imported



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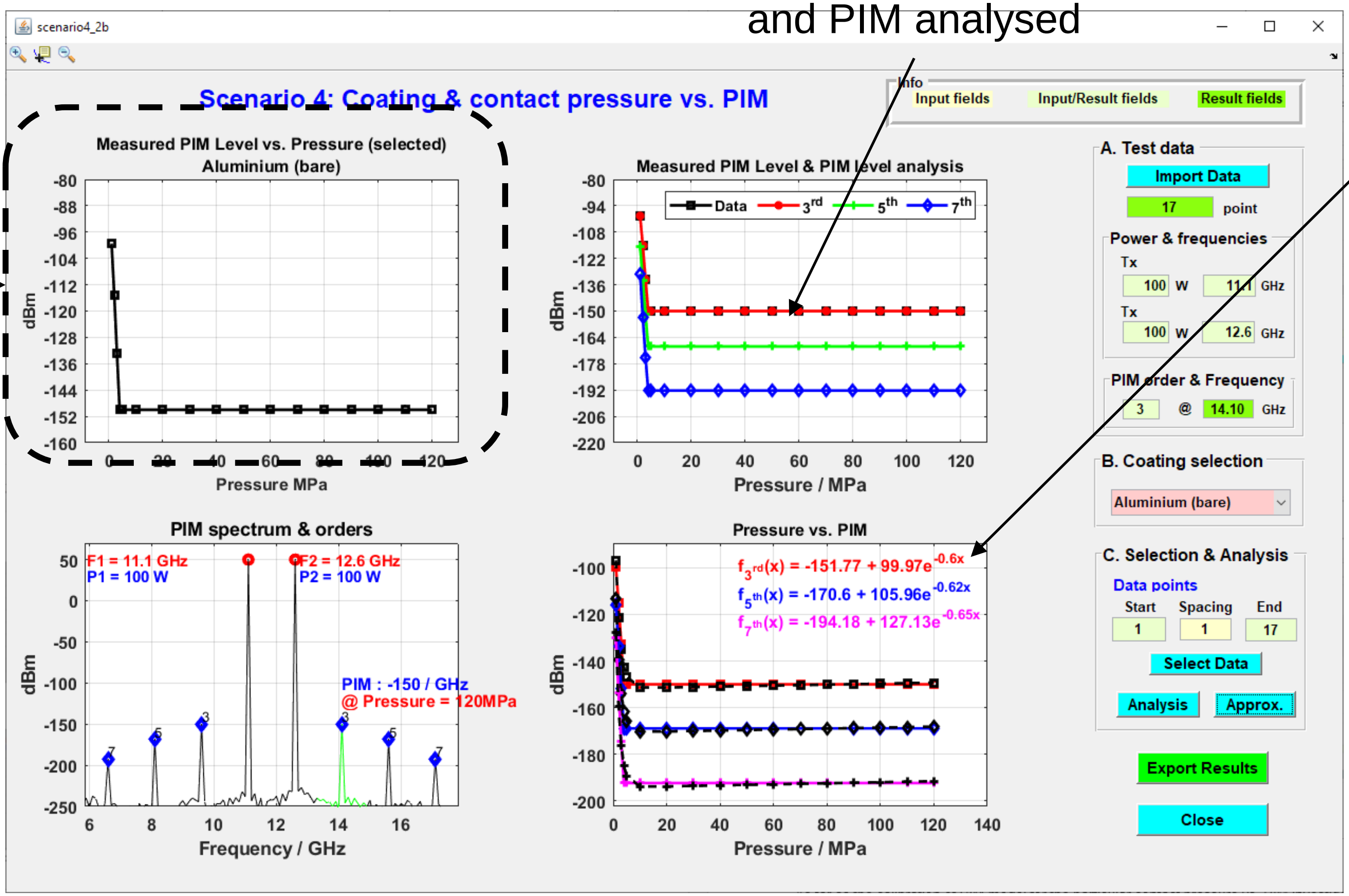
# Test data selection and PIM model calibration for Aluminium

PIM model obtained and PIM analysed

approximation function obtained.

Aluminium test data selected

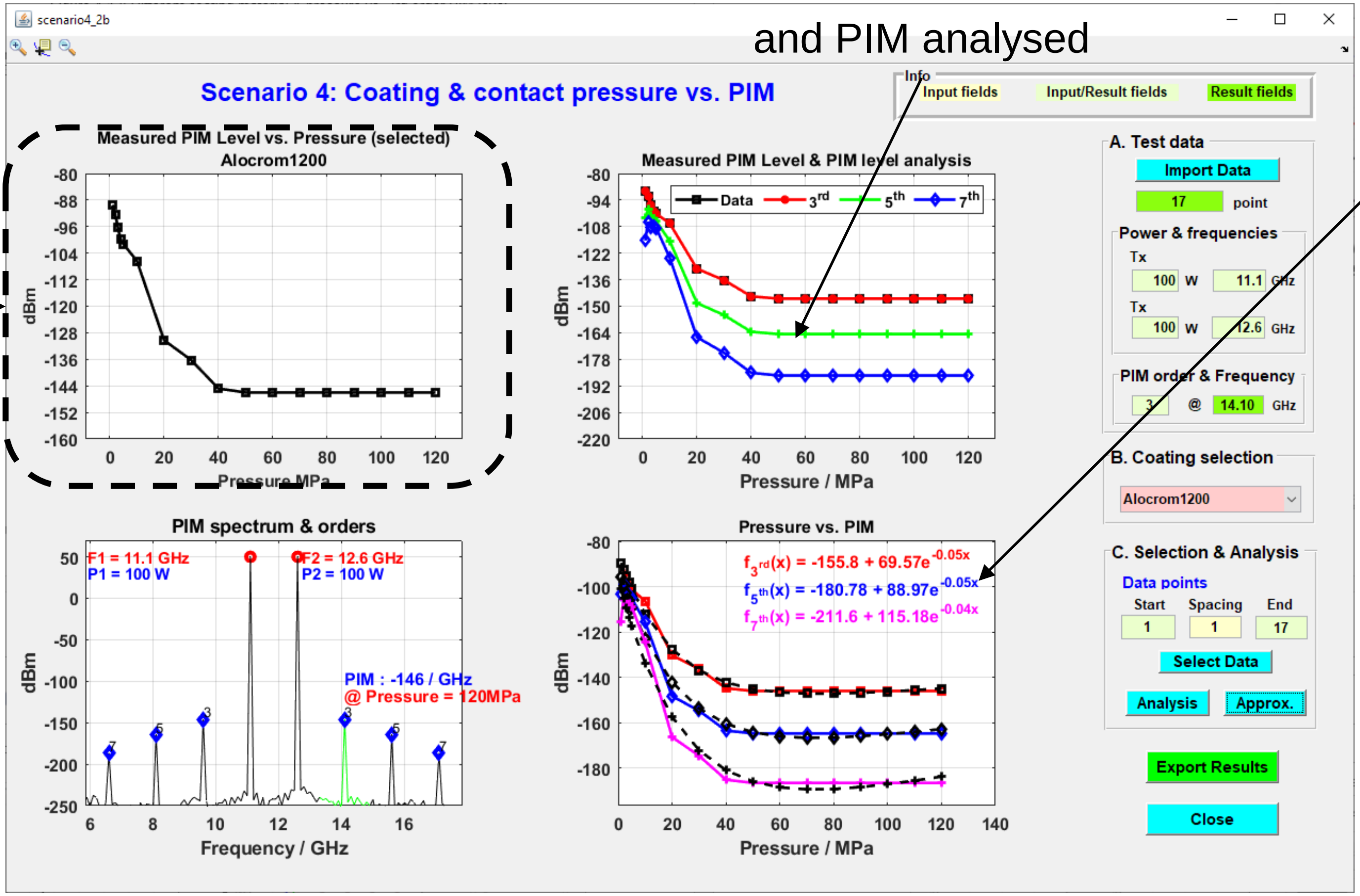


# Test data selection and PIM model calibration for Alocrom

PIM model obtained and PIM analysed

Alocrom test data selected

approximation function obtained.



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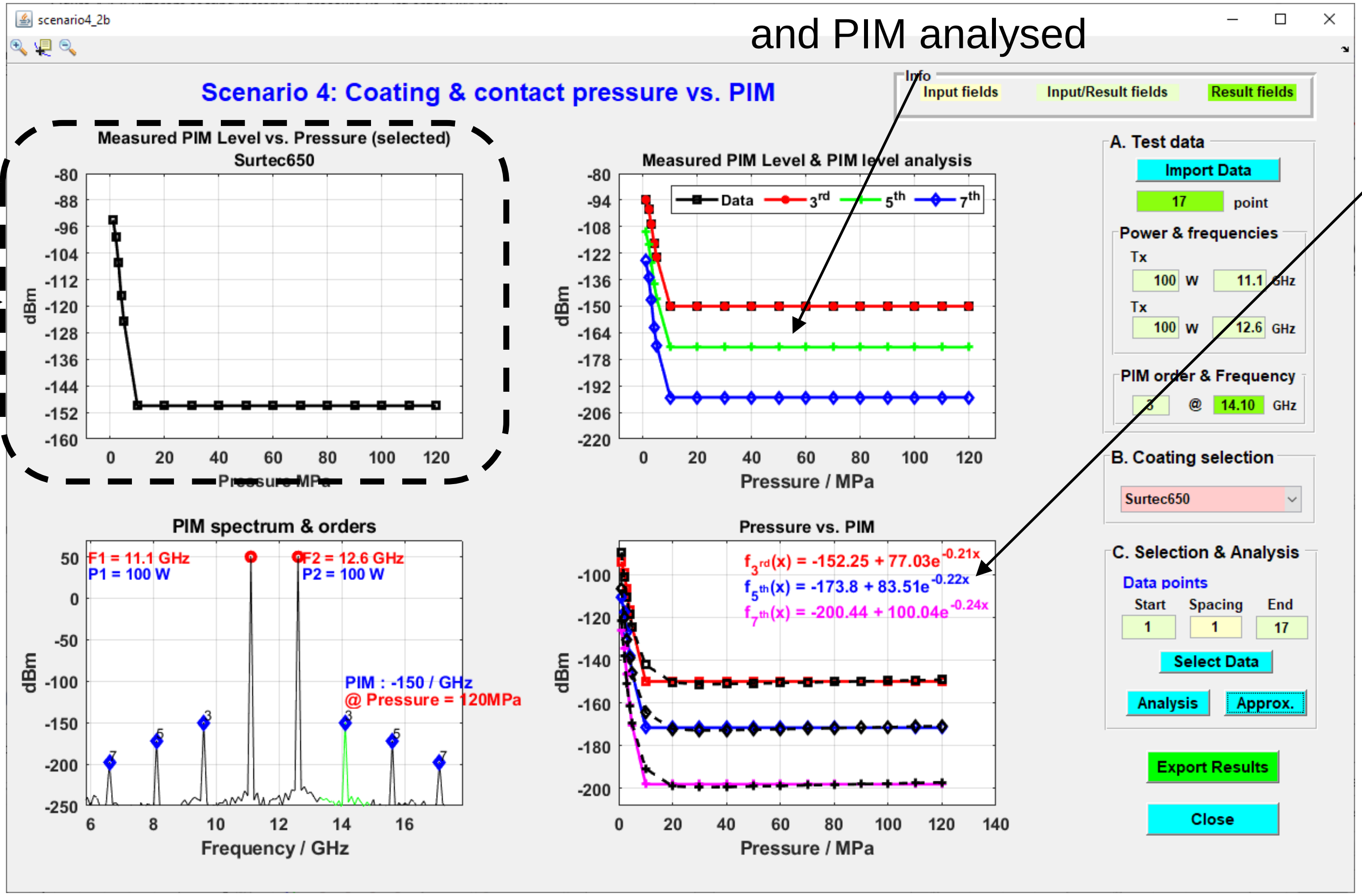
# Test data selection and PIM model calibration for Surtec650

PIM model obtained and PIM analysed

Surtec650 test data selected

approximation function obtained.



