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Calibration of the JIG v1.2 for the SKA-TPM-ADU v1.6

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The purpose of the calibration

What is a JIG

A JIG is a printed circuit board (PCB) with a custom-made AI used to easily test other PCB. It must have programmable functions to provide stimulus and to measure quantities that once processed the board under test can be checked as “verified” with additional remarks such as “passed”, “accepted”, “qualified”, and/or reporting details in case of failures.

The specifications of the JIG are given by the device under test (DUT) requirements.

Why calibrate a JIG

Since the JIG PCB is the instrument with which the test is done, it must be free of any components that will compromise the measurements, or at least, they must be well known, and eventually they must be calibrated when possible. It is important that the measurements results done by using a JIG, are fully representative of the device under test, and not limited or affected by the JIG capabilities.

The SKA-Low TPM in brief

The Square Kilometer Array (SKA) Radio Telescope will be the biggest and widest telescope in the world. The project is spread in two frequency ranges from 50 to 350 MHz (SKA-Low) and 350 MHz to 15.4 GHz (SKA-Mid).

The selected SKA-Low digital backend is the Italian Tile Processing Module (TPM).

The TPM is a device that:

1. Receives Radio Frequency (RF) signals of a group of 16 dual polarization antennas
2. Provides course frequency channels to the SKA correlator to compute calibration coefficients
3. Produce the beam of the Tile and by using a incremental beamforming between TPMs provide the station beam of 256 antennas
4. Load calibration coefficients for the beam steering to point the telescope to the desired target

The TPM is a device composed by:

A. 2x PreADU boards that receive RF over fiber signals using wavelength division multiplexing technology, with the capability to amplify, filter and equalize the level of each RF signal via digital step attenuators
B. 1x ADU board equipped with 16 dual channel ADCs that sample 32 single ended RF signals up to 1 GSPS

The 2 PreADU boards are connected respectively to the TOP and the BOTTOM of the ADU board, like a sandwich, by 4 RF IJ5 ISORATE[R] connectors and 2 small ERF8 EgdeRate™ connectors to supply and program the receivers.

PreADUs have their own JIG and their own RF tests to verify the performances.

The Analog to Digital Unit (ADU) of the TPM is a double FPGAs board which digitizes the 32 Antenna polarization signals and internally processes the course channels and the beamformed data.

The TPM ADU RF Test Bench with the JIG

The following picture shows the integration between the JIG (left) and the TPM ADU (right).

The ADU RF performances

The ADU RF performances must be verified as well, and should not degrade the TPM overall performances. The method applied to measure the RF performances is described in the Analog Devices Application Note AN-835[(3)] "*Understanding High Speed ADC Testing and Evaluation*" by Alex Arrants, Brad Brannon and Rob Reeder. The ADU v1.2 test description and results by using the RF JIG v1.1 are available in the INAF/IRA technical report[(4)] "*SKA iTPM ADU Board 1.0 Performance Measurements*" by Giovanni Naldi, Andrea Mattana, Federico Perini, Simone Rusticelli, Marco Schiaffino and Jader Monari.

The ADU RF performance parameters that must be measured and their respective limits are:

Single Tone Analysis			
Name	**Unit**	**Description**	**Limit**
Gain Flatness	dBFS	The level of the fundamental tone referenced to full scale	> 0.9
Signal to Noise Ratio referenced to Full Scale	dBFS	The ratio of the rms full scale to the rms value of the sum of all spectral components except the first six harmonics and dc	> 48.6
Spurious Free Dynamic Range	dBc	The ratio of the rms value of the signal to the rms value of the worst spurious signal (HD or not) regardless of where it falls in the frequency spectrum	> 60.0
Harmonic Distortion	dBc	The level of the first six harmonics referenced to the carrier	HD2 < -69 HD3 < -65
Worst Other Spur	dBc	The level of the worst spurious component excluding the first six harmonically related components referenced to the carrier	< -60.0
Total Harmonic Distortion	dBc	The ratio of the rms signal energy to the rms value of the sum of the first six harmonics	-
ENOB	bits	Effective Number of Bits	> 7.80
Cross-Talk	dBc	The measure of any feedthrough coupling onto the quiet channel referenced to the carrier	< -44.0

Two Tones Analysis			
Name	**Unit**	**Description**	**Limit**
Second-Order and Third-Order Input Intercept Point	dBm	$IIPn = P + \frac{\Delta P}{n-1}$, $n = 2$ ($IIP2$), 3 ($IIP3$) where P is the output power of the fundamental, and ΔP is the difference between P and the n^{th} -order Intermodulation Distortion (IMD) product	-

The RF performance measurements consist of injecting a CW tone (or two tones in case of the Intermodulation Distortion product tests) **at -1 dB with respect to the ADC full scale sweeping the SKA-Low frequency range**. The analog frequencies are chosen such that the captured data samples exercise as many converter codes as possible in the record length. This is accomplished by using a prime relationship between the analog frequency and the encode rate. Integer cycles ensure that the power is well described in the proper frequency bin.

$$Cycles = \frac{f\ desired\ frequency}{\frac{Sample\ Rate}{FFT\ Samples}}$$

It is very important that the CW signal satisfies as much as possible this specification, achievable if the frequency can be set with the accuracy of the Hz. Anyway, the number of cycles should be rounded to the nearest possible integer.

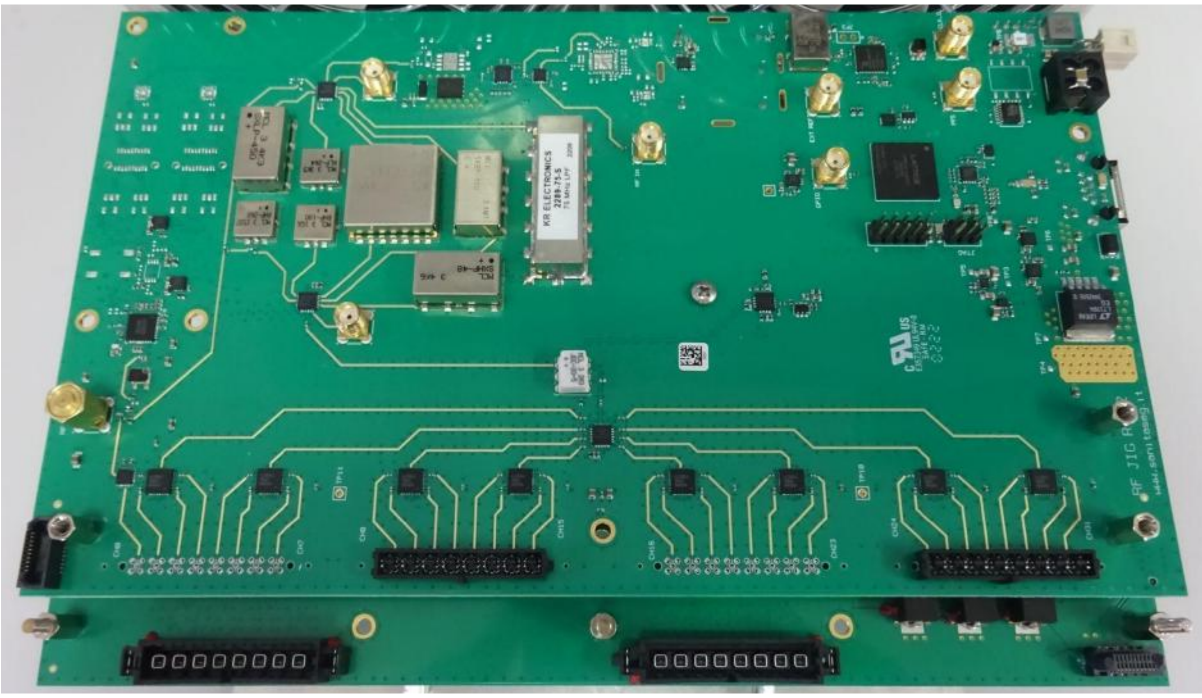
The -1 dBFS value of the TPM-ADU input signals depends on each matching network between the ADU IJ5 RF input connector and the ADC. It is computed by using the ADC RMS and **is typically a level value around +10 dBm.** This will be the target value during the RF Performance Test.

The ADU RF JIG

The ADU RF JIG is described in the document "SKA_RF-JIG_UM_R1.1.pdf" which is part of the SKA-Low deliverables.

It is a board equipped with a low power high performance *Lattice Semiconductor* CPLD that enables ethernet communications for the board management and diagnostic by using the UCP (Uniboard Control Protocol), the same protocol used by the ADU management CPLD.

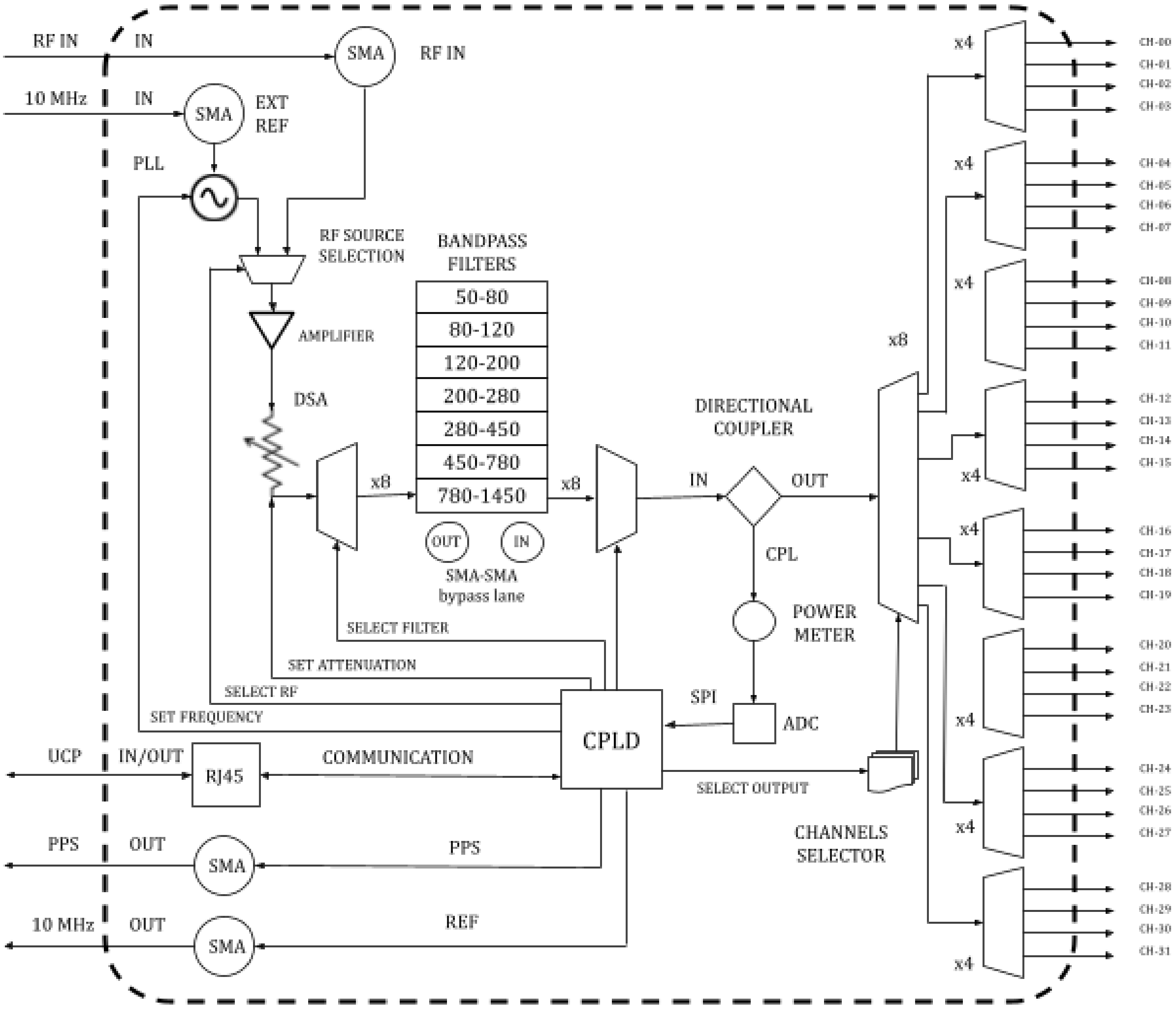
The JIG is able either to generate a CW signal for the tests internally by using a PLL and to accept an external RF signal. The RF signal is amplified to compensate for the loss of the remaining chain. The level can be controlled by setting a programmable digital step attenuator from 0 to 31.5 dB with a step level of 0.5 dB.



The above picture shows the RF JIG: on the upper right there is the supply connector and the RJ45 Ethernet port (mounted in the bottom side). Going to the left the big black chip is the CPLD, the smaller on top of it is the PLL. The SMA connectors around it are 10 MHz reference IN and a pair of 10 MHz and PPS OUT. Then in the left there is an SMA connector for an external signal and a programmable switch to select if the PLL tone or the external signal will be used. Then the signal level controller with a programmable digital step attenuator.

On the left there are 7 bandpass selectable filter lanes and an SMA-SMA bypass to use an external setup. The RF signal is measured by a power meter and goes to the switching lanes to address one of the 32 JIG outputs.

The following picture is the schematic of the main JIG functions.



The following table reports the 7 selectable bandpass filter lanes. An additional lane is a SMA-SMA bypass to allow the user to use external devices in the chain.

FILTER LANE	BANDPASS (MHz)
1	50 - 80
2	80 - 120
3	120 - 200
4	200 - 280

5	280 - 450
6	450 - 780
7	780 - 1450
8	bypass

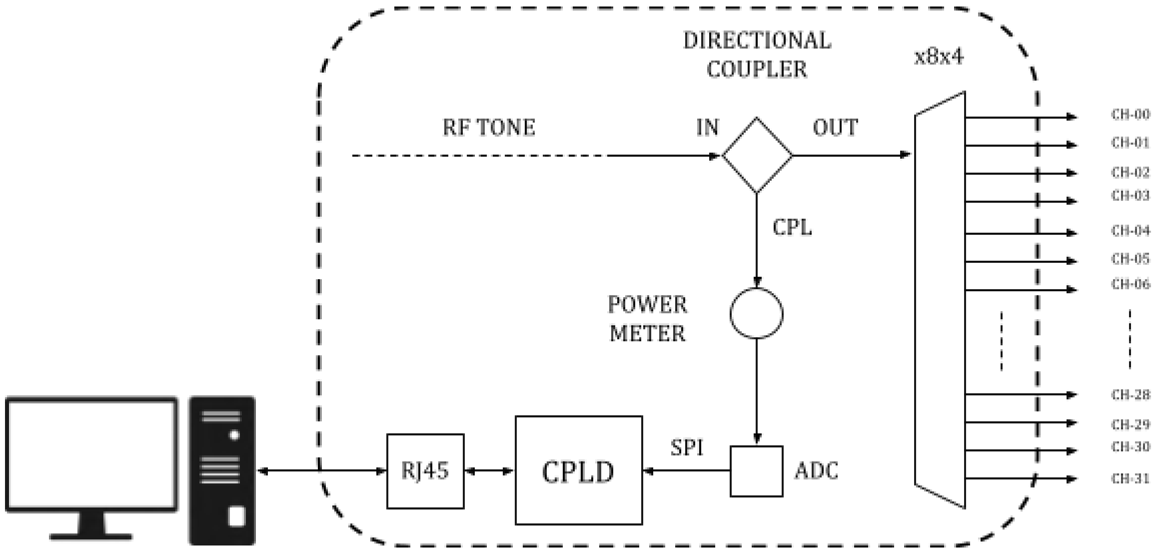
The range of the bandpass filters were chosen to ensure the attenuation of the CW signal harmonics.

The JIG addresses the RF signal to only one of the 32 output channels at time.