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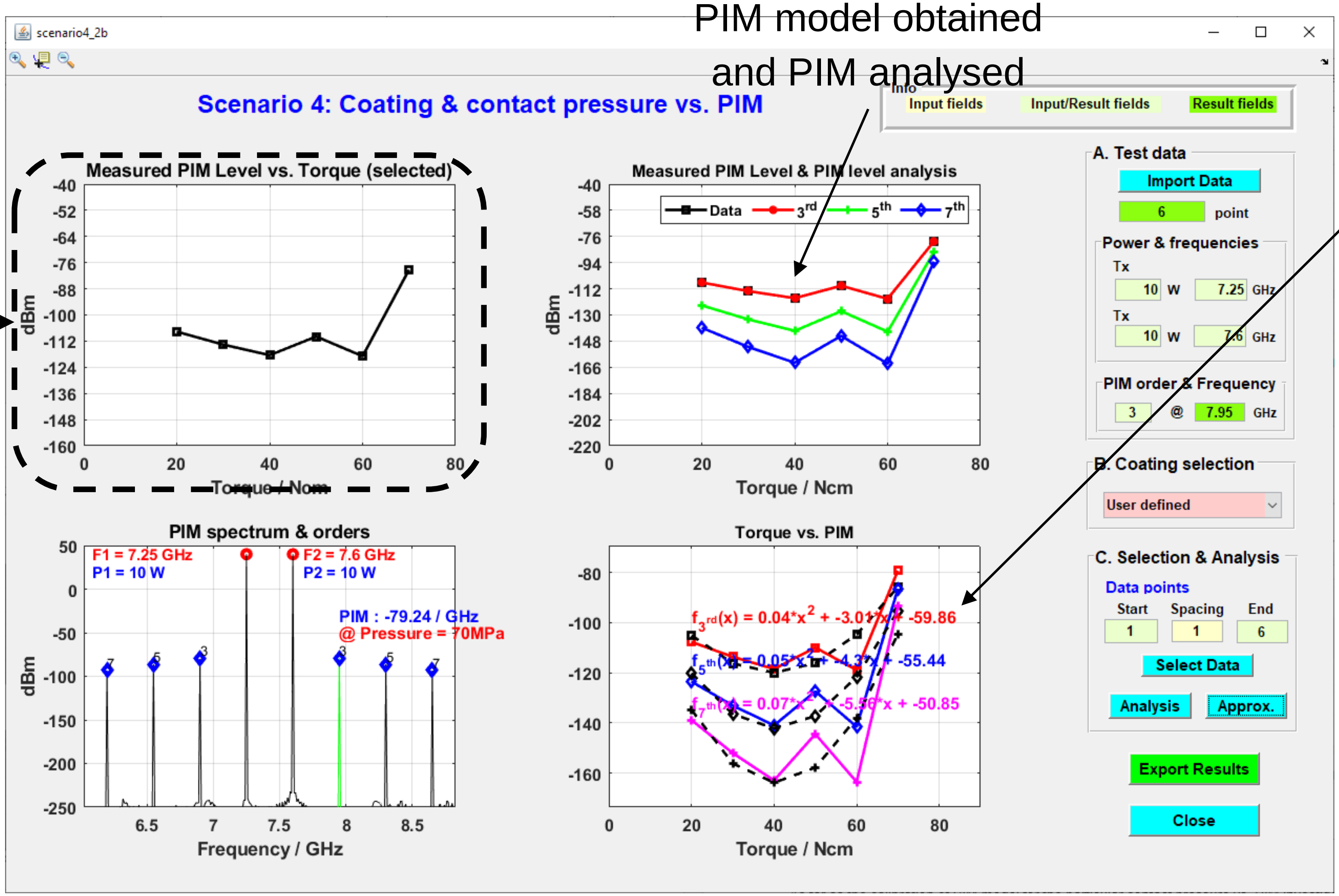
# Test data selection and PIM model calibration for TNC

TNC
Test data
imported

PIM model obtained
and PIM analysed

approximation function
obtained.



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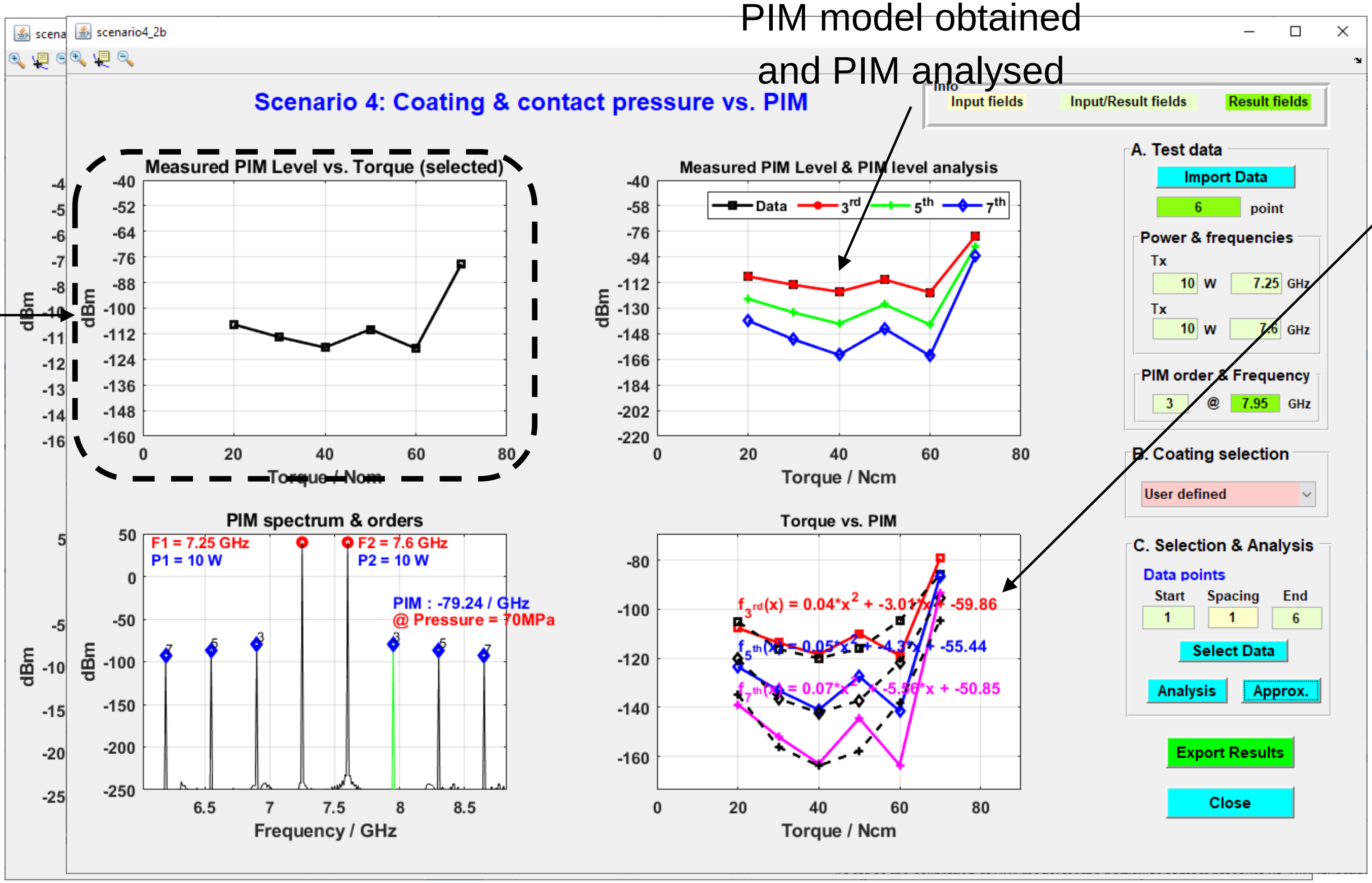
# Test data selection and PIM model calibration for SMA

TNC
Test data
imported

PIM model obtained
and PIM analysed

approximation function
obtained.



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# Recommendations and guidelines for PIM related to contact pressure

- The test data shall be available for calibration.
- Equation with calibrated parameters can be derived and applied for the particular pressure values.

case1: exponential PIM behaviour

$$PIM\ level_{Estimated} = \alpha + \beta \cdot e^{\gamma \cdot P} + margin$$

$\alpha, \beta, \gamma$: constant
$P$: contact pressure

case1: Polynomial PIM behaviour

$$PIM\ level_{Estimated} = \alpha \cdot P^2 + \beta \cdot P + \gamma + margin$$

$\alpha, \beta, \gamma$: constant
$P$: contact pressure



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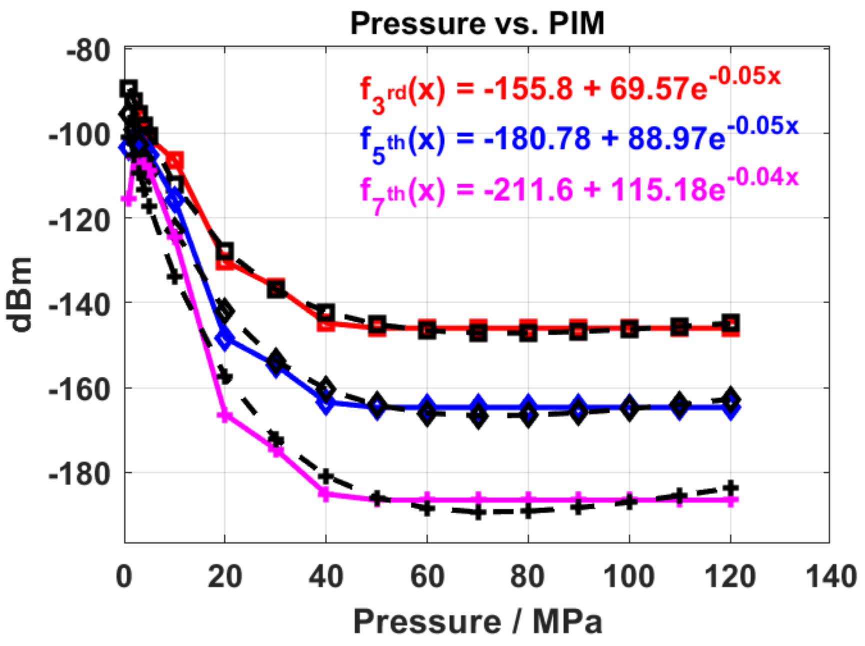
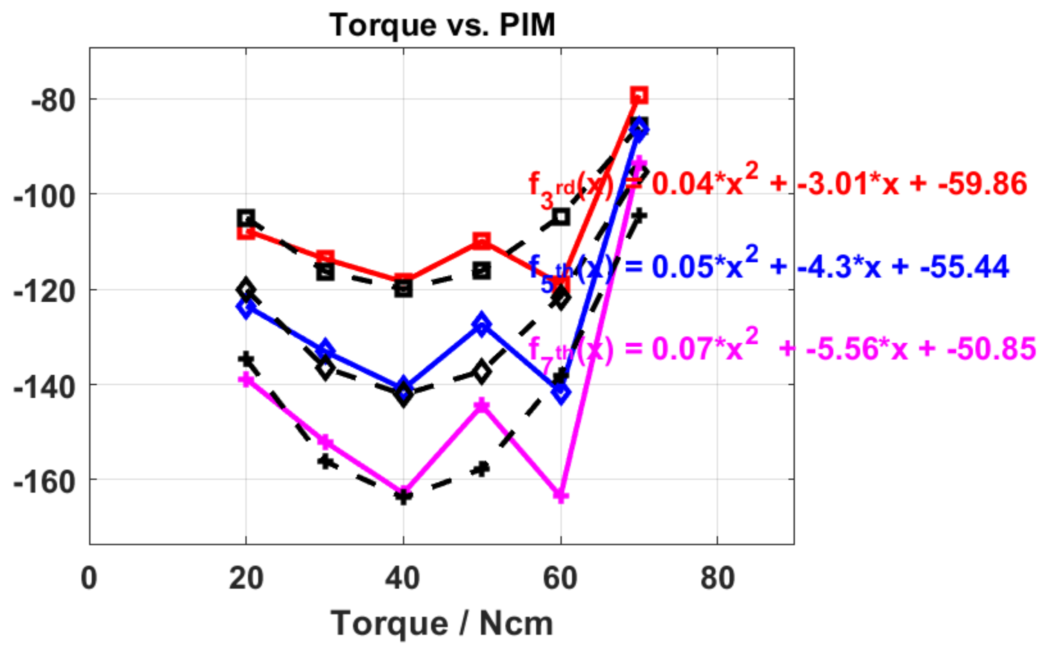
# Example

3rd order was calibrated contact pressure vs. PIM
5th and 7th order PIM

The PIM level at every contact pressure for order of interest can be calculated using the approximation function.



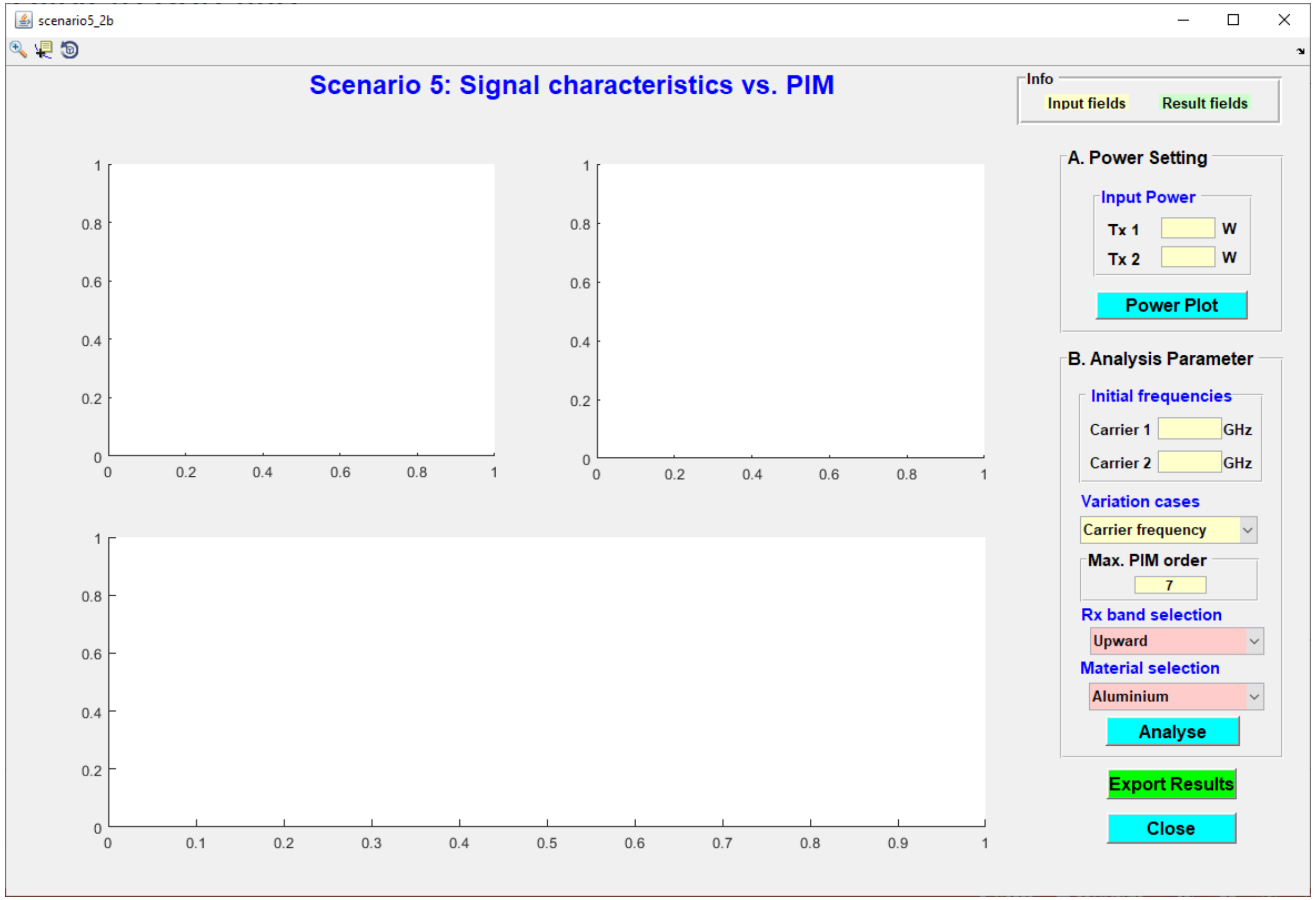

Alocrom waveguide




TNC coaxial sample

# Analysis tool: scenario #5 (Signal characteristics vs. PIM)

- PIM model calibration performed using
- The Alocrom waveguide sample with 1 MPa contact pressure used
- Power: 2 x 120 W



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# Test scenario and results with frequency, spacing and phase variation in C-/X-/Ku-Band)

## Waveguide samples

Ku-Band WG Sample | X-Band WG sample | C-Band WG sample

## C-Band

| seq | Variation | Tx1 Freq. [GHz] | Tx2 Freq. [GHz] | PIM Freq. [GHz] | PIM 3rd [dBm] @ 13 Ncm (1MPa) |
|---|---|---|---|---|---|
| 1 | carrier spacing | 3,65 | 4,80 | 5,95 | -93,26 |
| 2 | | 3,70 | 4,80 | 5,90 | -93,01 |
| 3 | | 3,95 | 4,80 | 5,85 | -92,94 |
| 4 | carrier frequencies | 3,65 | 4,75 | 5,85 | -93,14 |
| 5 | | 3,64 | 4,77 | 5,90 | -92,67 |
| 6 | | 3,63 | 4,76 | 5,95 | -92,94 |
| 7 | carrier phase | 3,65 | 4,80 | 5,95 | -93,21 |
| 8 | | 3,65 | 4,80 | 5,95 | -93,23 |
| 9 | | 3,65 | 4,80 | 5,95 | -93,33 |

## X-Band

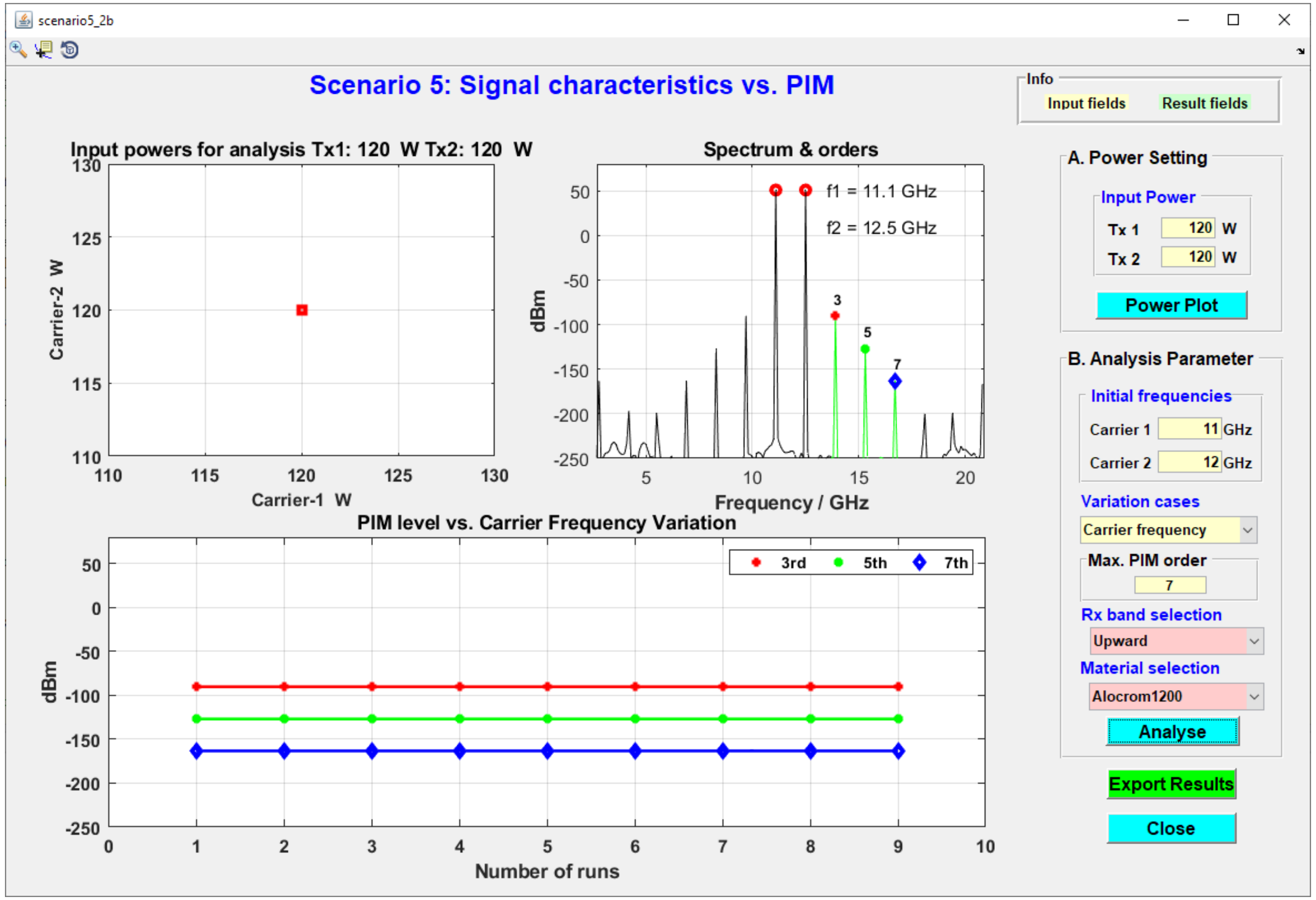
| seq | Variation | Tx1 Freq. [GHz] | Tx2 Freq. [GHz] | PIM Freq. [GHz] | PIM 3rd [dBm] @ 4,2 Ncm (1MPa) |
|---|---|---|---|---|---|
| 1 | carrier spacing | 7,25 | 7,60 | 7,95 | -93,61 |
| 2 | | 7,25 | 7,64 | 8,03 | -92,97 |
| 3 | | 7,25 | 7,68 | 8,11 | -94,8 |
| 4 | carrier frequencies | 7,26 | 7,62 | 7,98 | -93,31 |
| 5 | | 7,28 | 7,65 | 8,02 | -93,40 |
| 6 | | 7,30 | 7,67 | 8,04 | -94,18 |
| 7 | carrier phase | 7,25 | 7,60 | 7,95 | -93,50 |
| 8 | | 7,25 | 7,60 | 7,95 | -93,39 |
| 9 | | 7,25 | 7,60 | 7,95 | -93,13 |

## Ku-Band

| seq | Variation | Tx1 Freq. [GHz] | Tx2 Freq. [GHz] | Freq. [GHz] | PIM 3rd [dBm] @ 3,5 Ncm (1MPa) |
|---|---|---|---|---|---|
| 1 | carrier spacing | 11,10 | 12,60 | 14,10 | -93,12 |
| 2 | | 11,10 | 12,55 | 14,00 | -93,73 |
| 3 | | 11,10 | 12,50 | 13,90 | -94,75 |
| 4 | carrier frequencies | 11,00 | 12,60 | 14,20 | -95,12 |
| 5 | | 10,95 | 12,65 | 14,35 | -96,83 |
| 6 | | 10,90 | 12,70 | 14,50 | -94,85 |
| 7 | carrier phase | 11,10 | 12,60 | 14,10 | -95,19 |
| 8 | | 11,10 | 12,60 | 14,10 | -95,56 |
| 9 | | 11,10 | 12,60 | 14,10 | -95,8 |

# Analysis with frequency variation

- **Frequency variation**
- The Alocrom with 1 MPa contact pressure used
- 2 x 120 W
- Carrier frequency variation showed no change of the PIM level