Lastly, the JIG is able to lock the internal PLL to an external 10 MHz reference, and it outputs a pair of synchronization signals such a 10 MHz clock and a Pulse Per Second (PPS). The absolute maximum electrical ratings of 2 Amp current at 12 Volt supply.

How the JIG measure the RF Level

The JIG has an onboard power meter (ADL5902) that is read by a 12 bit ADC (AD7466). The RF tone is extracted by using the Mini-Circuits directional coupler JDC-20-5+ (low mainline loss, 0.5 dB typical).



The power meter

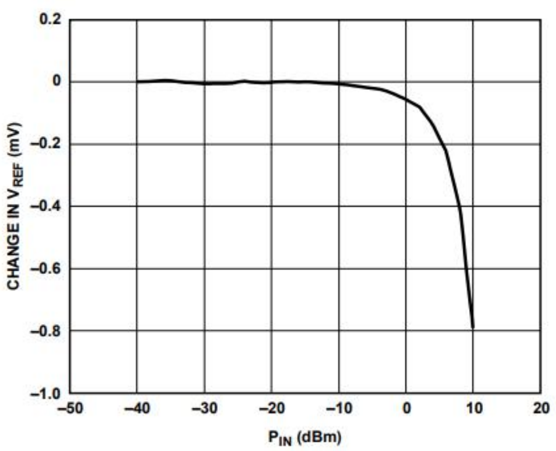
The ADL5902 is a true rms responding power detector that has a 65 dB measurement range when driven with a single-ended 50 Ω source. The ADL5902 can operate from 50 MHz to 9 GHz and can accept inputs from −62 dBm to at least +3 dBm.

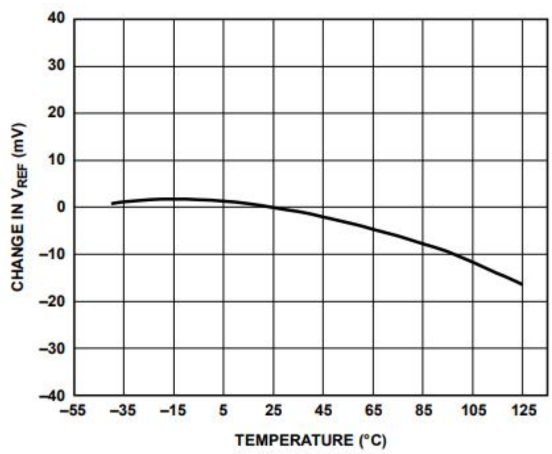
The ADL5902 datasheet[(5)] provides information about the deviation from output at 25°C when the temperature changes:

- for signals at 100MHz: in the temperature range of −40°C < TA < +85°C, with a PIN = 0 dBm the deviation is −0.11/+0.25 dB, for a PIN = −45 dBm the deviation grows up to −0.22/+0.15 dB.
- for signals at 700MHz: in the temperature range of −40°C < TA < +85°C, with a PIN = 0 dBm the deviation is +0.3/−0.2 dB, for a PIN = −45 dBm the deviation grows up to −0.1/0 dB.

The absolute maximum ratings of the ADL5902 are: Supply Voltage VPOS 5.5 V, and, Input Average RF Power +21 dBm for long durations. Excursions above this level, with durations much less than 1 second, are possible without damage.

The following pictures show the change in VREF vs. Input Amplitude with Respect to −40 dBm, 25°C (left) and the change in VREF vs. Temperature with Respect to 25°C, RF Input = −40 dBm (right). It is clear that the level of input signals above 0 dBm affects the VREF much more than small changes of the lab temperature.

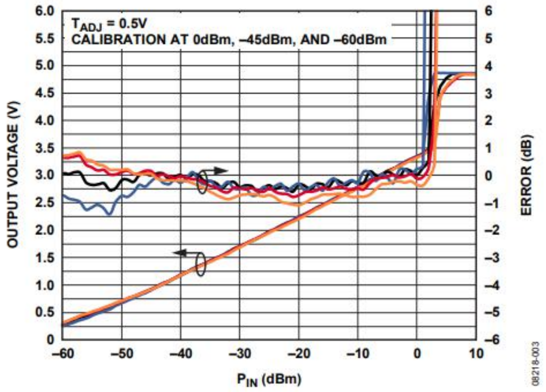


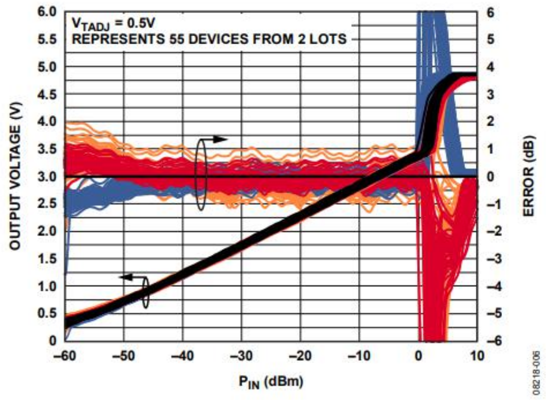


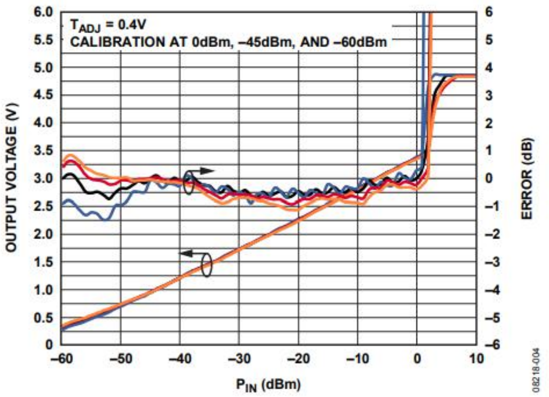
The next pictures show the typical performance characteristics. Trace colors mean a different temperature condition: TA = +25°C (black), −40°C (blue), +85°C (red), +125°C (orange).

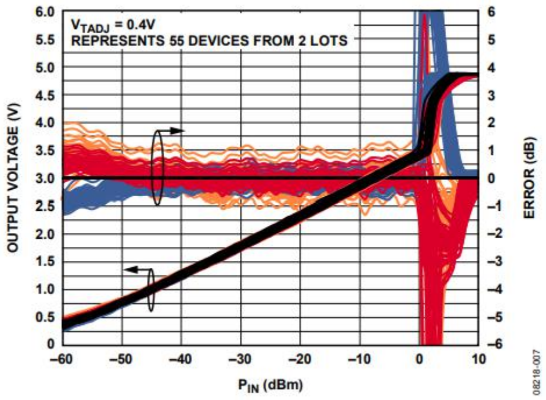
The ADL5902 PIN1 (TADJ/PWDN) is a dual function pin used for controlling the amount of nonlinear intercept temperature compensation at voltages <2.5 V and/or for shutting down the device at voltages >4 V. The next test case plots unfortunately set this function to shutdown the device at about 3 dBm, therefore the range of -20/+15 dBm is not fully covered, however it is useful to understand the distribution of the Error over Temperature and P_{IN}.

Typical VOUT and Log Conformance Error with Respect to 25°C Ideal Line over Temperature vs. Input Amplitude at 100 MHz (left), and, Distribution of Error with Respect to 25°C over Temperature vs. Input Amplitude, CW, Frequency = 100 MHz (right). Then, a second pair of plots are shown with slightly changing the TADJ and by using a 700 MHz tone.





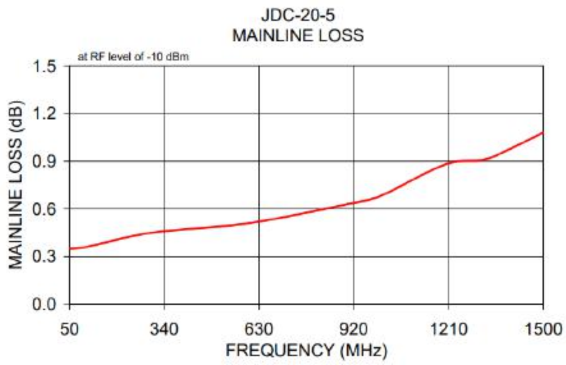


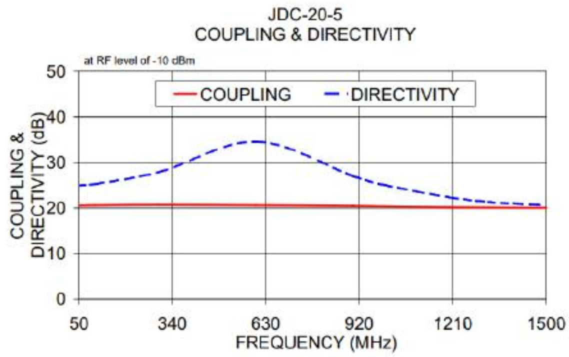


The Error reported by the datasheet at ambient temperature (black line) should be in the range of ±0.5 dB.

The directional coupler and ADC

The RF tone is extracted by using the Mini-Circuits directional coupler[6] JDC-20-5+. The following plots show the mainline loss (dB) as a function of frequencies (MHz), and the coupling loss which is very low.





The power is sampled by the Analog Devices AD7466[7] that is a 12 bit ADC with VRef = 3.3 Volt. The resultant code (from 0 to 4095) is read by the CPLD and available on a memory mapped register.

The output selection

The JIG addresses the RF signal only to one of the 32 outputs by using a switching path.

The signal routing is implemented with low insertion loss switches:

- the pSemi (Murata) PE42582 UltraCMOS® SP8T RF Switch[9], max insertion loss ~1.3 dB and return loss < -24 dB
- the pSemi (Murata) PE42540 UltraCMOS® SP4T RF Switch[10], max insertion loss ~1.1 dB and return loss < -23 dB

The output of the JIG calibration will be a “calibration curve” that applied to the converted ADC code of the power meter will provide the real RF level at the JIG end (IJ5 Isorate connector), taking into account (compensating) all the power loss over frequencies of the RF chain between the directional coupler and the ADU input. Eventually, a calibration curve for each RF JIG output channel will be measured to improve the accuracy of the ADU RF performance measurements.

Also, it would be tested at different temperature conditions to estimate how the system is sensitive to the environment.

Since **the ADU RF Performance Tests target value is something around +10 dBm**, and, **the loss** of the JIG RF path between the directional coupler mainline and the IJ5 RF connector at the end of the chain of switches x32 output signals **is about 3 dB**, **the point of +13 dBm** will be always highlighted in the following analysis.

The calibration

Mandatory Tools

What is really important to use to calibrate an instrument? The devices used must be calibrated! For the same reason of the JIG calibration we don’t want to add noise/errors of the calibration device. Its capabilities must have performances much better than the minimum fail parameters of the JIG Tests.

The main requirement of the JIG is to output a CW signal of a specific level, that will be controlled in a closed loop by reading the power and commanding the source to adjust the level to the desired one. It is not uncommon to find signal generators that slightly change the output level during a frequency sweep. Also, the datasheet of every chip reports transfer functions that show a drift in level as a function of frequency and/or temperature.

The use of an external high precision power sensor allows to measure the transfer function of the JIG and will provide the calibration curve that will be applied to what the JIG internal power meter measures.

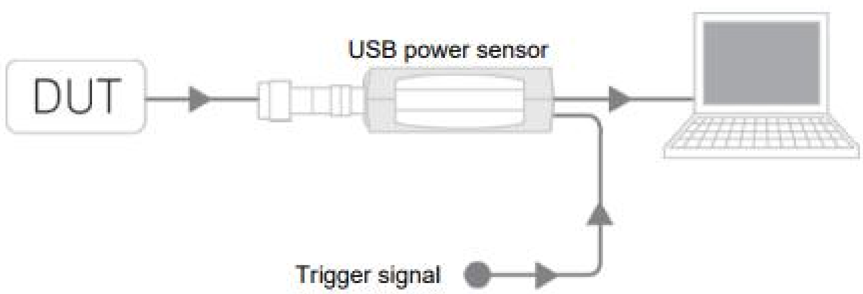
Recommendations

The temperature may affect the power measurements, it is highly recommended that the environment does not change either calibrating and while taking measurements, and possibly, the JIG calibration should be done at the same temperature conditions of the ADU RF performance tests.

If this condition cannot be satisfied, different calibration curves must be applied as a function of temperature.

Power Sensor

The choice of the Power Sensor went to the USB Agilent (now Keysight) U2004A[1].



It is a compact portable device that requires only an USB connection. It provides average power measurements of CW and several modulated signals.

The U2000 Series has both internal and external zeroing capabilities. With internal zeroing, high isolation switches in the sensor are opened to isolate the sensor from the device-under-test (DUT) it is connected to. As such, you don't need to power-off the DUT or disconnect the sensors. This speeds up testing and reduces sensor wear-and-tear.

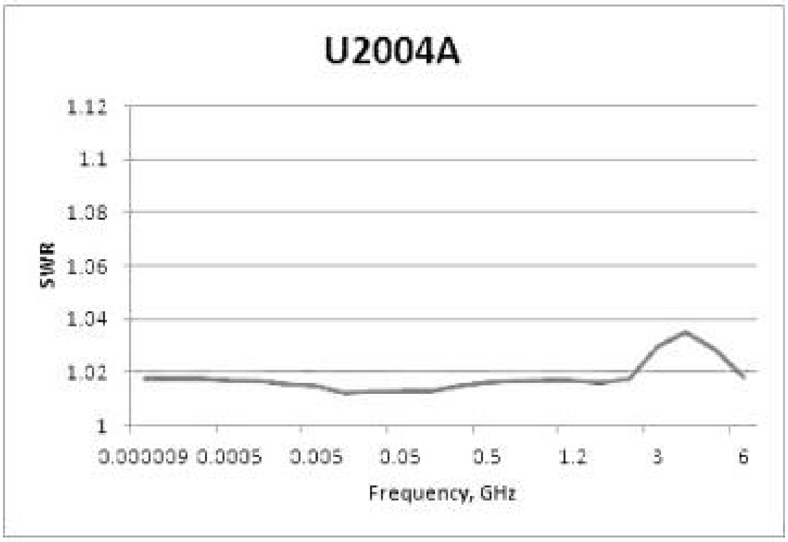
No manual input of calibration data is required. All calibration factors, as well as temperature and linearity corrections, are stored in the sensors' EEPROM, auto-downloaded at calibration.

The communication with the PC is implemented via standard SCPI commands.

By default, the measurement read is an average of 20 readings, this can be incremented by the proper SCPI command (Normal: 20 readings/s, x2: 40 readings/s, Fast: 110 readings/s, Buffered: 1000 readings/s).

The U2004A frequency range is 9 kHz to 6 GHz and the power range is from –60 to +20 dBm (at maximum: +25 dBm avg with 5 VDC, +33 dBm pk for < 10 µs).

The U2004A Maximum SWR in the range 9 kHz to 2 GHz is 1.13 in the condition TA = 25 °C ± 10 °C, as reported in the next picture.

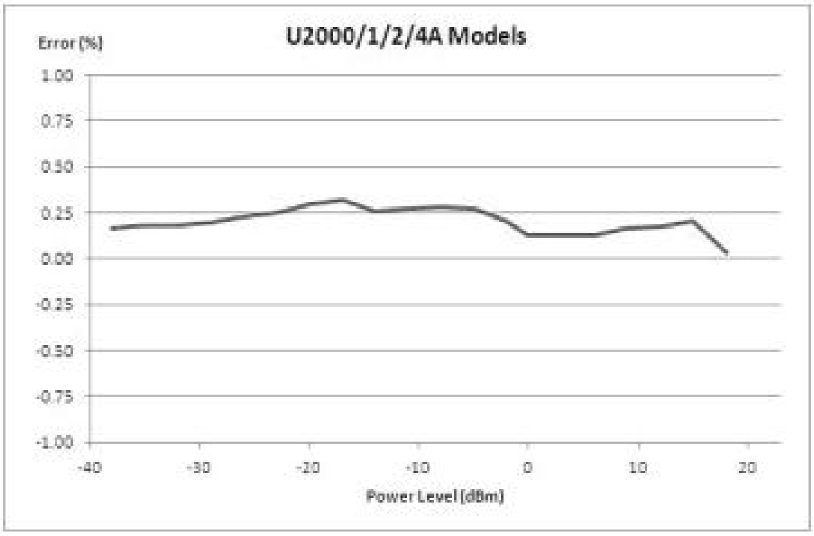


The U2000 Series power sensors have two measurement paths: a low-power path (from –60 to –7 dBm) and a high-power path (–7 to +20 dBm) with –7 dBm as switching point.

The power sensor automatically selects the proper power level path. To avoid unnecessary switching when the power level is close to the switching point there is a *switching point hysteresis* of ± 0.5 dB.

The hysteresis causes the low power path to remain selected until approximately –6.5 dBm as the power level is increased. Above this power, the high-power path is selected. The high-power path remains selected until approximately –7.5 dBm is reached as the signal level decreases. Below this power, the low power path is selected.

The typical power accuracy at 25 °C for the U2004A sensor in average mode operation is ± 3.0% in the power range of -30 and +20 dBm.



The following table shows the measured noise at different power ranges for the U2004A in average mode.

Power range	Measurement noise
–60 to –35 dBm	1 nW
–38 to –15 dBm	1.5 nW
–20 to –6.5 dBm	15 nW
–7.5 to –2 dBm	650 nW
–4 to 15 dBm	1 µW
10 to 20 dBm	10 µW

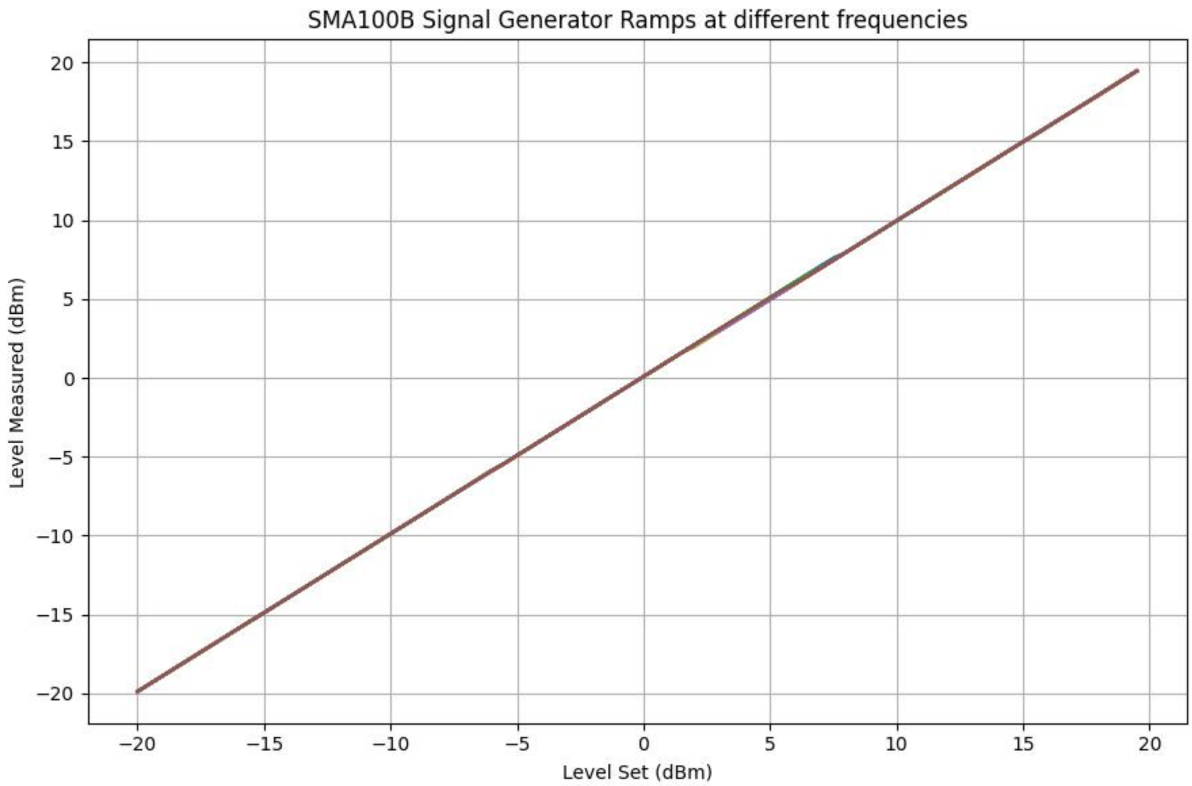
Signal Generator

The signal generator used is the Rohde & Schwarz SMA100B(2).

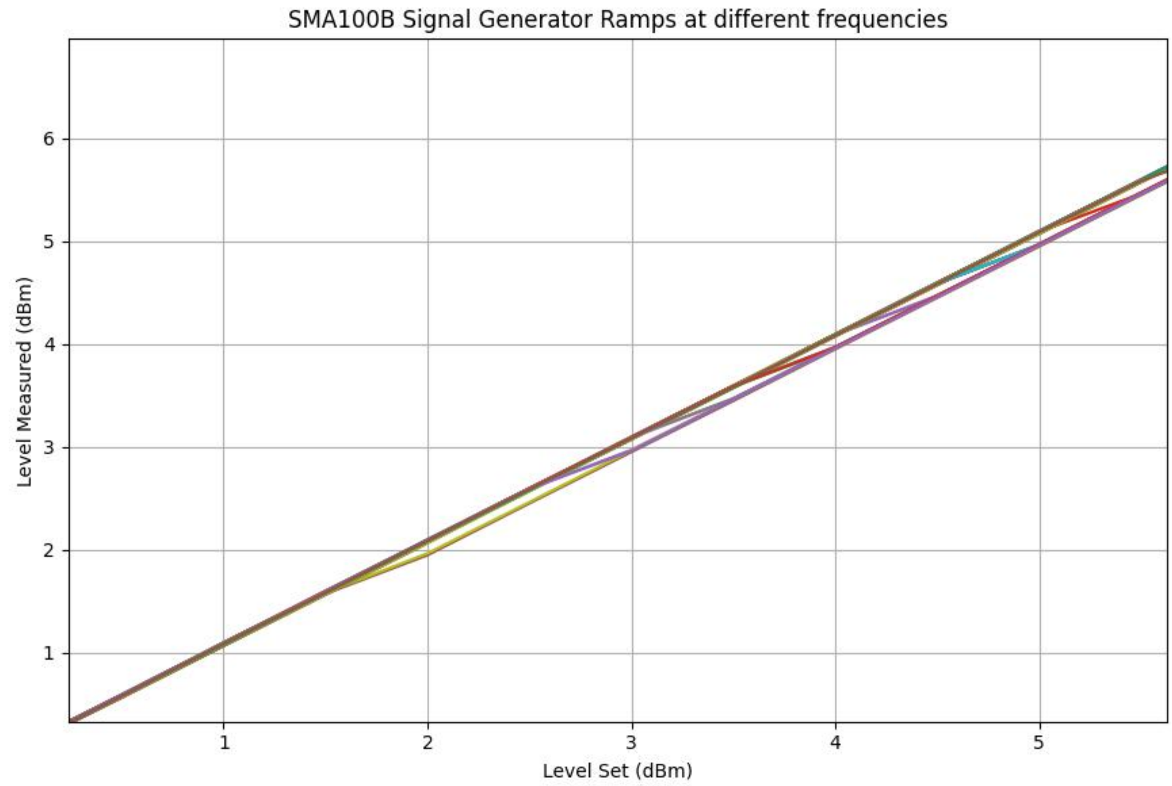
Before running the JIG calibration measurements, the signal generator is tested alone to be sure it is working as expected. The software used to run this preliminary test is the same used for the calibrations without querying and commanding the JIG devices.

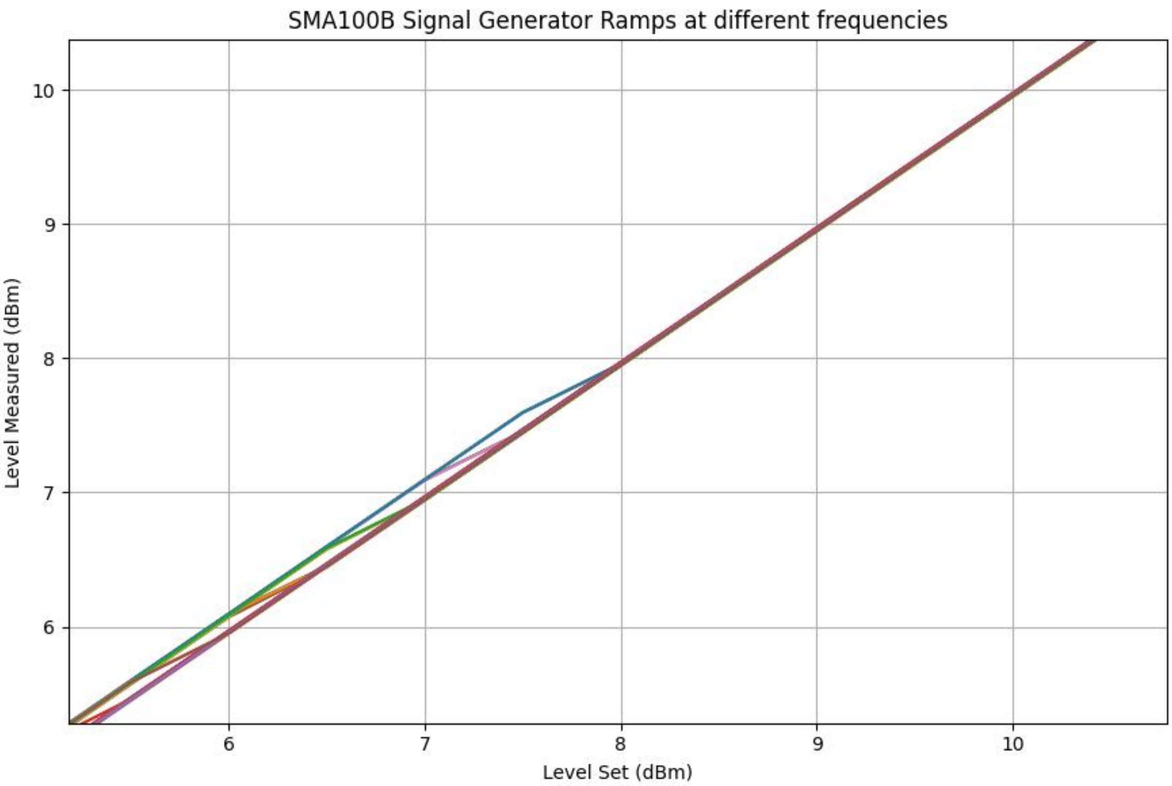
The signal generator output is connected to the Agilent U2004A USB power sensor. Measurements are taken with a constant TA of 23 °C. The temperature is read by the power sensor itself having an internal thermometer that can be queried via SCPI commands.

The following pictures show the plot of the selected 46 frequency traces from 50 to 350 MHz, on X axes there is the Signal Generator output level set, and on the Y axes there is the level measured by the Agilent U2004A USB power sensor.

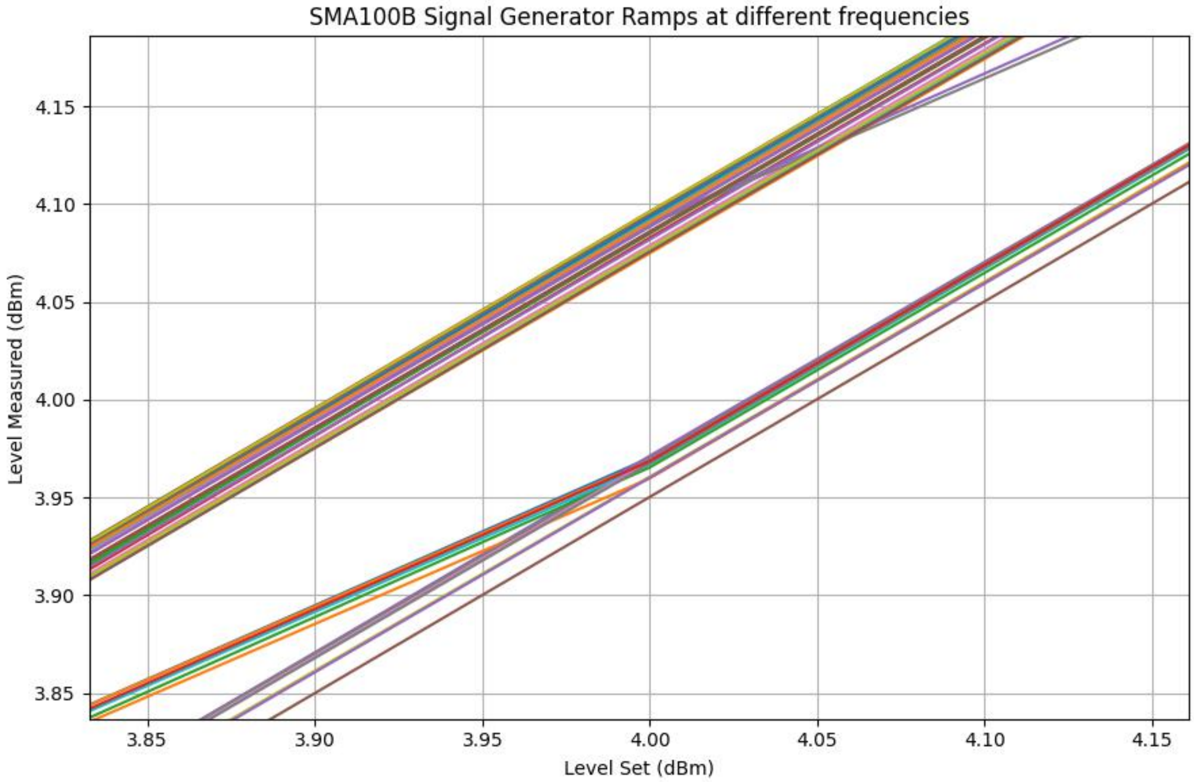


Zooming a little bit we can identify a small region between +2 and +8 dBm where there is a bit of drift in level on some frequencies.