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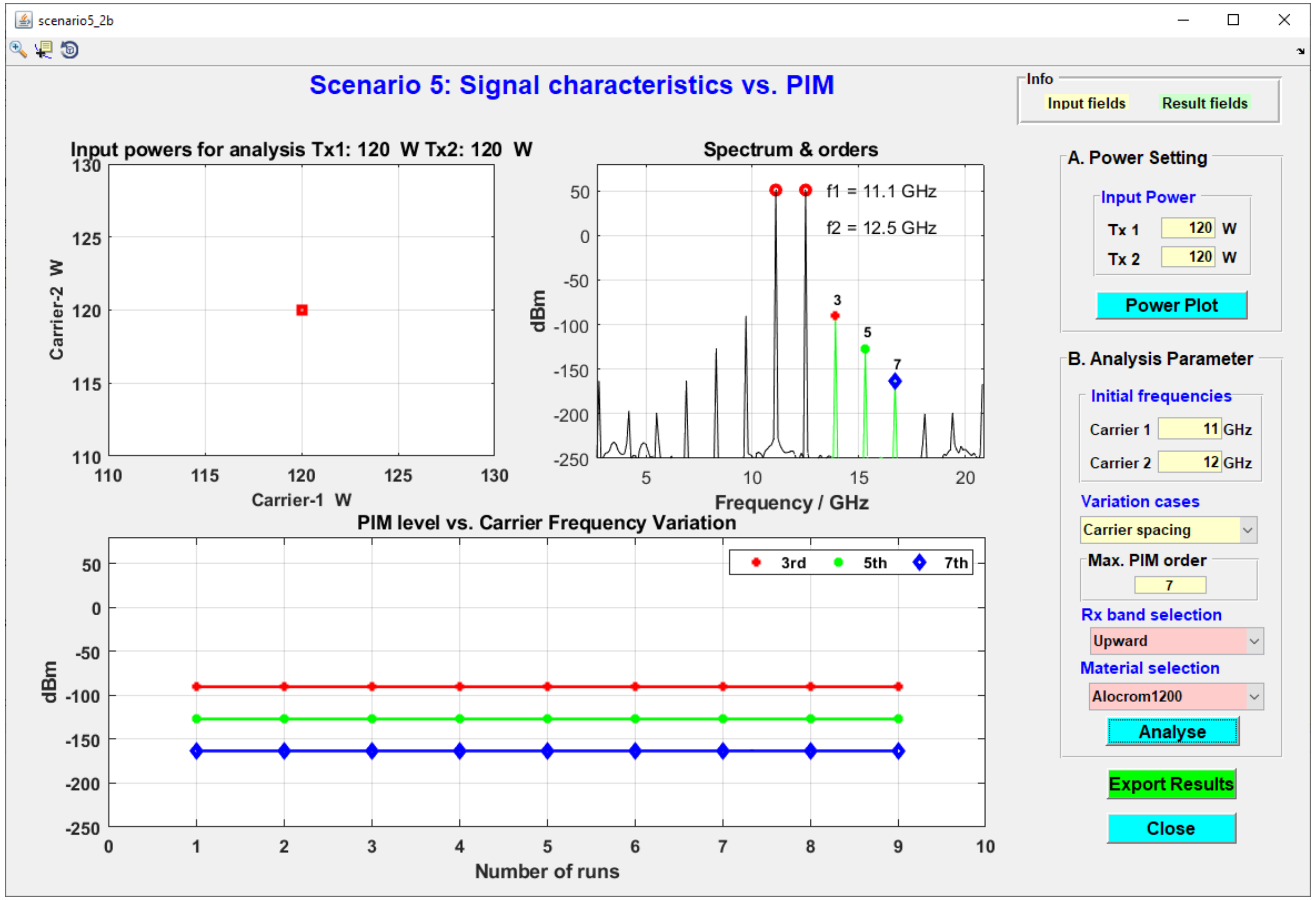
# Analysis with carrier spacing variation

- **Carrier spacing variation**
- The Alocrom with 1 MPa contact pressure used
- 2 x 120 W
- Carrier frequency spacing variation showed no change of the PIM level



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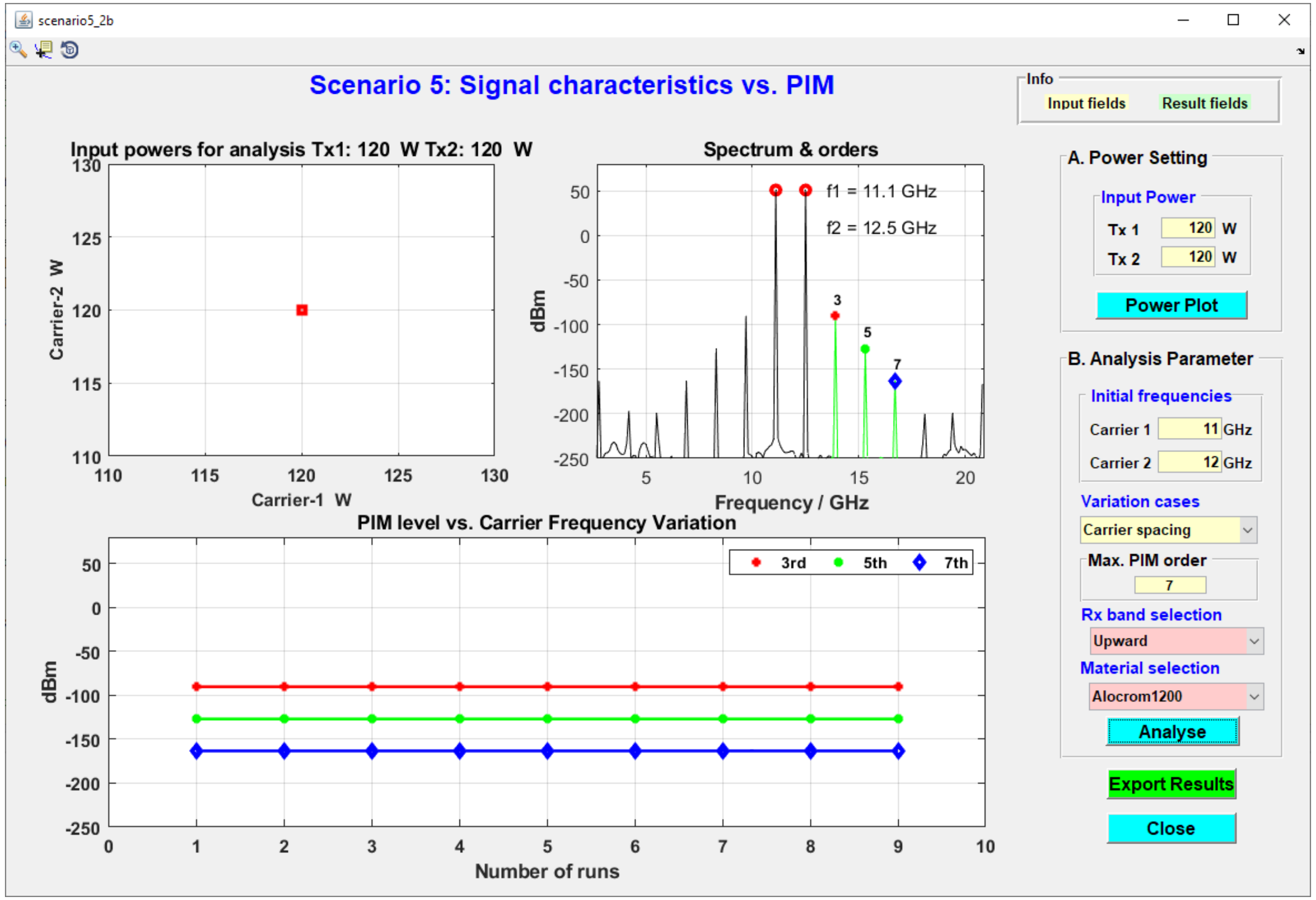
# Analysis with carrier phase variation

- **Carrier phase variation**
- The Alocrom with 1 MPa contact pressure used
- 2 x 120 W
- Carrier phase variation showed no change of the PIM level



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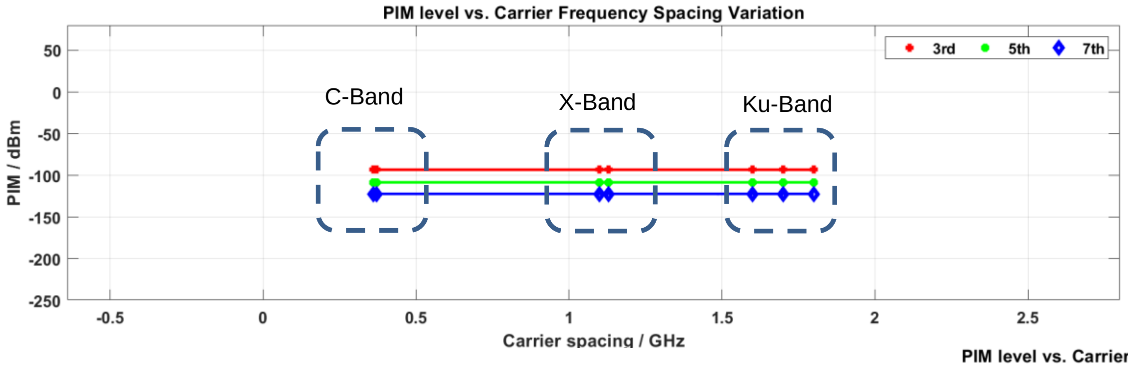
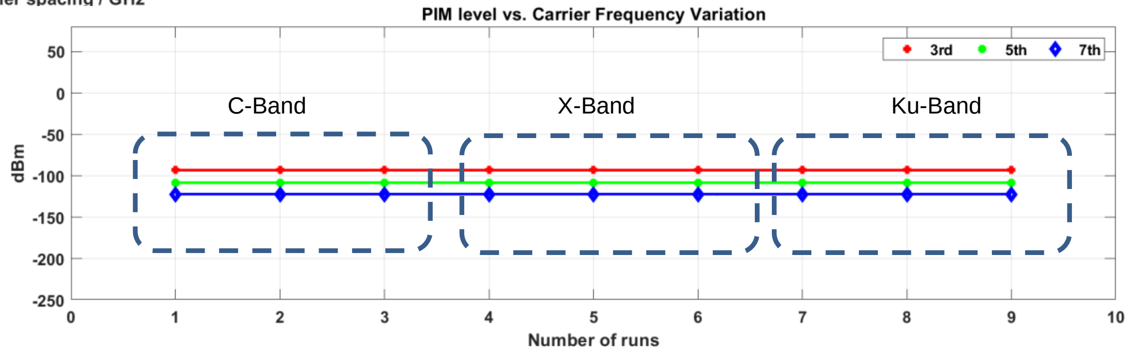
# Analysis with carrier spacing, frequency and phase variation