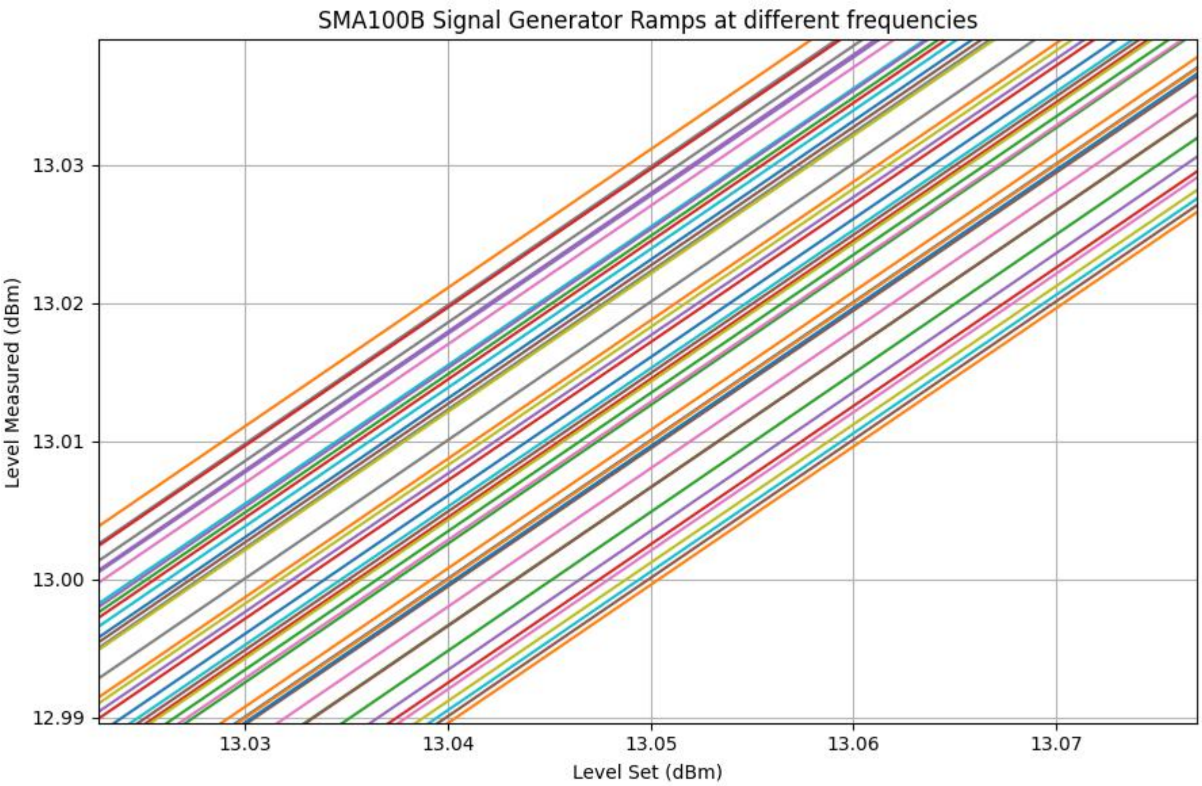




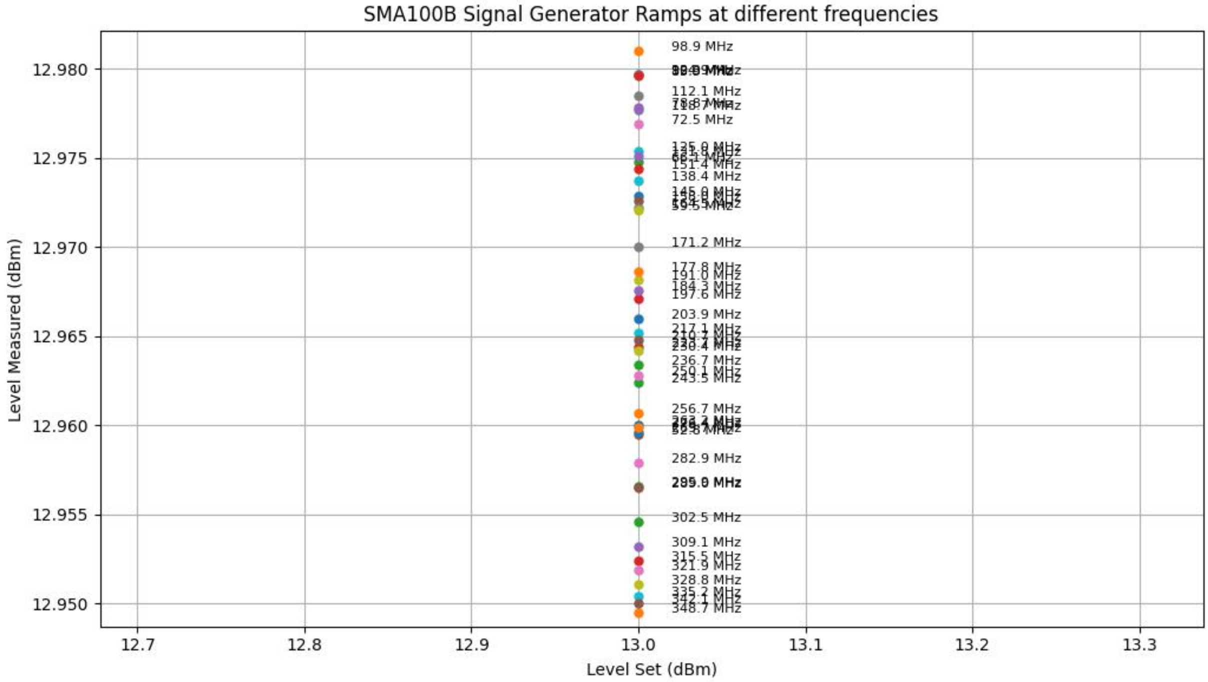
The maximum delta in this region is 0.15 dB.

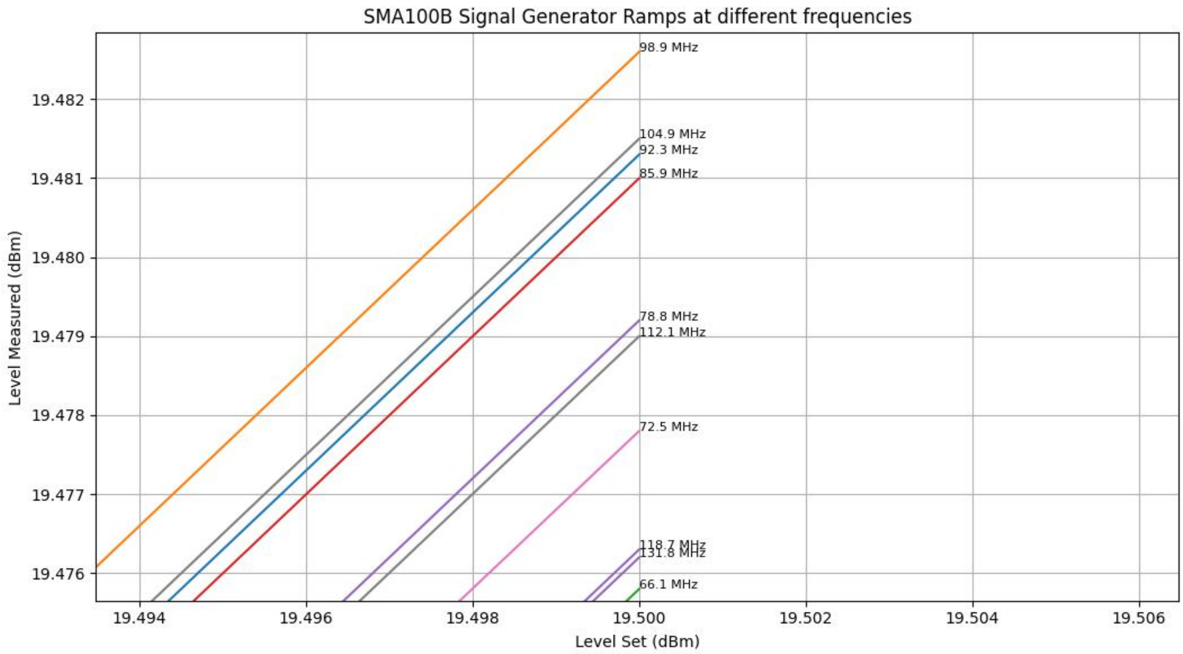


The difference of the traces around +13 dBm is constant within 0.03 dB.



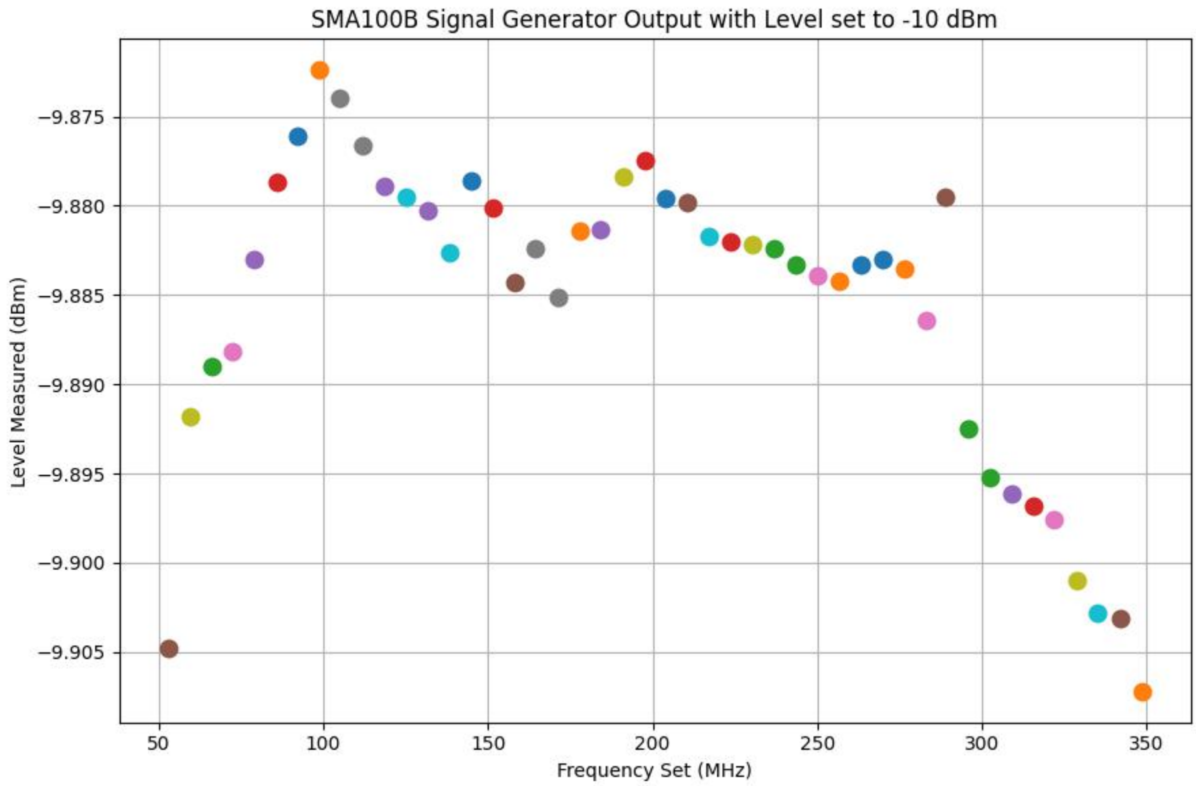
Plotting markers instead of lines with the annotations of the frequency traces highlights the relationship “frequency-output level”.

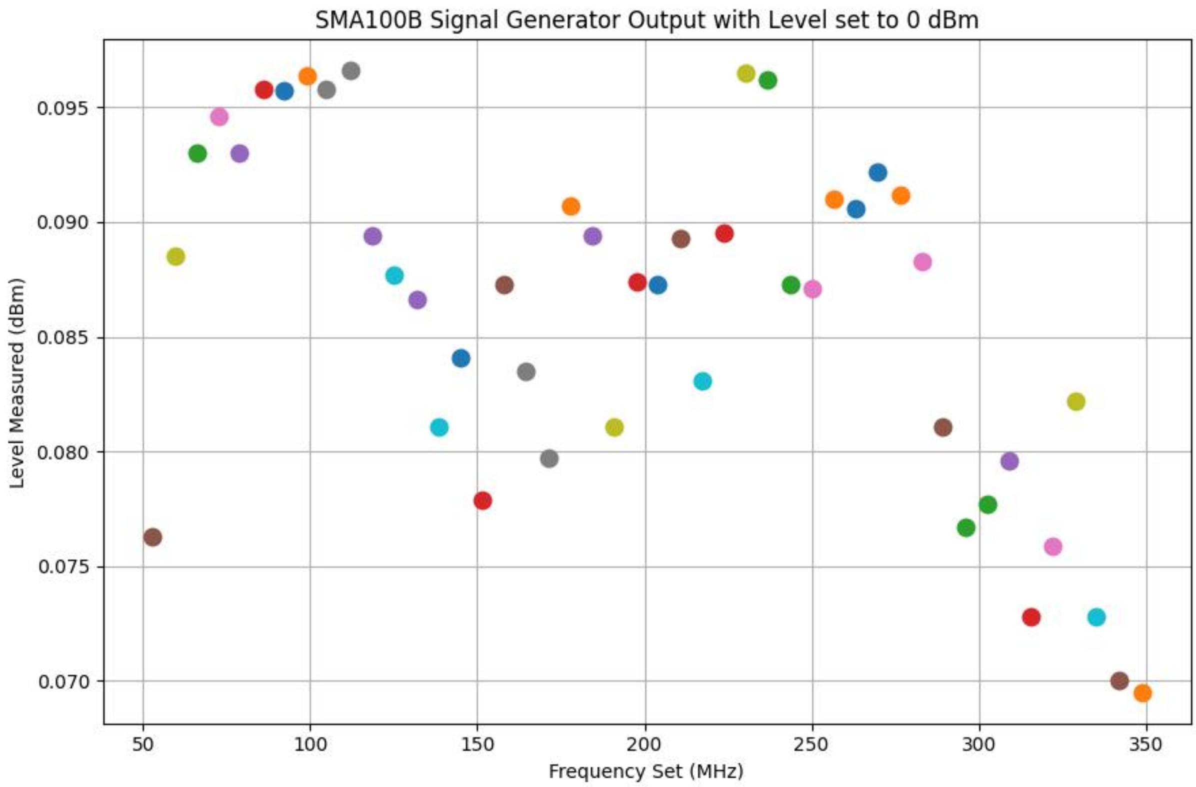




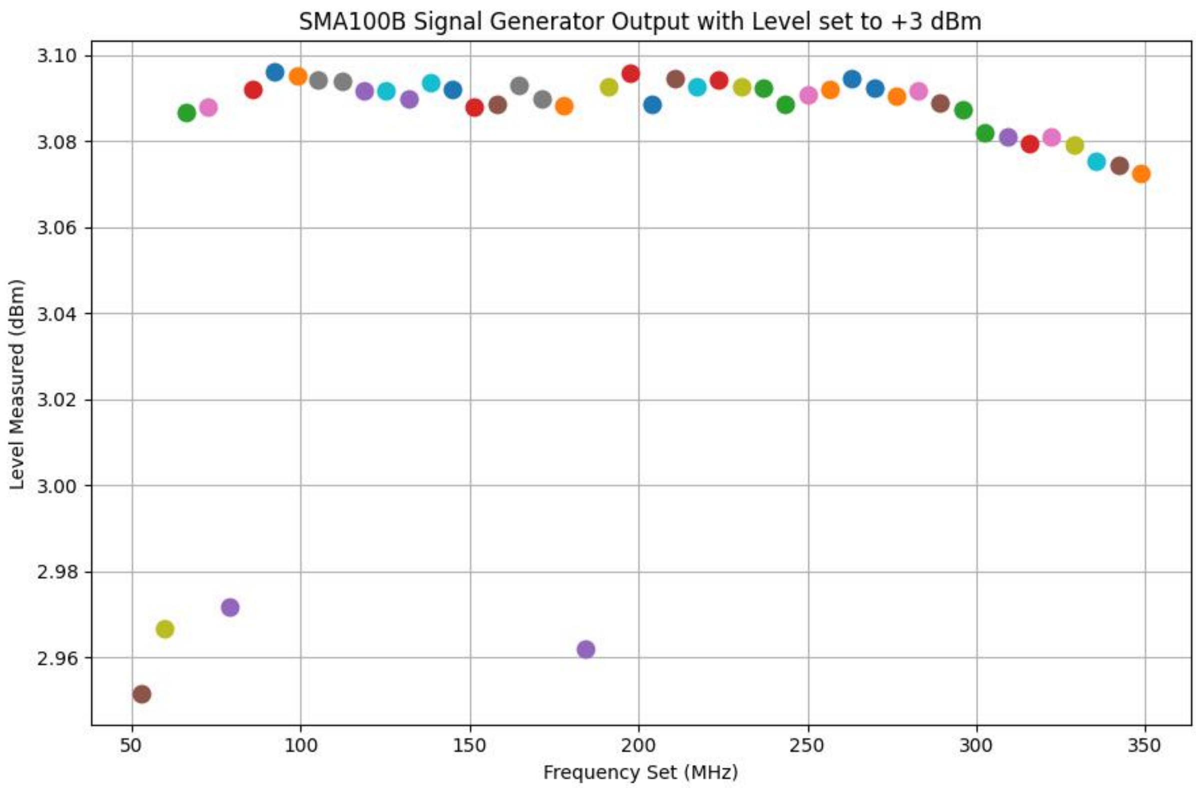
The relationship “frequency-output level” can be more appreciated on the next plots where on X axes there is the frequency and on Y axes there is the measured Level for a specific set point reported on the plot title.

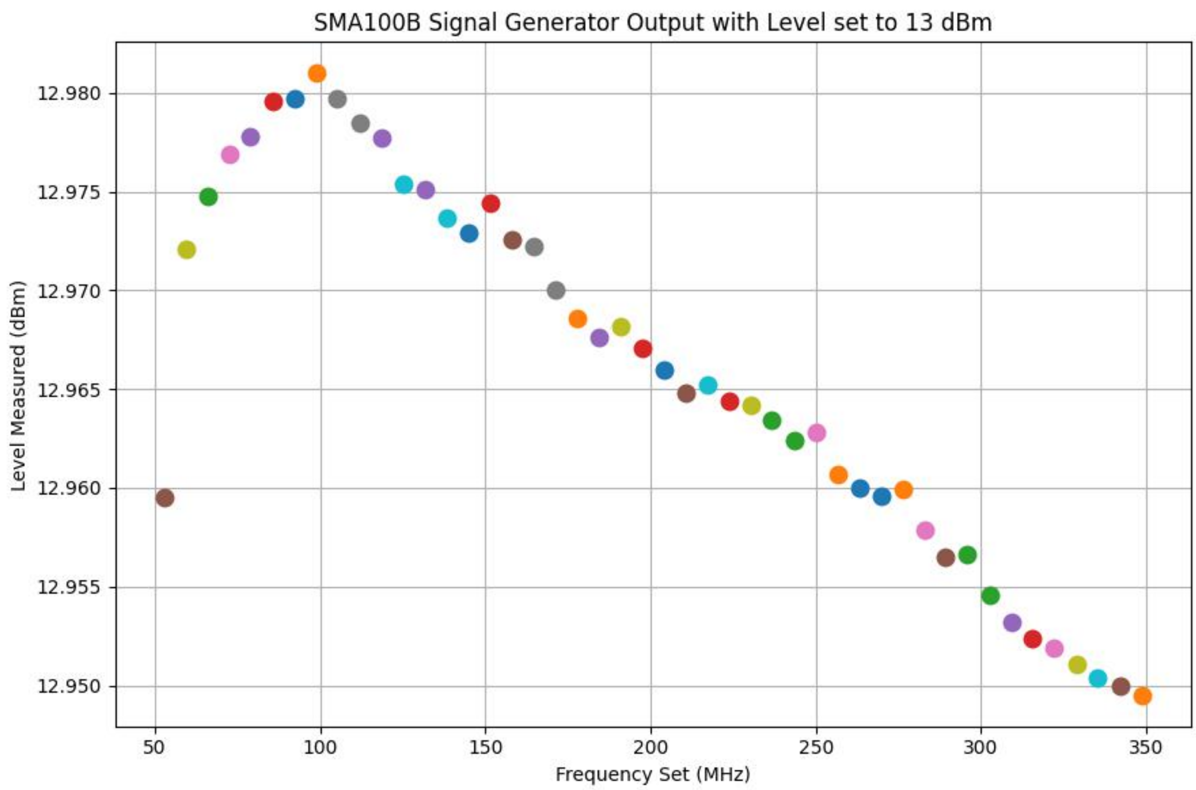
To emphasize the level differences between frequency traces a millesimal dB scale on Y axes has been used. At -10 dBm and 0 dBm the difference is about 0.03 dB.





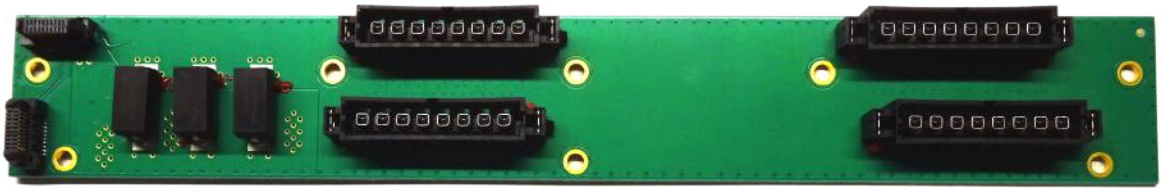
As stated before, in the range of level from +2 and +8 dBm there are some outsiders who deviate from the average value a little more, and the highest difference becomes greater but < 0.2 dB, **while at +13 dBm get narrows again at about 0.03 dB.**

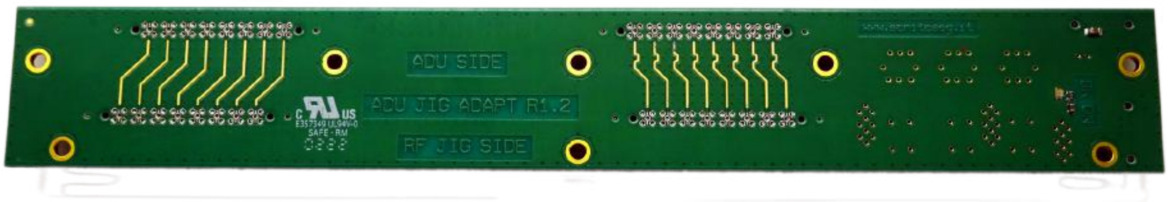




RF Interfaces

The IJ5 RF JIG output connectors are exactly the same type of the ADU board and two PCB adapters are needed to connect the 16 TOP RF chains and the 16 BOTTOM RF chains of the ADU.



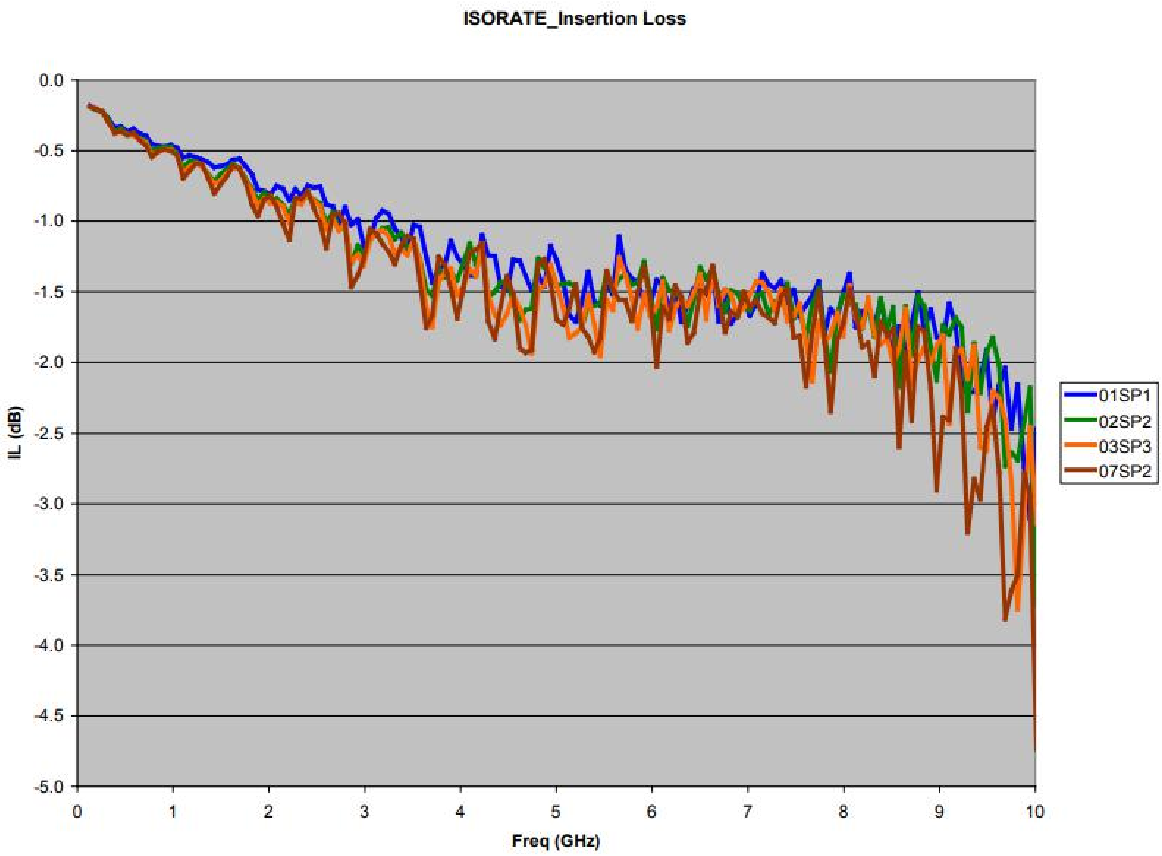


The RF paths of the adapters are fully passive. Resistors are available to emulate the current consumption of the PreADU boards.

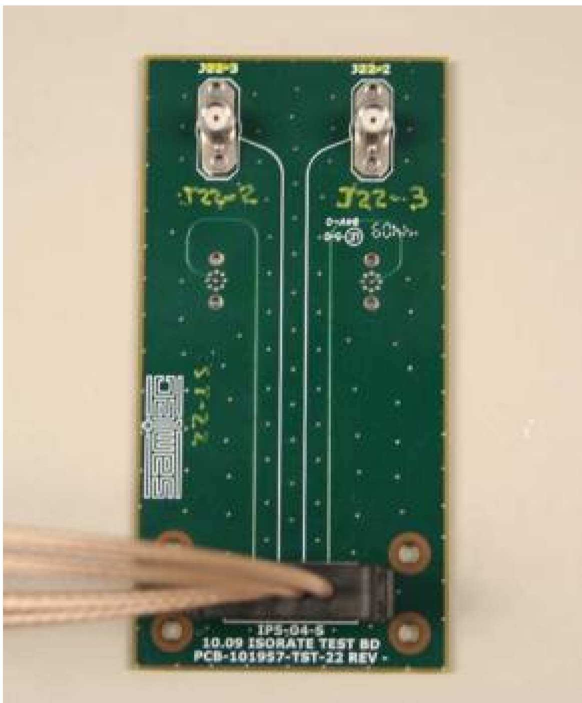
A SAMTEC IJ5H-08-0500-S-2-01SP1 interface cable[8] is needed to draw the RF signal from the IJ5 connector to an SMA end to connect the USB Power Sensor.

The coaxial cable type is an RG-316 cable, 50 cm length, 50 Ω impedance, 24 AWG.

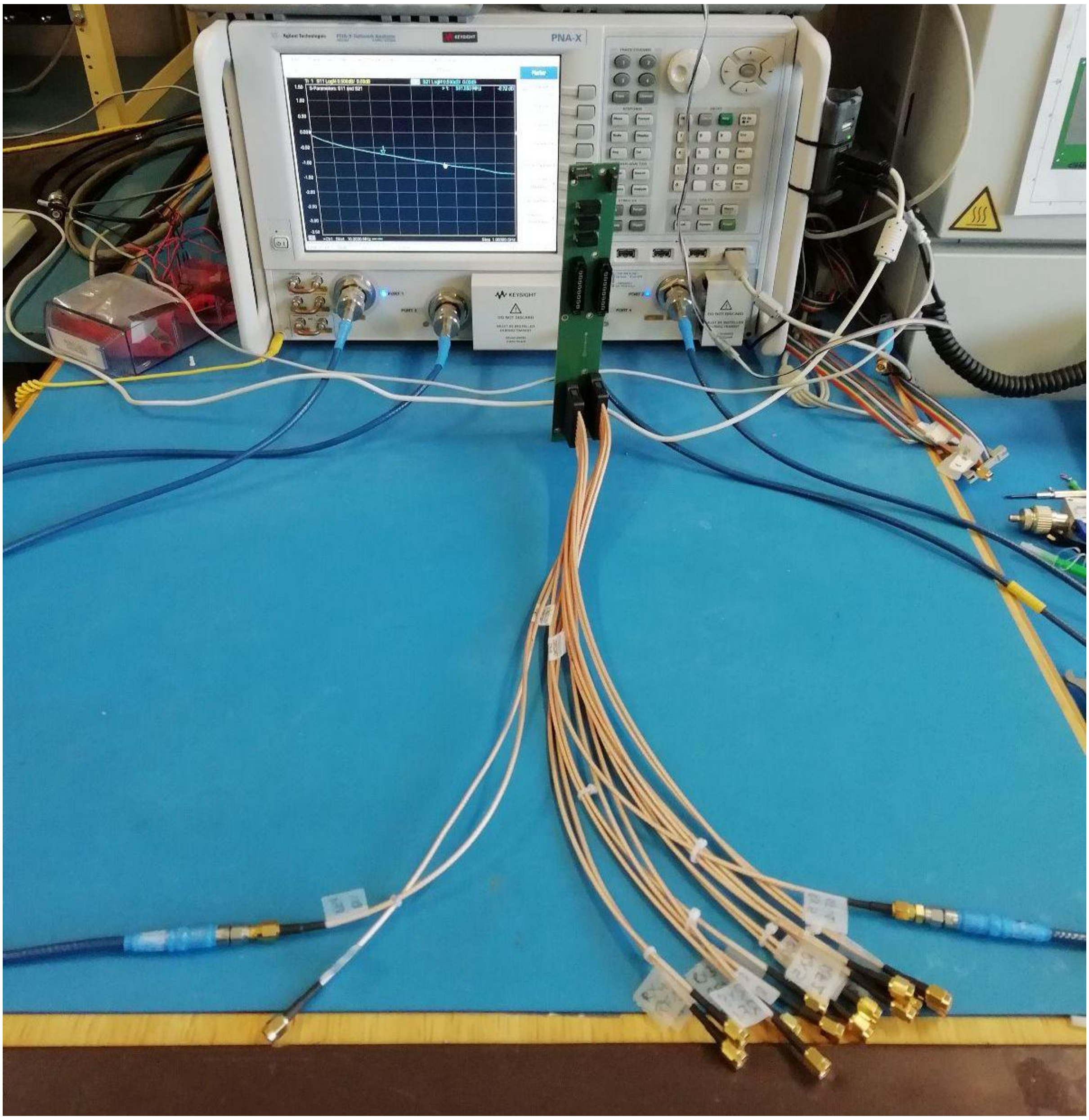
The contribution of this cable must be compensated in the calibration curve since it will not be used during the ADU RF performance measurements. The datasheet reports insertion loss measurements from 150 MHz to 10 GHz which is quite unusable for our usage, we need to measure again S-parameters by using a vector network analyzer.



Since the nature of the IJ5 connector this measurement requires the use of the adapter board itself. In fact also SAMTEC did the measurements by using its own adapter board as shown in the next pictures together with the measurement results.