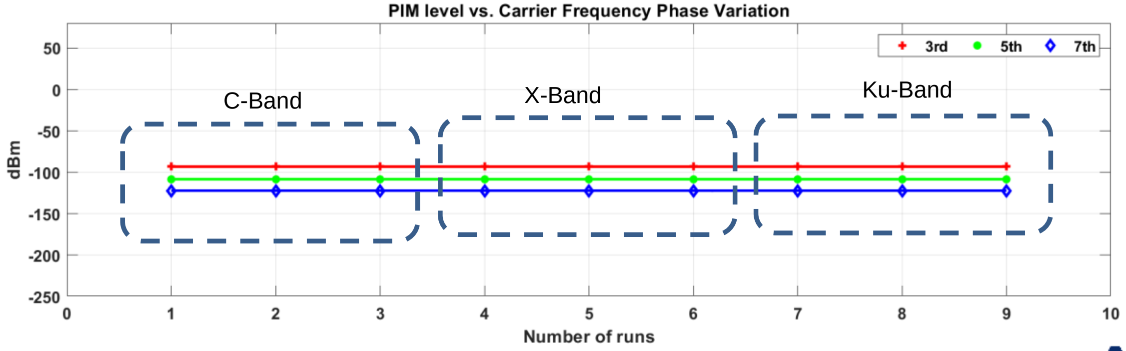
carrier spacing variation




carrier frequency variation

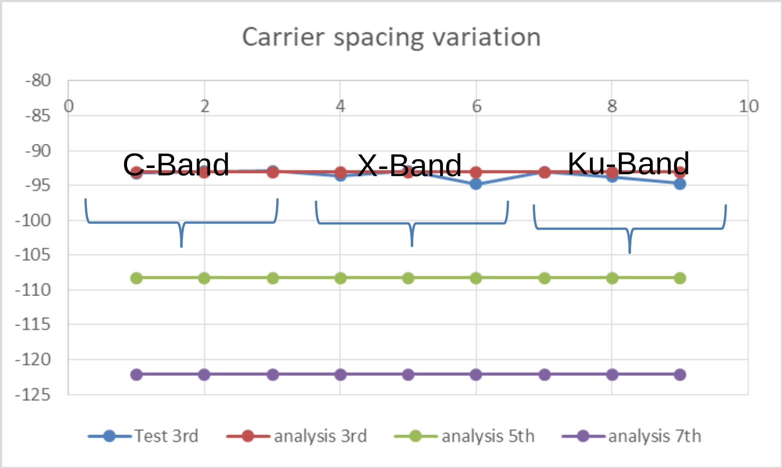



carrier phase variation

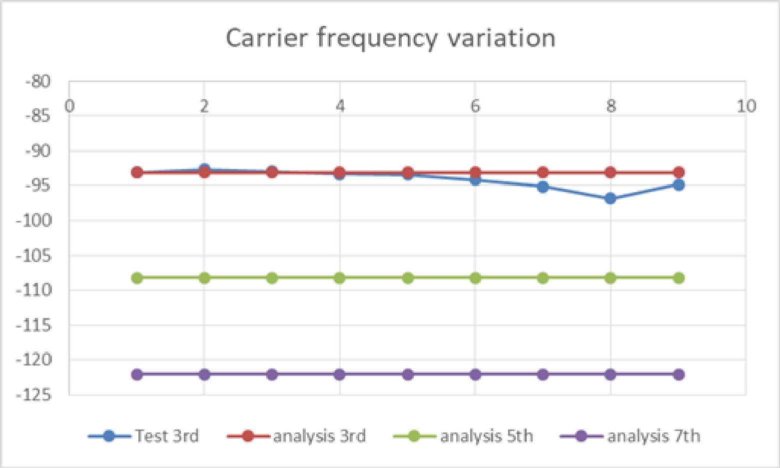


# Analysis vs. test results with carrier spacing, frequency and phase variation

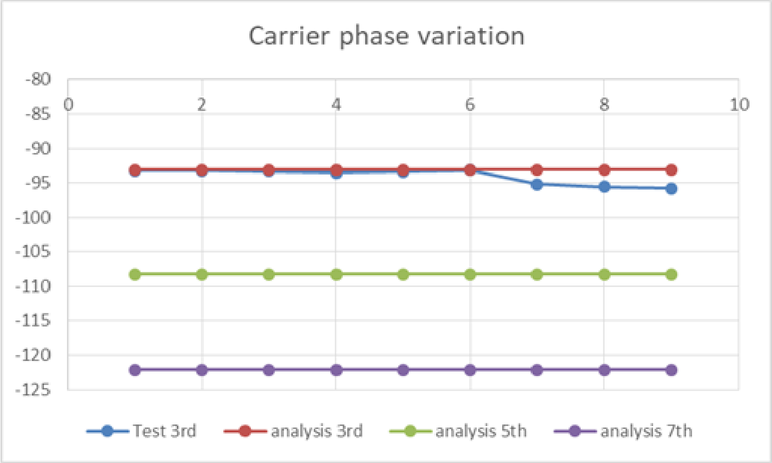
## carrier spacing variation




## carrier frequency variation




## carrier phase variation




No changes in PIM amplitude were tested and also analysed during carrier frequency , carrier spacing and carrier phase variation using 2 carriers

→

In case of two-tone PIM test carrier frequency selection is flexible.



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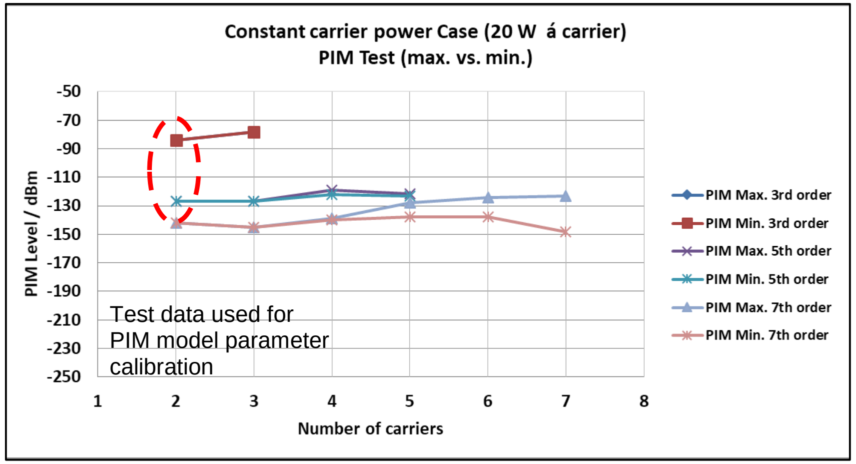
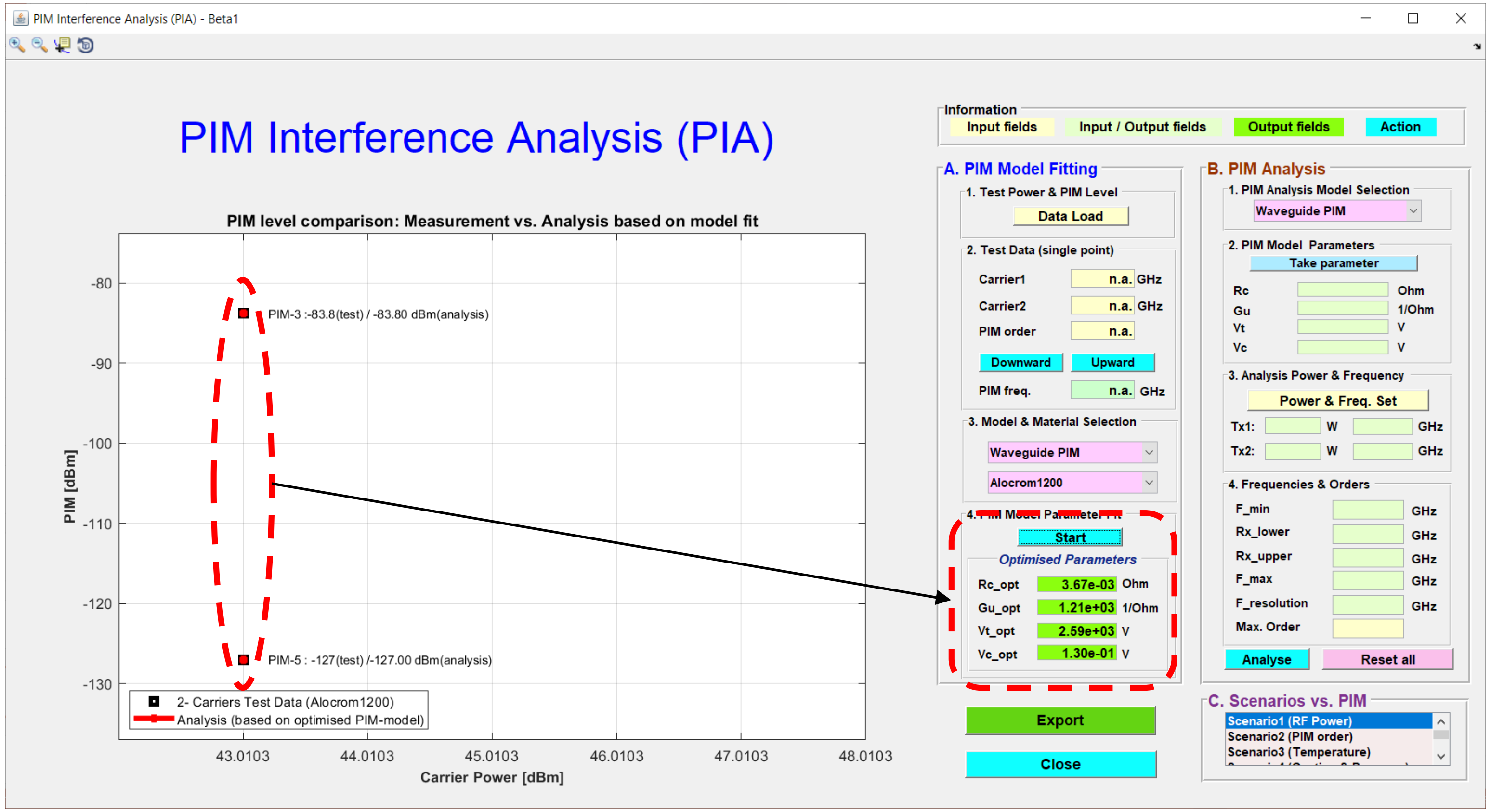
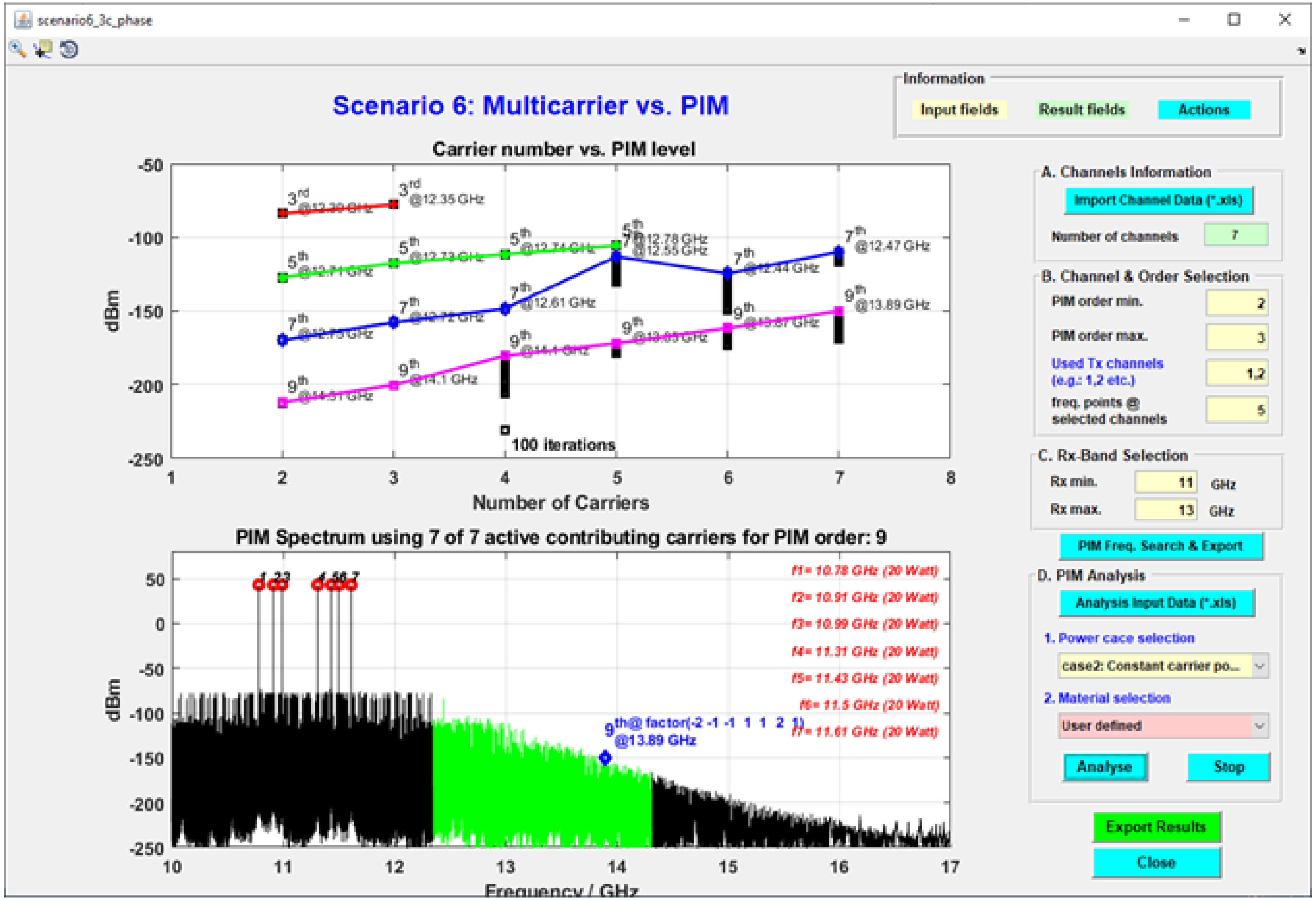
# PIM model calibration and analysis: scenario #6 (Multicarrier vs. PIM)

Two test data from 3rd and 5th order were taken for the PIM model calibration.



# Analysis and with 7 carriers including random phase variation ( 2x 20 W)




- Base on the obtained/calibrated PIM model, analysis were performed.
- The carrier phases were randomly varied at each carrier combination for specific order PIM calculation.
- Maximum values were recorded.



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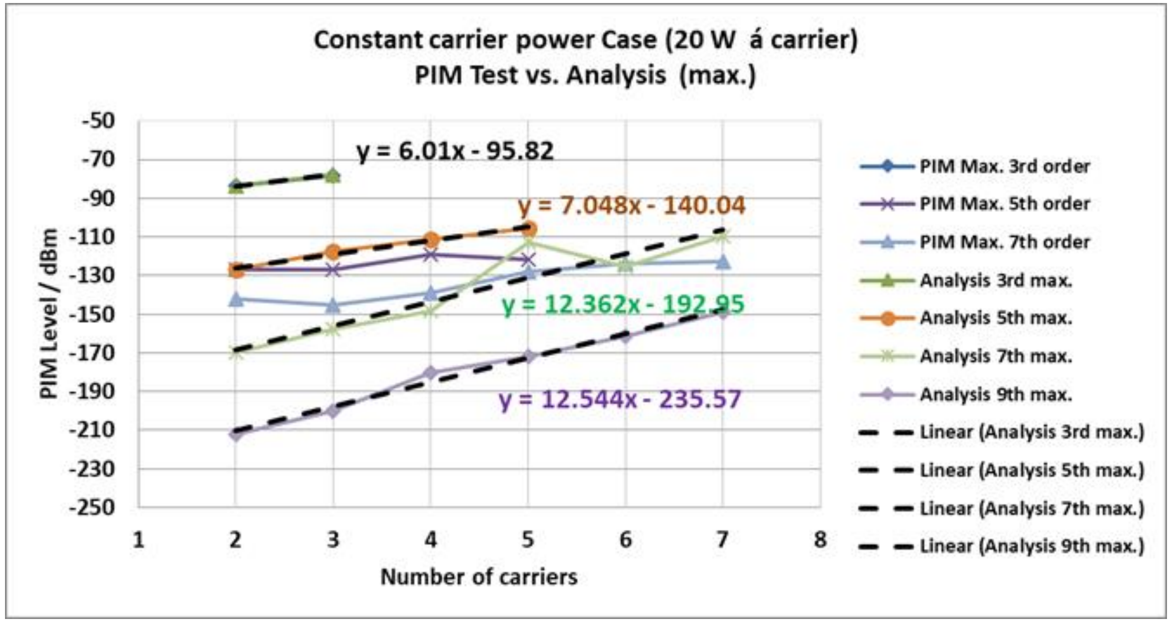
# Recommendations and guidelines for PIM related to carrier numbers




$$PIM_{multicarrier} = slope * \Delta n + PIM_{ref} + margin$$

$\Delta n$ = (# of carriers) – 2,

$PIM_{ref}$ = PIM level with 2 carrier test

Example:

| | |
|---|---|
| Tested PIM level | = -141 dBm |
| Power per carrier | = 2 x 20 W |
| Material | = tbd |

Estimated 3rd PIM level with 3 carriers ?

| | |
|---|---|
| Slope | = 6 dB |
| $\Delta n$ | = (3 – 2) = 1 |
| $PIM_{\_level@200\ W}$ | = 6*1 – 78 dBm |
| | ≈ - 72 dBm |



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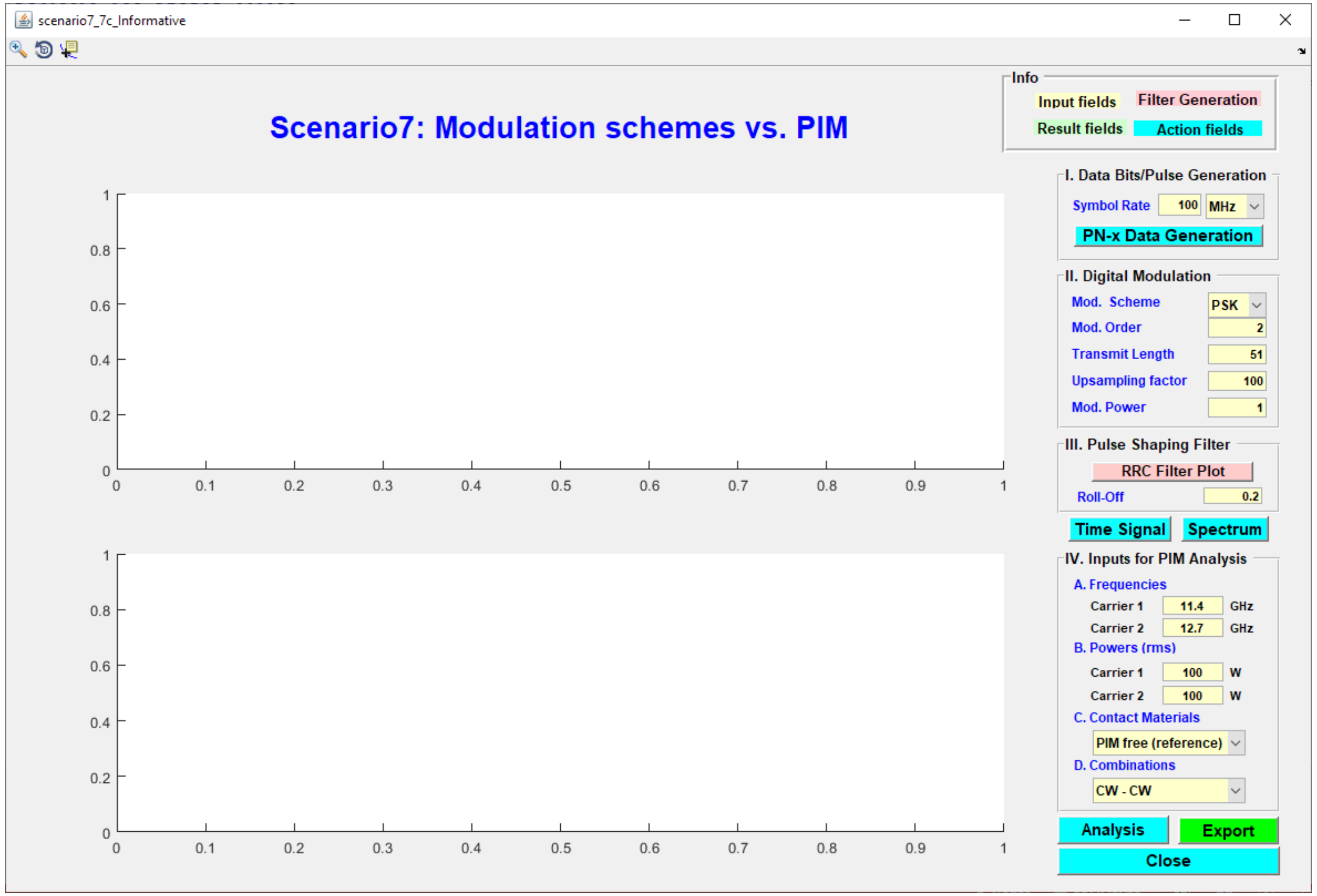
# Analysis tool: scenario #7 (Modulation schemes vs. PIM)

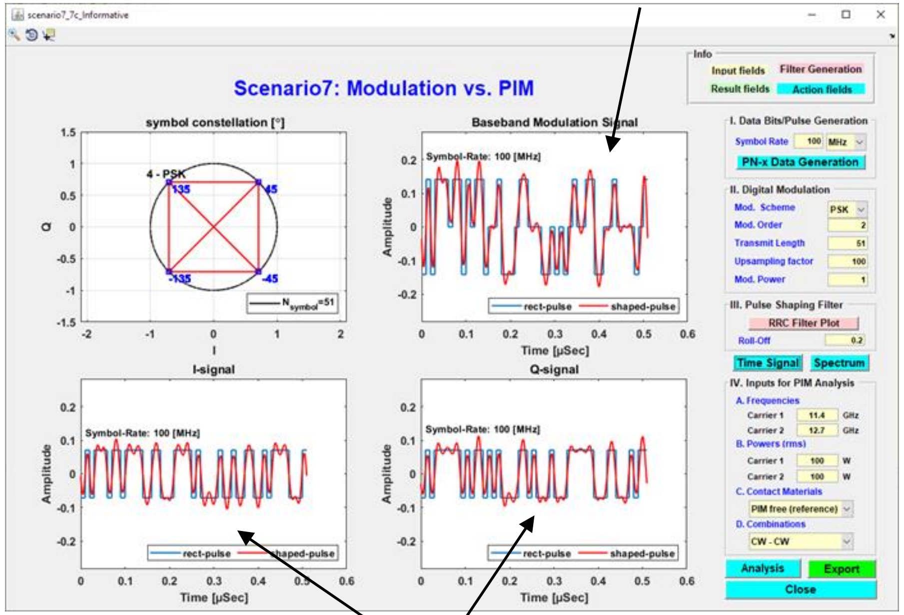
Demonstration follows!