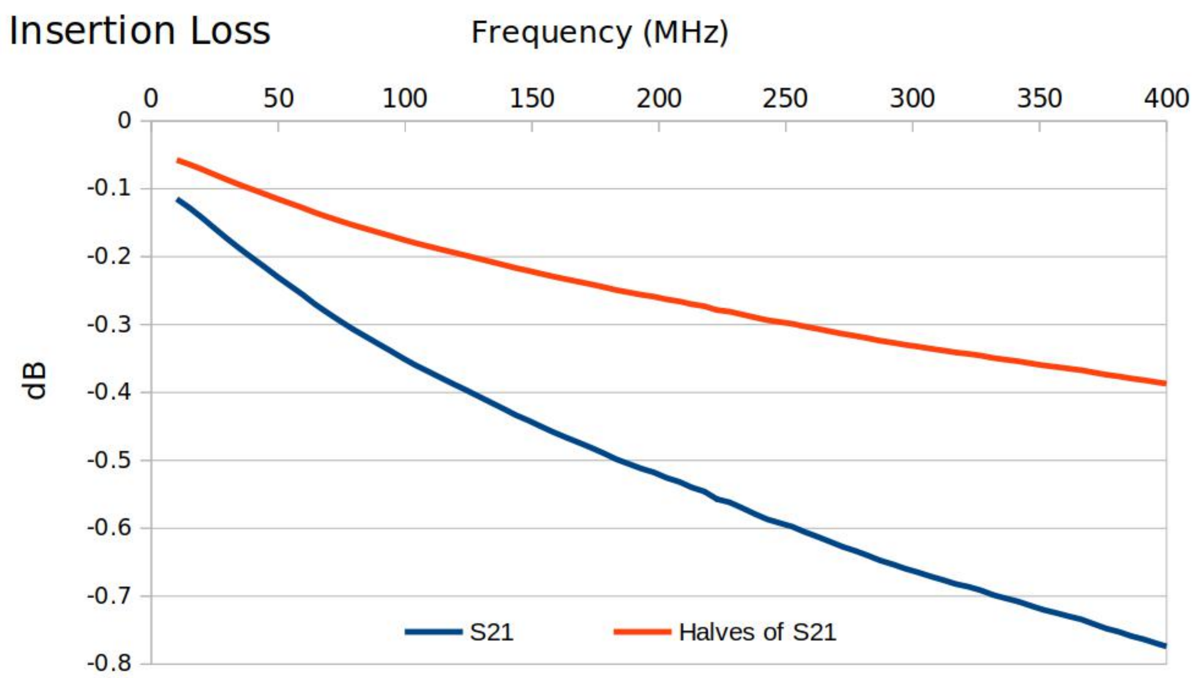


Unfortunately we don't have such a card to connect SMA-SMA ends to the VNA, therefore we have used the ADU RF adapter with 2 SAMTEC IJ5H-08-0500-S-2-01SP1 interface cables.



Assuming that the ADU RF Adapter is well matched at 50 Ω impedance we can extract the measure of one cable by the resulting S21 insertion loss data dividing by a factor of 2, as shown in the next picture.

The insertion loss of the SAMTEC IJ5H-08-0500-S-2-01SP1 interface cable in the frequency range of 50-350 MHz is between 0.11 and 0.36 dB.



The red trace in fact looks very like the one reported in the SAMTEC datasheet.

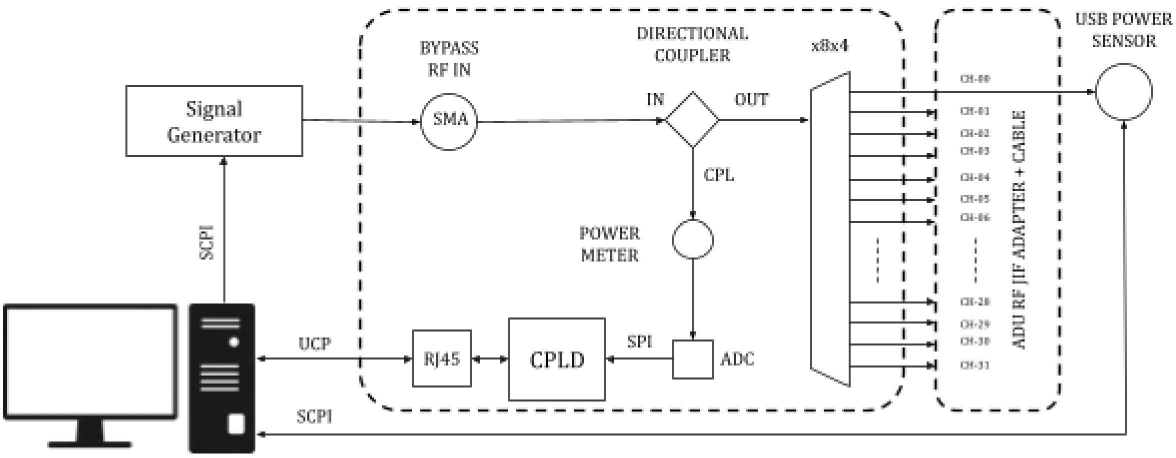
This set of data will be subtracted at the JIG calibration curves since the cable will be not used in the ADU RF Performance tests configuration.

Power Supply

The JIG and the FANs mounted on the mechanical support are supplied by using the Rohde&Schwarz HMP4040. It has 4 channels with max. 384 W of total output power, max 32 V output voltage per channel and up to 10 A output current per channel.

Calibration Setup

The following diagram describes the calibration test bench.

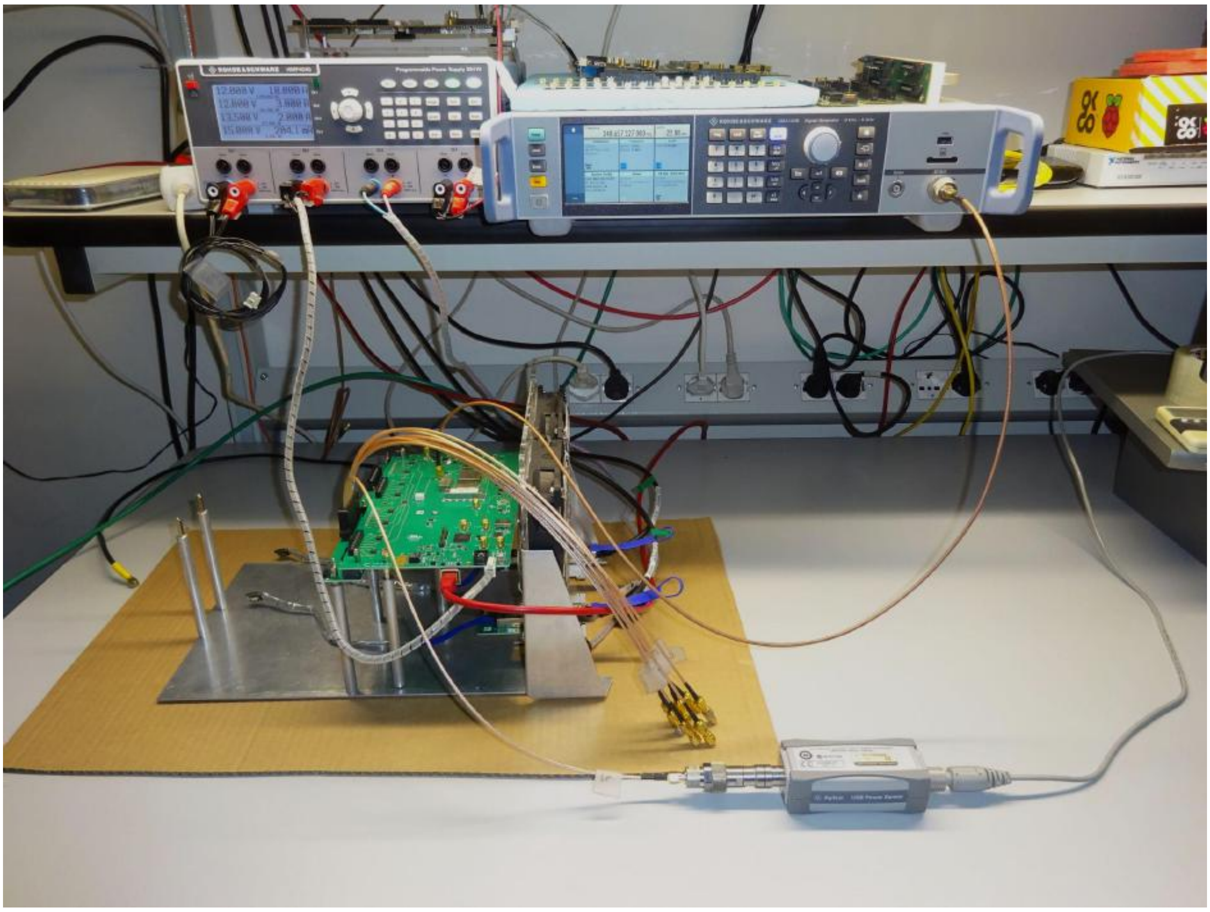


Operations are controlled by a Python script. The software communicates with the JIG CPLD via UCP protocol to select the output lane from channel 0 to channel 31, and read the power meter analog to digital units.

The python script commands the SMA100B signal generator via SCPI ramps from -20 dBm to +20 dBm (0.5 dB step level) for every of the 46 selected frequencies. The CW tone frequency is also set to the USB power sensor via SCPI useful for its internal calibration table to improve reading accuracy.

Dotted line box on the left represents the part involved in the JIG power meter calibration. The CW tone will be injected in the SMA bypass lane of the filter bank skipping the RF path of the PLL-Amplifier-DSA-Filters. Dotted line box on the right represents the ADU RF JIG adapters and the SAMTEC IJ5H-08-0500-S-2-01SP1 with SMA ends on its 8 cables. The unused cable ends are terminated to 50 Ω load.

The following is a picture of the calibration bench.



Analyzing Measurements

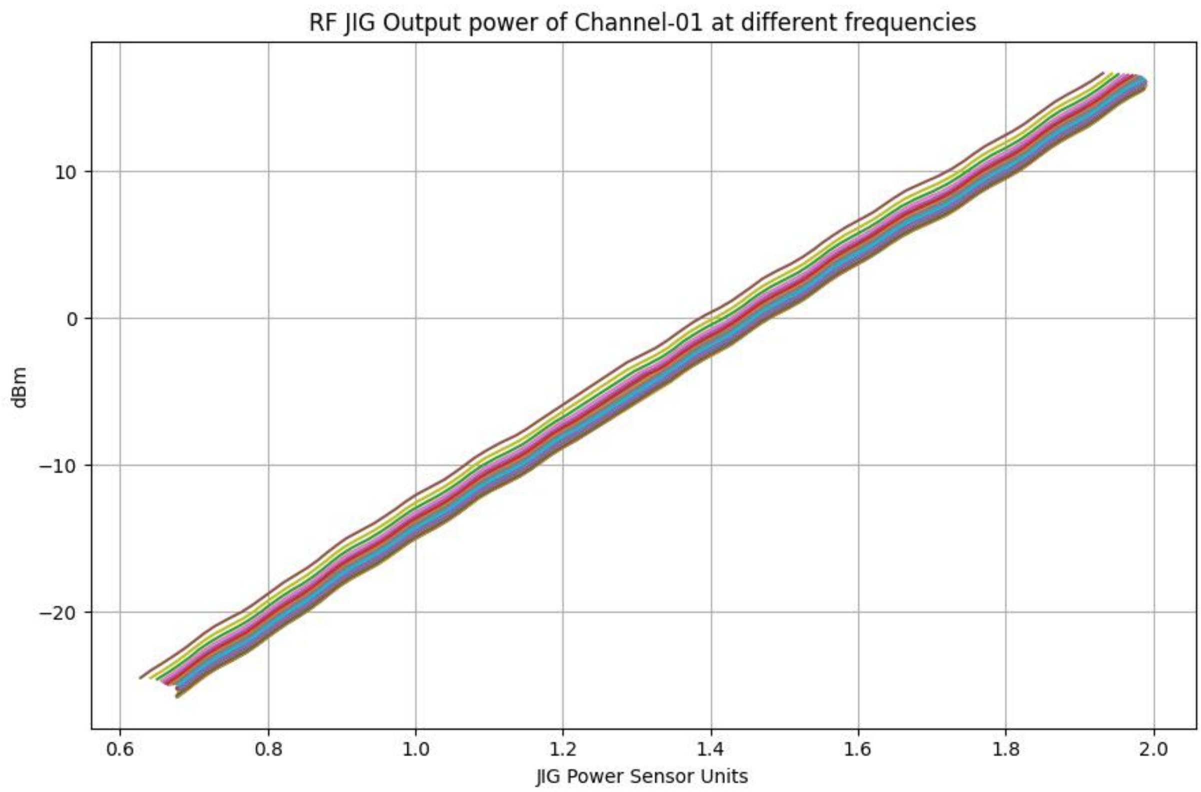
It is important to remark that the range from -7.5 dBm to -6 dBm has been skipped to avoid the fast continuous switching between the two measurement paths of the USB power sensor: low-power path –60 to –7 dBm, high-power path –7 to +20 dBm with –7 dBm as switching point (and a *witching* point hysteresis of ± 0.5 dB).

The software that will use the resultant calibration curves will interpolate the points to convert the JIG power meter values to calibrated dBm.

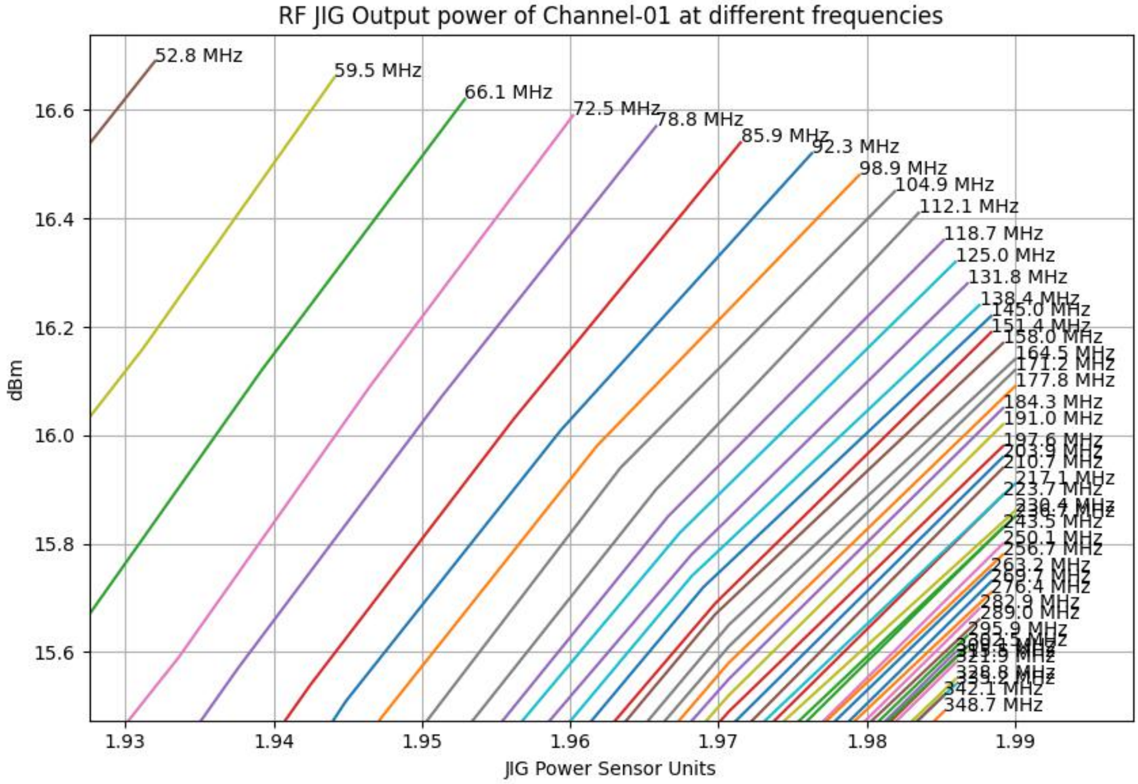
Single channel analysis

The following plot shows each of the 46 frequency ramps in the range of 50 to 350 MHz generated from -20 dBm to +20 dBm level commanded at the signal generator and measured by the USB Power Sensor.