# Time signal and spectrum of base band signal

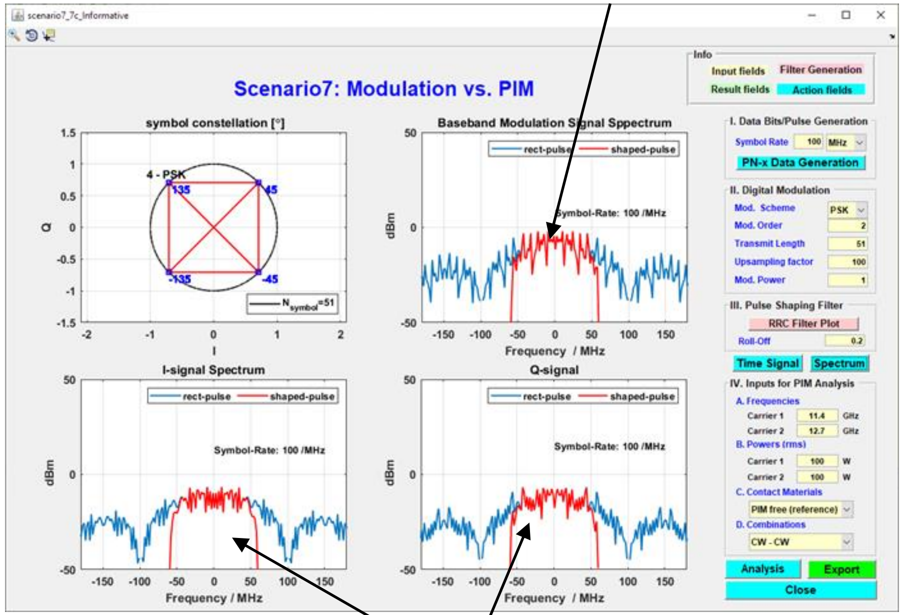
Constellation diagram

Baseband modulated time signal




Baseband I & Q signal components

Baseband filtered signal spectrum



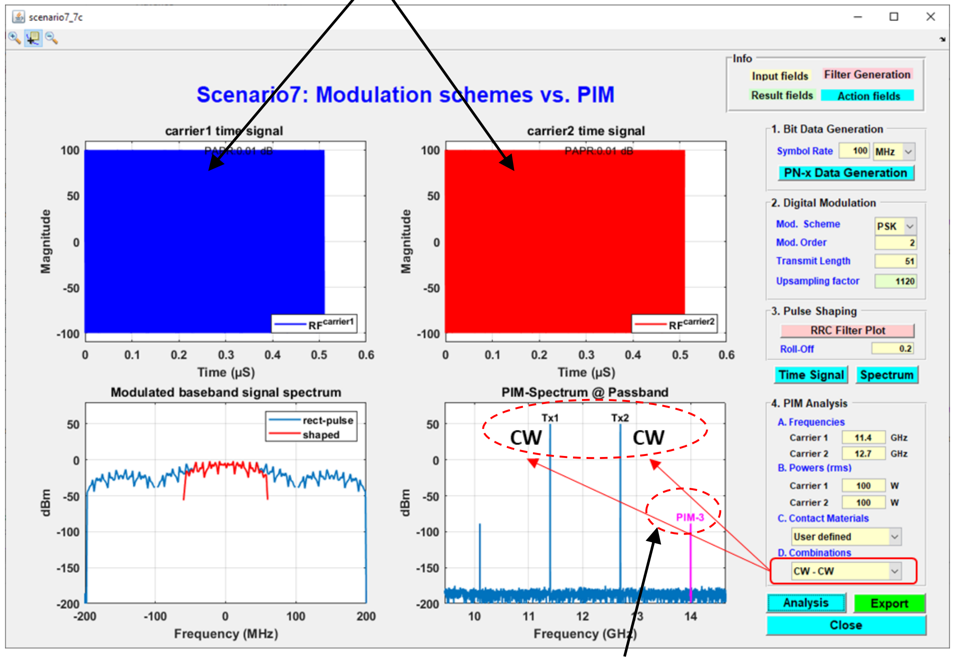

Baseband filtered I & Q signal spectrum

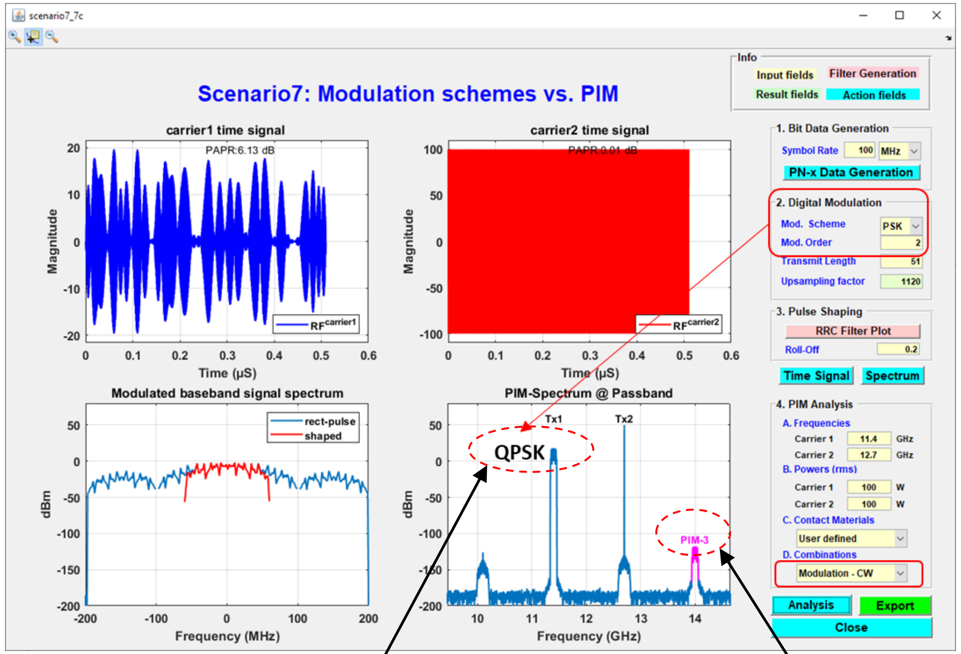
# Example: PIM analysis with QPSK

## CW-CW & QPSK-CW analysis

CW carrier time signals

PIM spectrum spreads over 1x bandwidth of the modulated Tx signal




Baseband filter spectrum

analysed PIM spectrum (line spectrum)

QPSK modulated Tx1 signal spectrum

analysed PIM spectrum (2 x bandwidth of modulated signal bandwidth)



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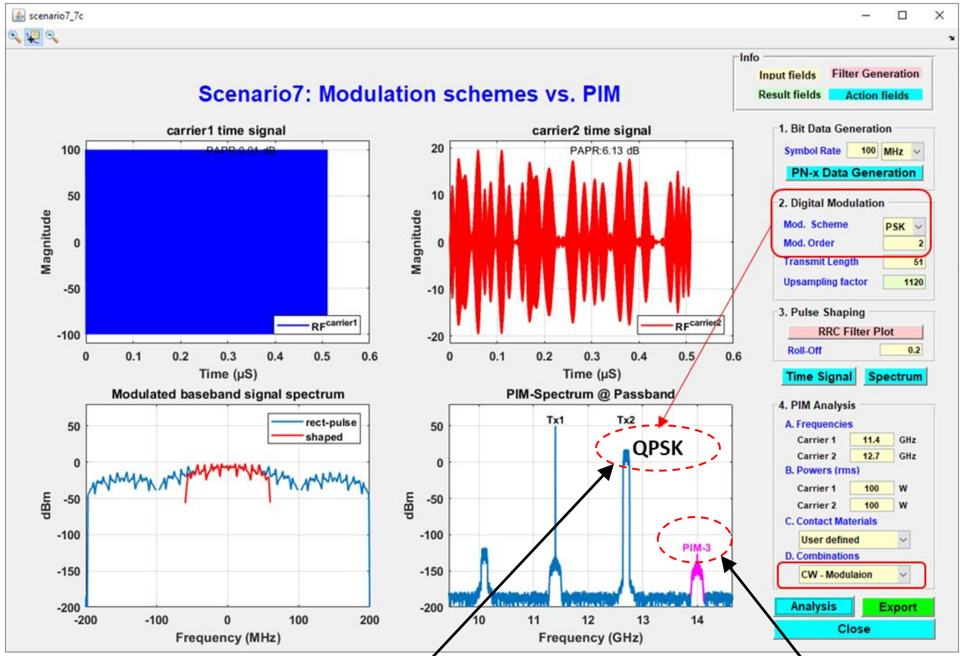
# Example: PIM analysis with QPSK
# CW-QPSK & QPSK-QPSK PIM analysis

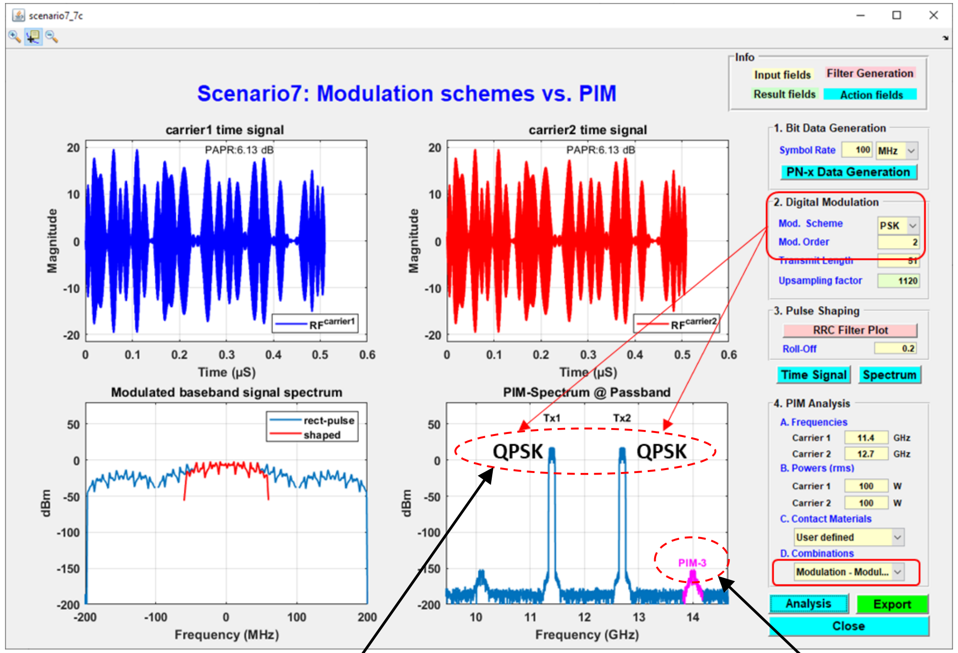
PIM spectrum spreads over 2 x bandwidth of the modulated Tx2 signal




QPSK modulated Tx2 signal spectrum

analysed PIM spectrum (2 x bandwidth of modulated signal bandwidth)

PIM spectrum spreads over 1 x Tx1 bandwidth and 2 x Tx2 bandwidth of the modulated signals




QPSK modulated Tx1 & Tx2 signal spectrum

analysed PIM spectrum (1xTx1 bandwidth and 2xTx2 of modulated signal bandwidth)

# PIM level estimation for modulated signals (recommendation & guideline)

$$PIM_{modulated\ \ signal} = PIM_{CW} + Spreading\ factor + \ margin$$

*$PIM_{cw}$ = Test level for specific order*

$$Spreading\ factor = 10 \cdot log10(PIM\ spectrum\ bandwidth)$$

$$\mathbf{PIM\ spectrum\ bandwith} = \ (\boldsymbol{m} \cdot \boldsymbol{BW_{Tx_1}} + \boldsymbol{n} \cdot \boldsymbol{BW_{Tx_2}})$$

***PIM order = m + n***

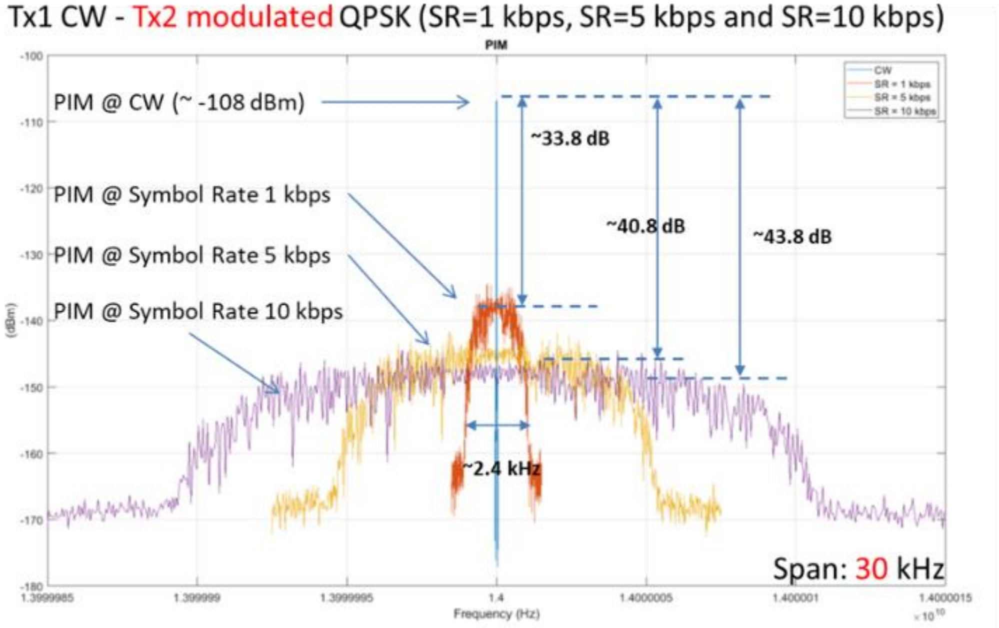
***$BW_{Tx1}$ = (1+roll-off)*(Symbol_rate of Tx1)***

***$BW_{Tx2}$ = (1+roll-off)*(Symbol_rate of Tx2)***

# Example for PIM level estimation based on the CW test results

$$\textbf{PIM spectrum bandwith} = (1+\alpha)\cdot(2\cdot SR_{Tx_2})$$

$$\textbf{PIM}\ level\ drop\ w.r.t.\ PIM_{CW} = 10 * log_{10}[(1+\alpha)\cdot(2\cdot SR_{Tx_2})]\ [dB]$$




$$Modulated\ PIM\ levelf@\ 1\ [kbps] = PIM\ level\ (CW) - 10 * log_{10}[(1+\alpha)\cdot(2\cdot SR_{Tx_2})]$$
$$= -108\ [dBm] - 33.8\ [dB] = -142.8\ [dBm]$$

# Conclusions

1. PIM amplitude increases with the RF power increase. The power of carrier 2 has more impact on the PIM amplitude than the power of carrier 1. The slope evaluation from power ramp-up tests gives useful factor for PIM level assessment for other power cases.

2. PIM level distance is strongly contact pressure dependent.
   For the reliable prediction, PIM levels shall be measured with other contact pressure values to get a test data base for PIM model optimisation.

3. Temperature impact on PIM level increase is dominant at cold case for both waveguide and coaxial contact. The temperature transition phase provides burst-like PIM behaviour particularly for the coaxial connectors.

4. The coating material investigation shows that the Alocrom passivated surface has the highest PIM level in comparison to the Surtec650 and bare Aluminium. However the increased contact pressure larger than 50 MPa for waveguide contact shows significant reduction of the PIM level for all materials. Therefore the contact pressure about 50 MPa can be considered as recommendation for interface of waveguide contact as a guideline.