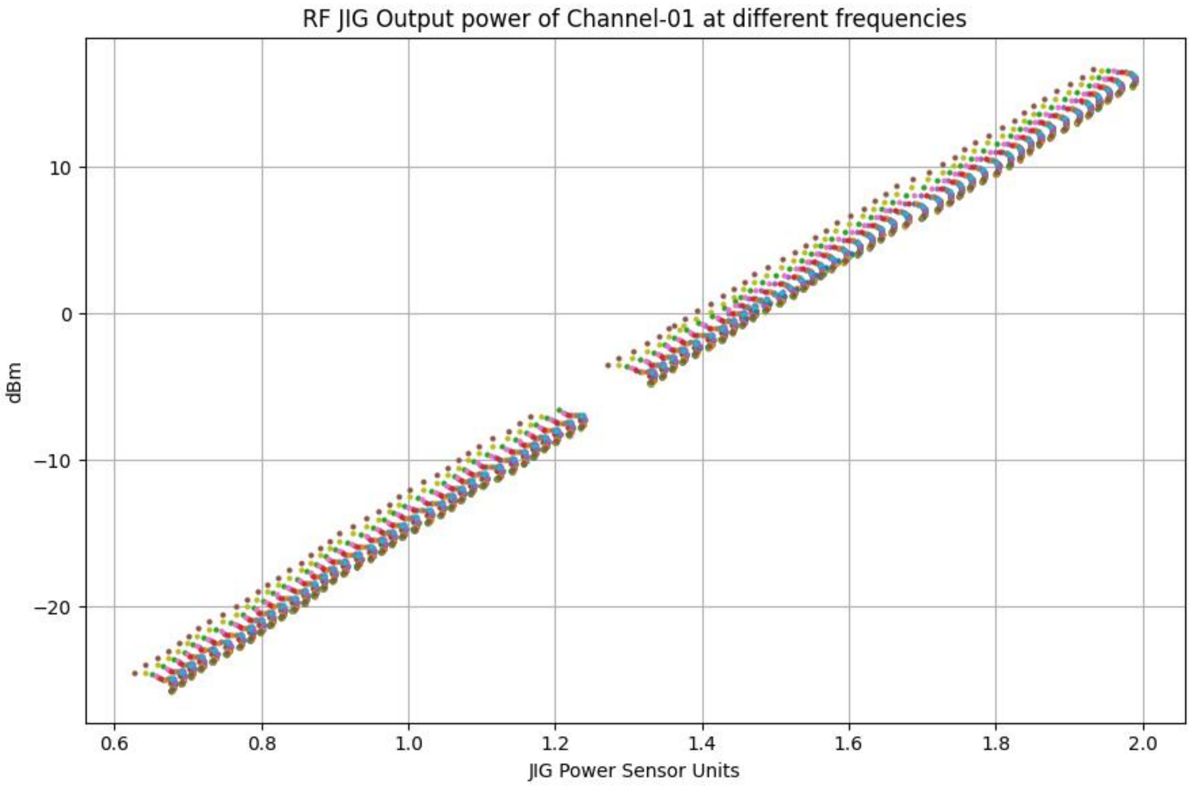
It is clear from the plot that changing the frequency of the source signal has an impact on the measured level, and apparently the difference is constant with respect to the level.



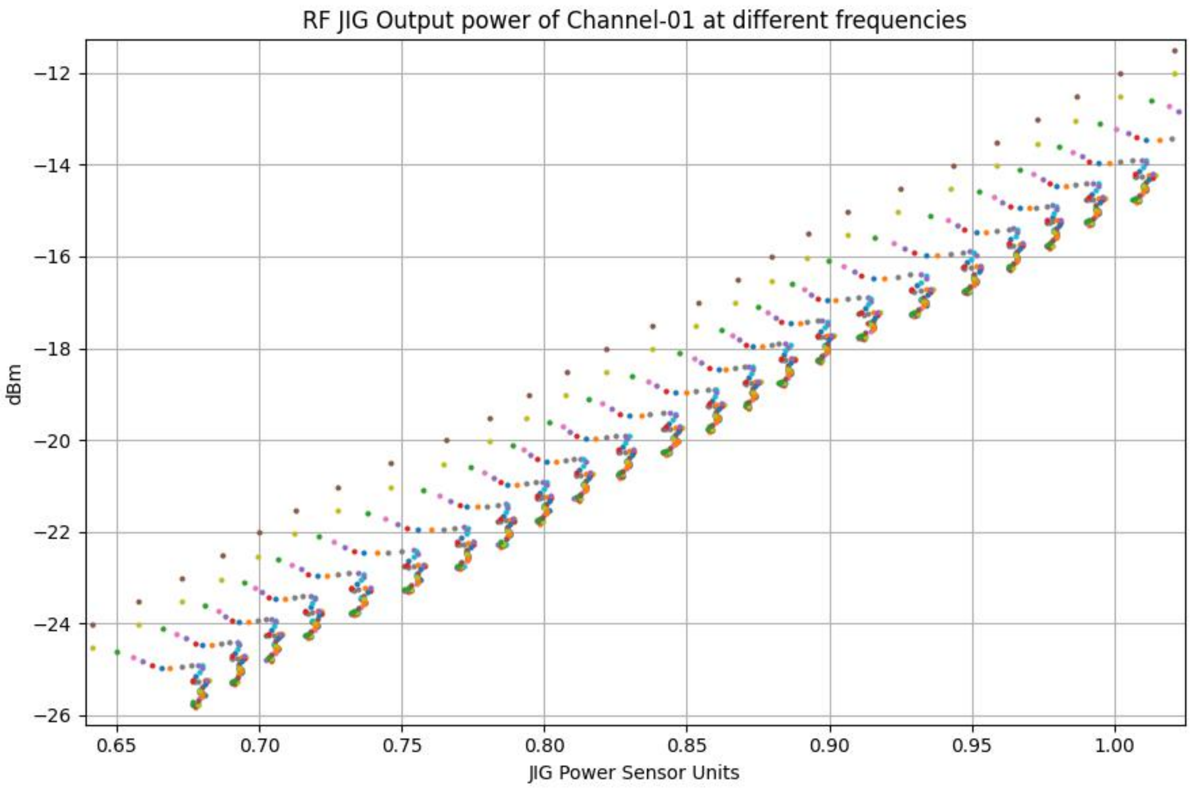
The next plot wants to identify the frequency of each trace annotating the legend.

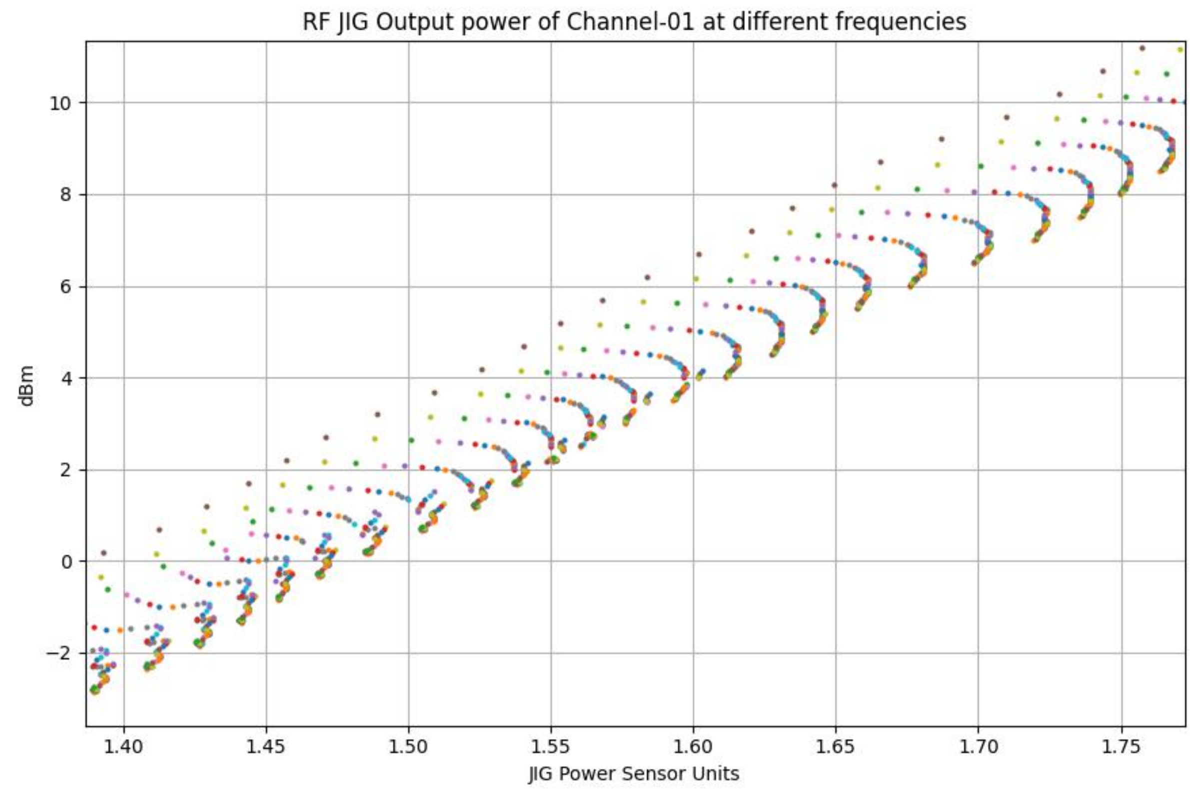


Plotting only markers instead of lines emphasizes the behavior along the full ramp.

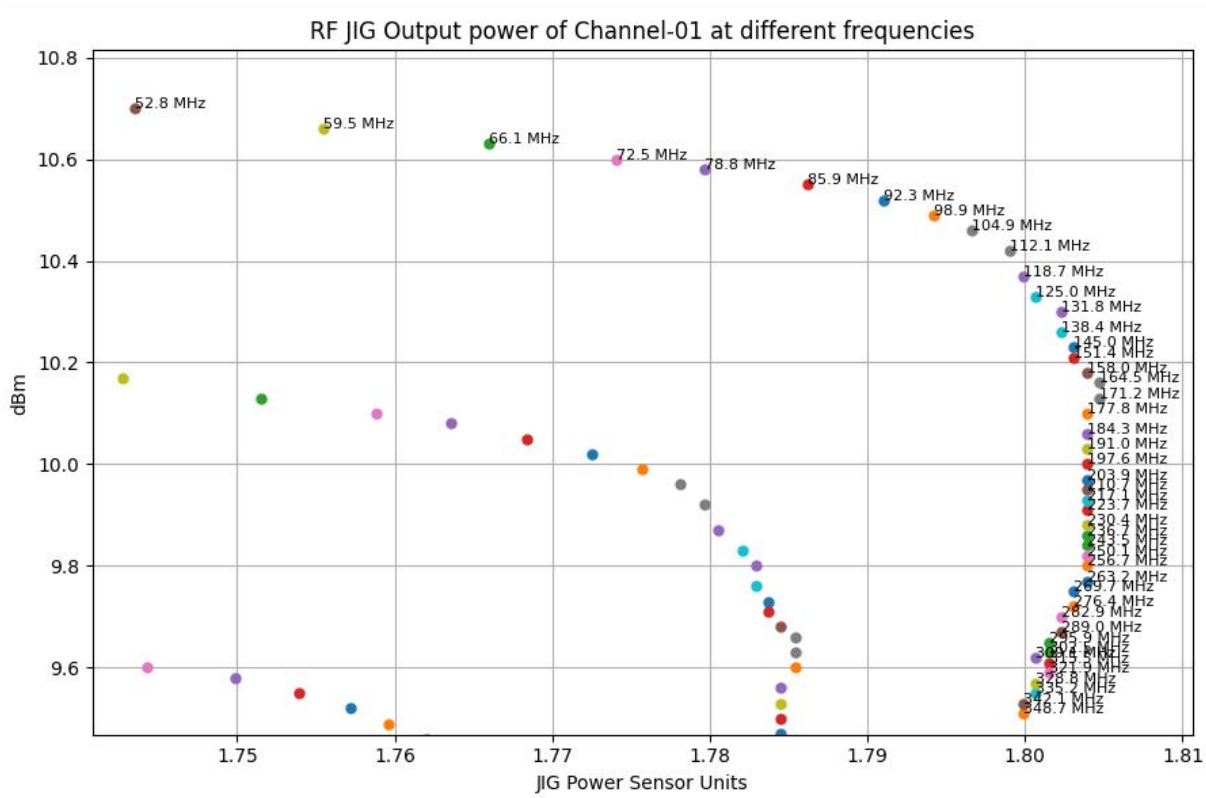


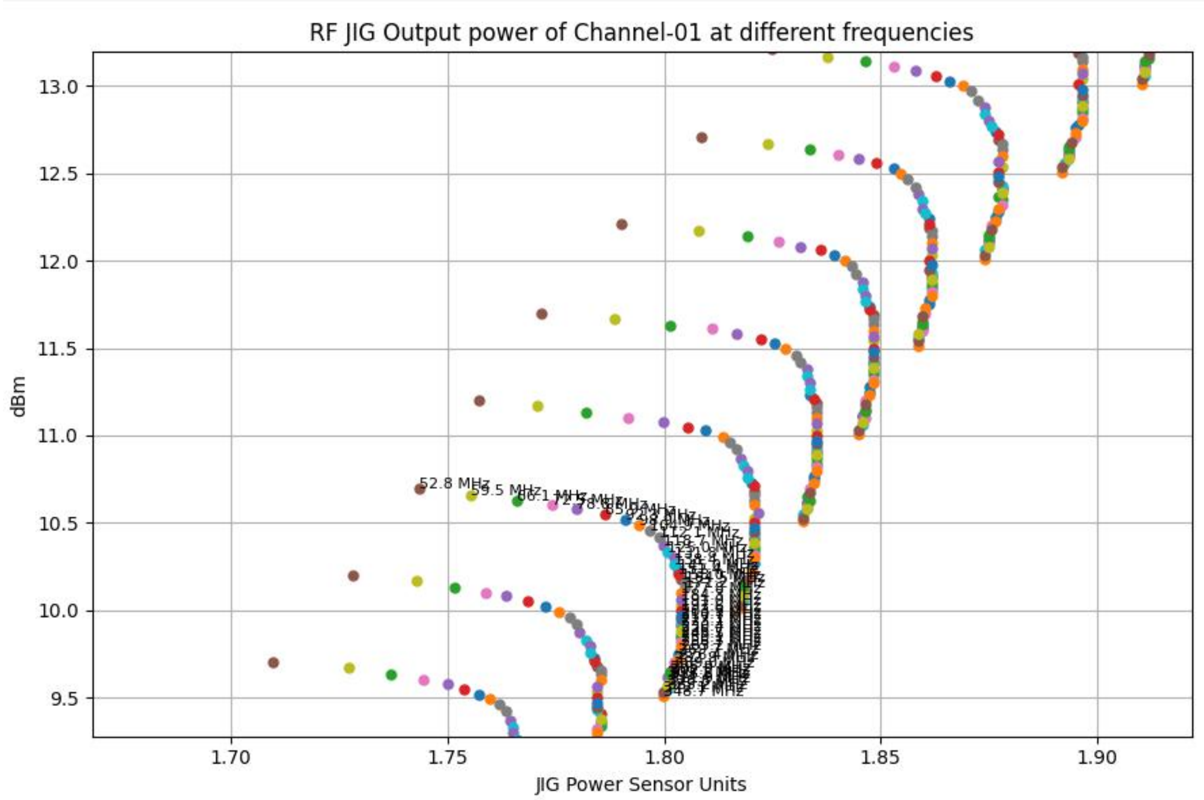
The behavior at low levels is slightly different from the behavior at high levels.