# Conclusions (cont’d)

5. Signal characteristic including carrier spacing, carrier frequency variation, and carrier phase variation shows marginal change of the PIM level. Moreover this signal characteristic shows frequency band independent behaviour for waveguide contact interfaces.

6. Complex multicarrier scenario analysis shows that the PIM model parameter determination using relevant test data seems to be a good basis for other PIM analysis for other complex multicarrier scenarios. The analyses with the random phase variation of each carrier showed good correlation to the PIM behaviour of the test cases. Based on the analysis the slope values in dependence on the carrier number can be derived. Using this slope the prediction for other cases are available.

7. Modulation scheme shows nearly independency on the PIM level. The main parameter for the PIM level is the symbol rate related to the band width of the modulated signal. The bandwidth of the signal is increased with the roll-off factor of the pulse-shaping filter response. For the modulated signal case, the spectrum spreading was identified as a key factor for the estimation for the modulated signal PIM level assessment. Complex modulated signal PIM level can be estimated using two carrier PIM test using this spreading factor related to the signal band width.

# Conclusions

- The ESA-TRP “Test methodology investigations and parameters influencing Passive Inter Modulation (PIM) interference (4000126012/18/NL/HK)” has been performed successfully.
- The valuable information for common understanding about PIM behaviour has been obtained based on studies, tests and analyses using seven defined scenarios.
- Based on the analysis results rule-of-thumbs could be derived with the help of tests and developed PIM analysis software.
- Complex scenarios concerning power, temperature, contract pressure, coating, signal characteristic, multicarrier and modulated signal cases can be simplified by two-tone PIM test
- The PIM model “calibration” based on the simple two-tone test data gives possibility for analyses with complex scenarios.
- The outcomes of this ESA-TRP may serve as input for the coming ECSS work in the near future.
- Airbus thanks to ESA-ESTEC for granting and lasting support for this very challenging TRP to achieve a common guidelines for PIM test investigation among the ESA member states.

# Appendix

System requirement for PIA

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# System requirement for using “PIM Interface Analysis (PIA)”

- Download Matlab runtime from:
  - https://www.mathworks.com/products/compiler/matlab-runtime.html

| Release (MATLAB Runtime Version#) | Windows | Linux | Mac |
|---|---|---|---|
| R2021a (9.10) | 64-bit | 64-bit | Intel 64-bit |

- Please follow “readme_main.txt” file

- Beta version test is required.



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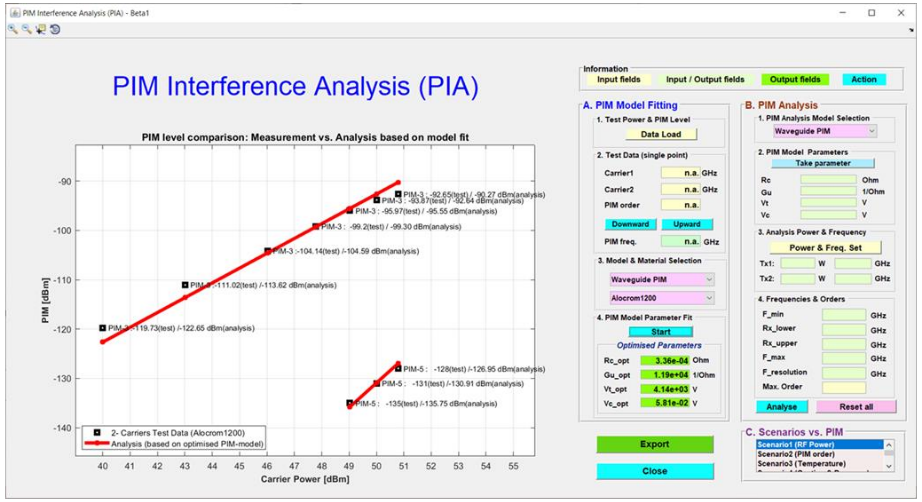
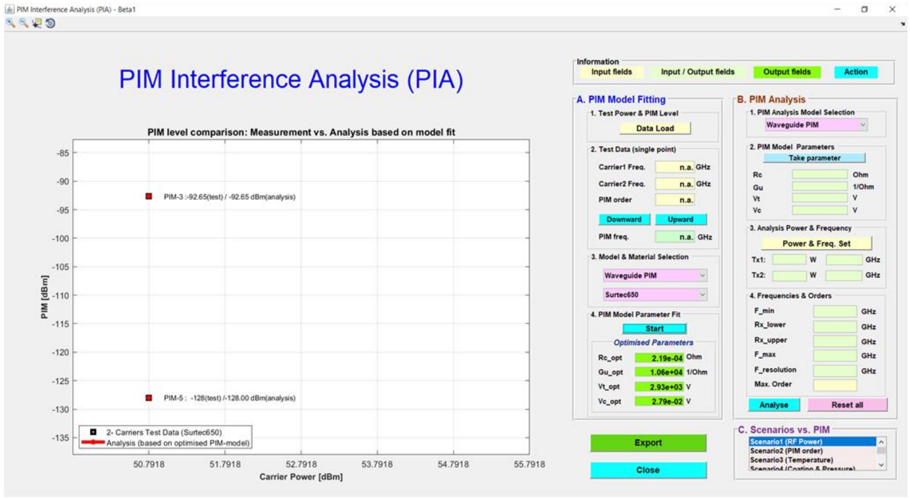
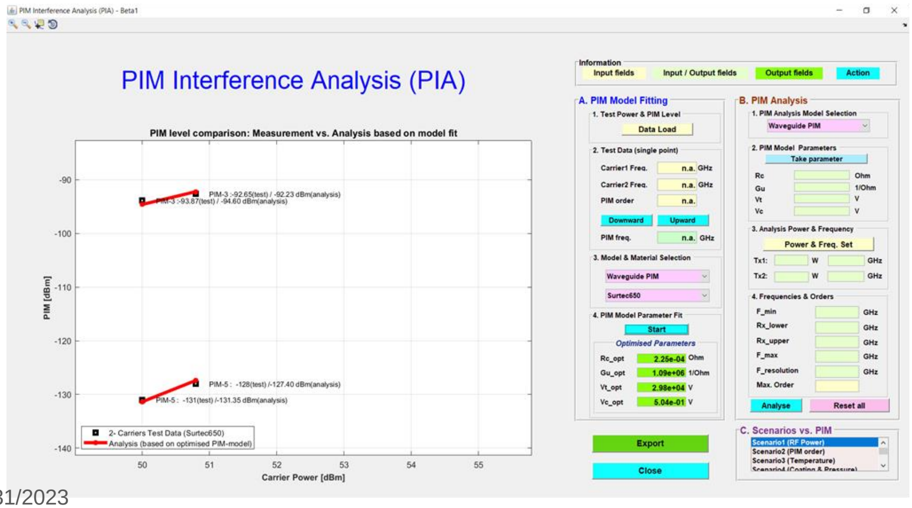
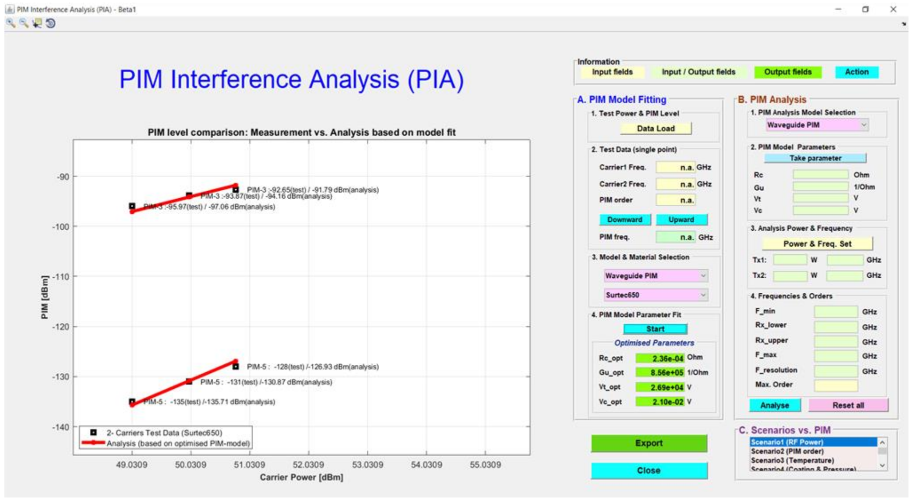
# Calibration Examples:
# PIM model calibration using different data points





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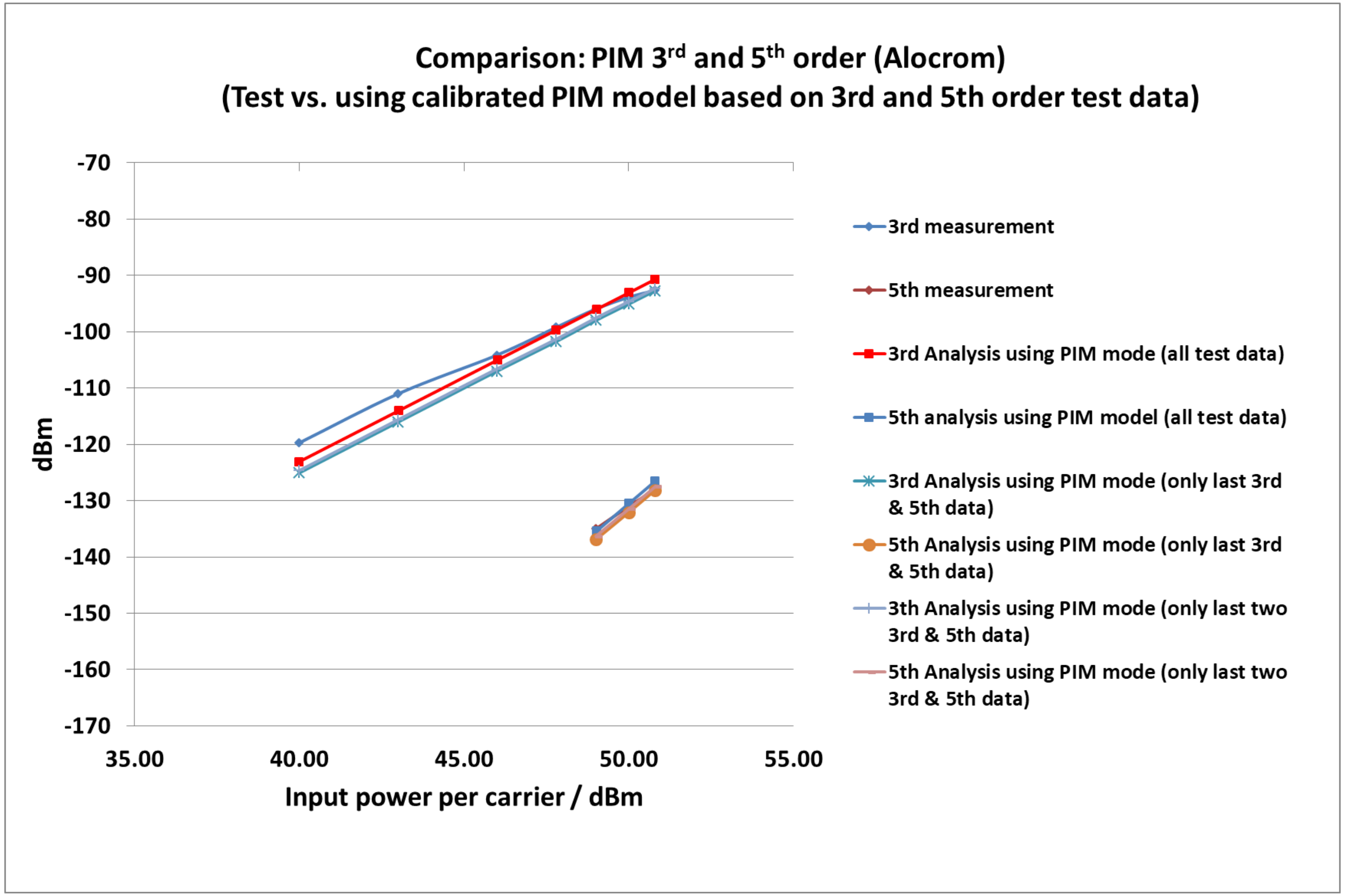
# Comparison: Test vs. Analysis
# PIM model calibration using different data points



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