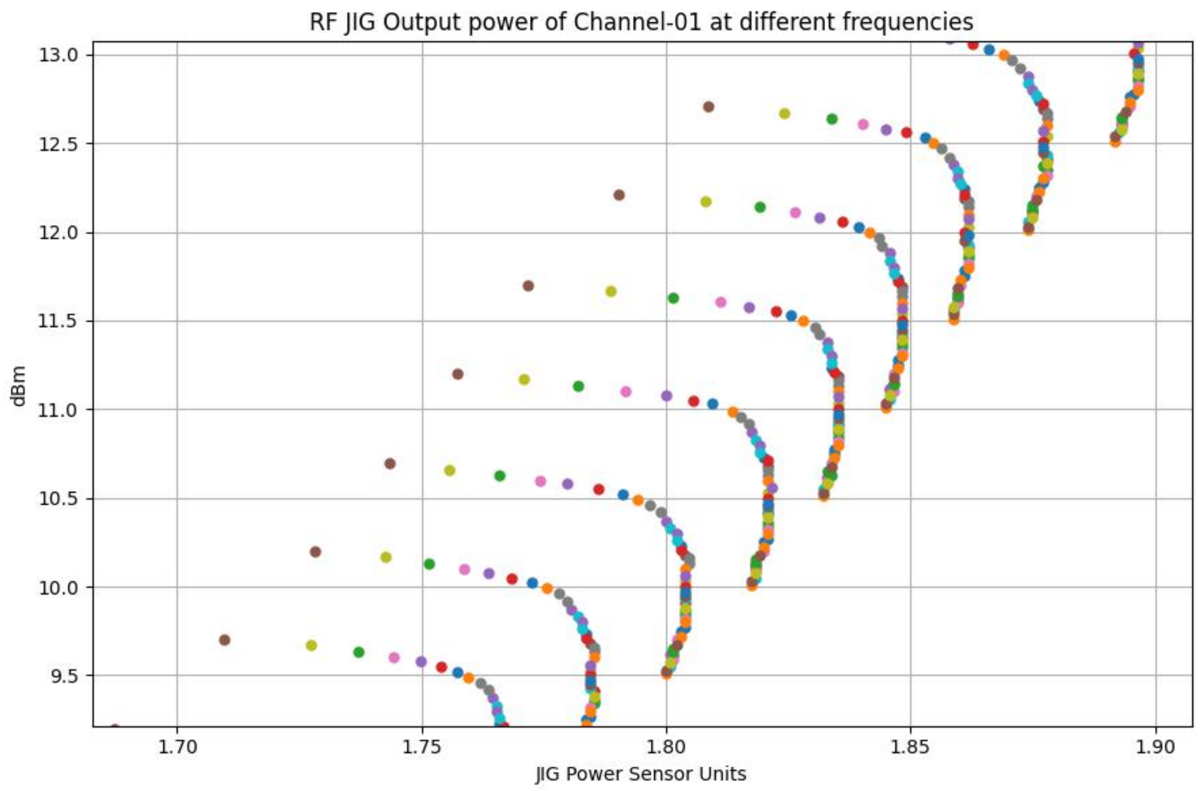


The next plot shows how the JIG power meter value 1.8 can be interpreted as a level of about +10.4 dBm for the frequency 118 MHz or +9.5 dBm for the frequency 350 MHz, an error of 1 dB for a non calibrated JIG.

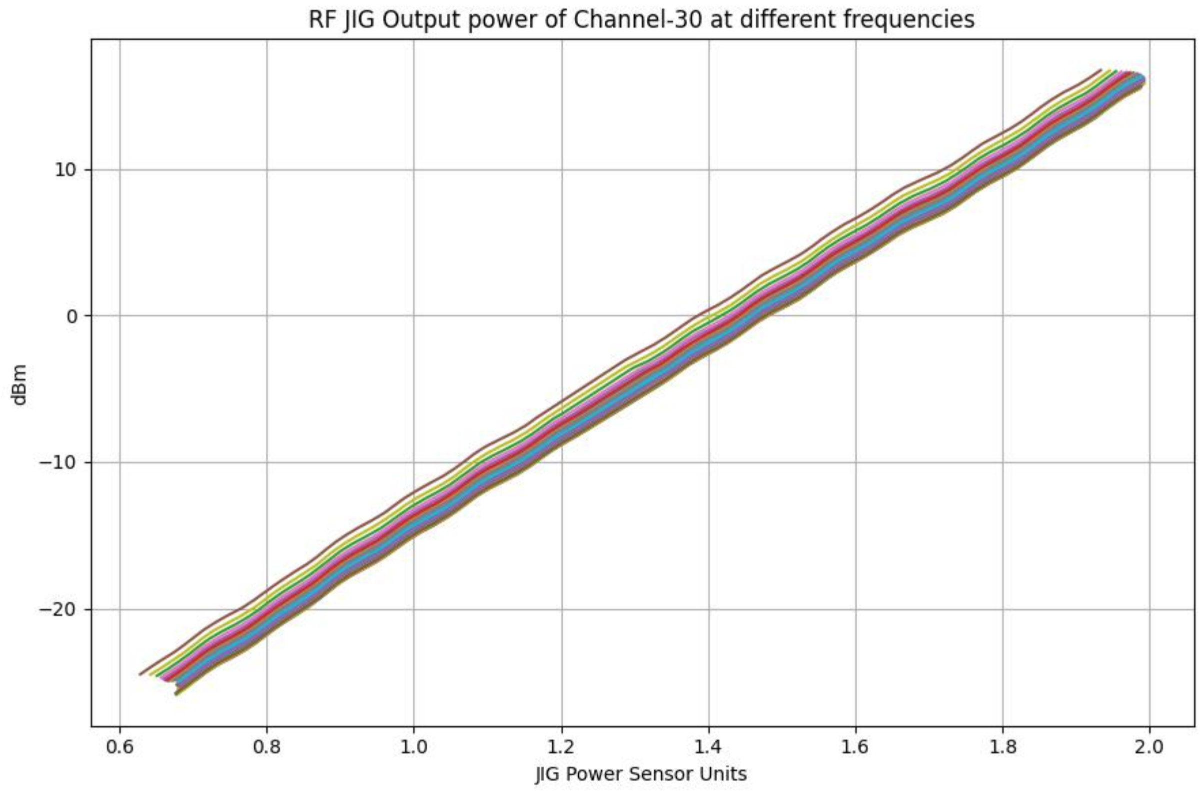


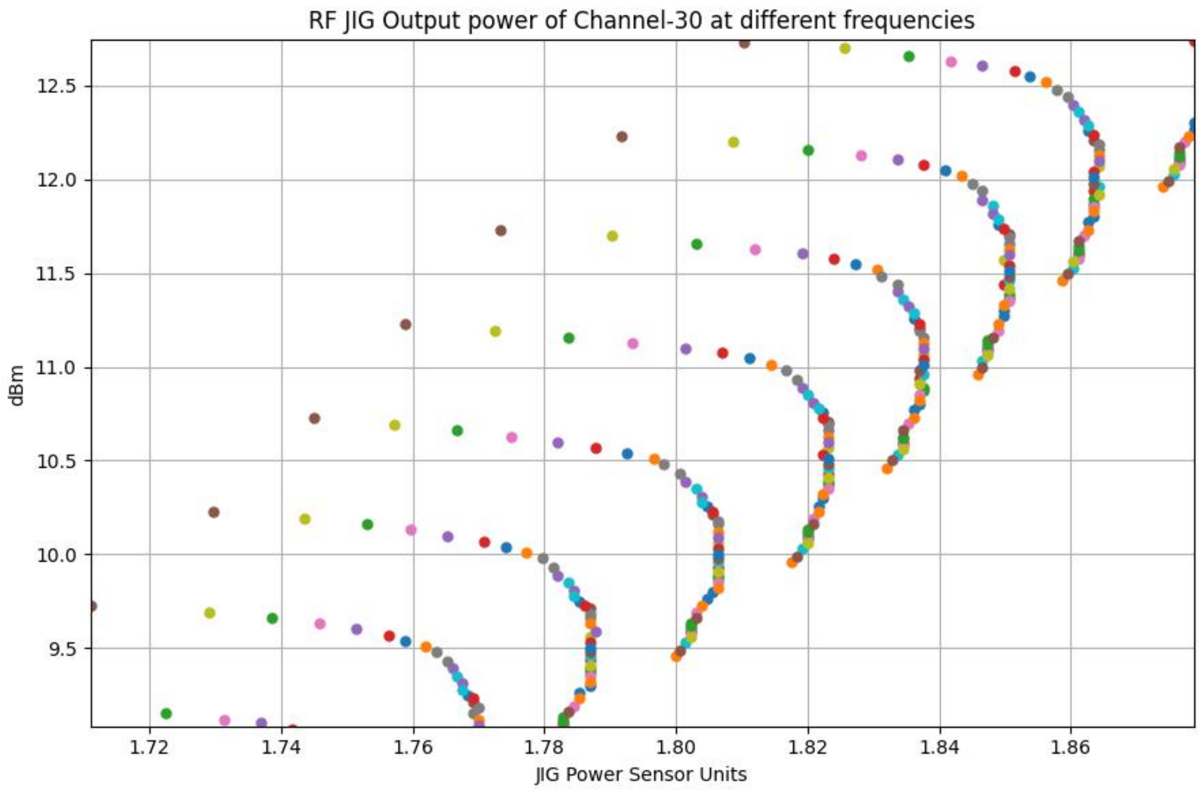


Changing a little bit the scale, the next plot shows the full range of misreading that an **uncalibrated power meter** may have: the value 1.8 measures 12.5 dBm at 50 MHz, **the total reading error in the range 50-350 MHz is 3 dB**.



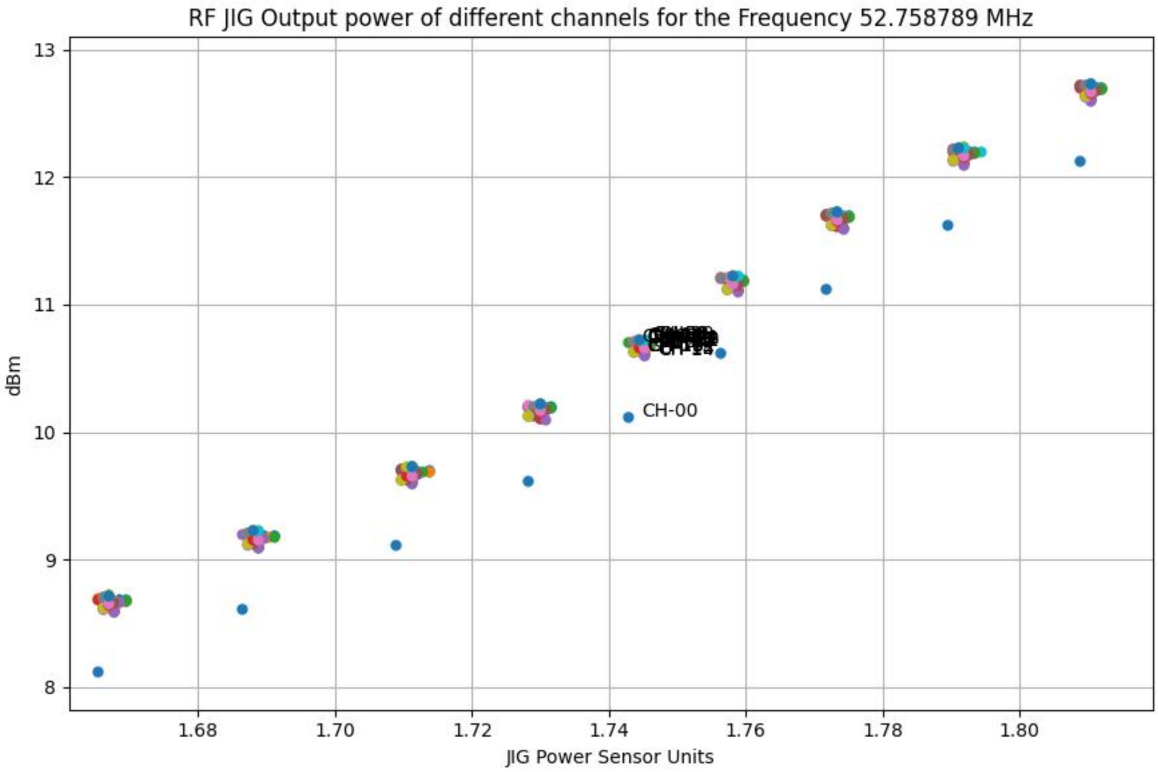
All the channels analyzed independently are very similar. The following plots show the analysis of the JIG output channel 30.

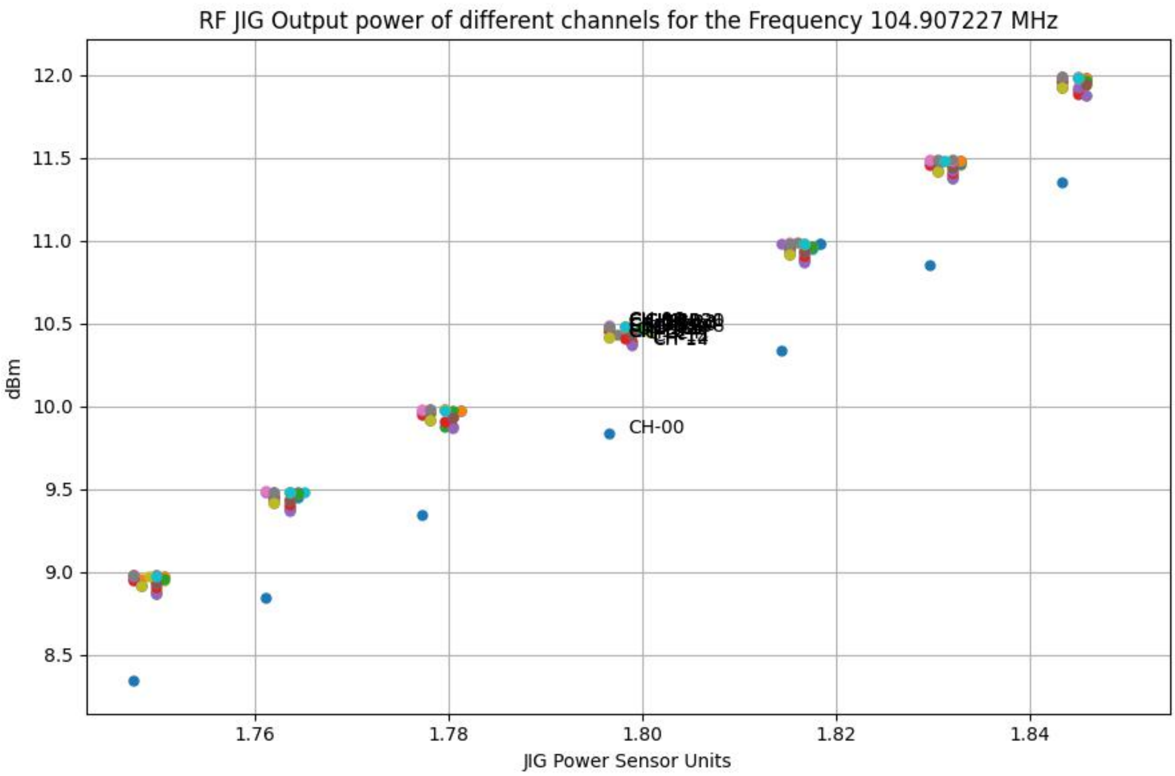

RF JIG Output power of Channel-30 at different frequencies
10
0
−10
−20
dBm
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
JIG Power Sensor Units

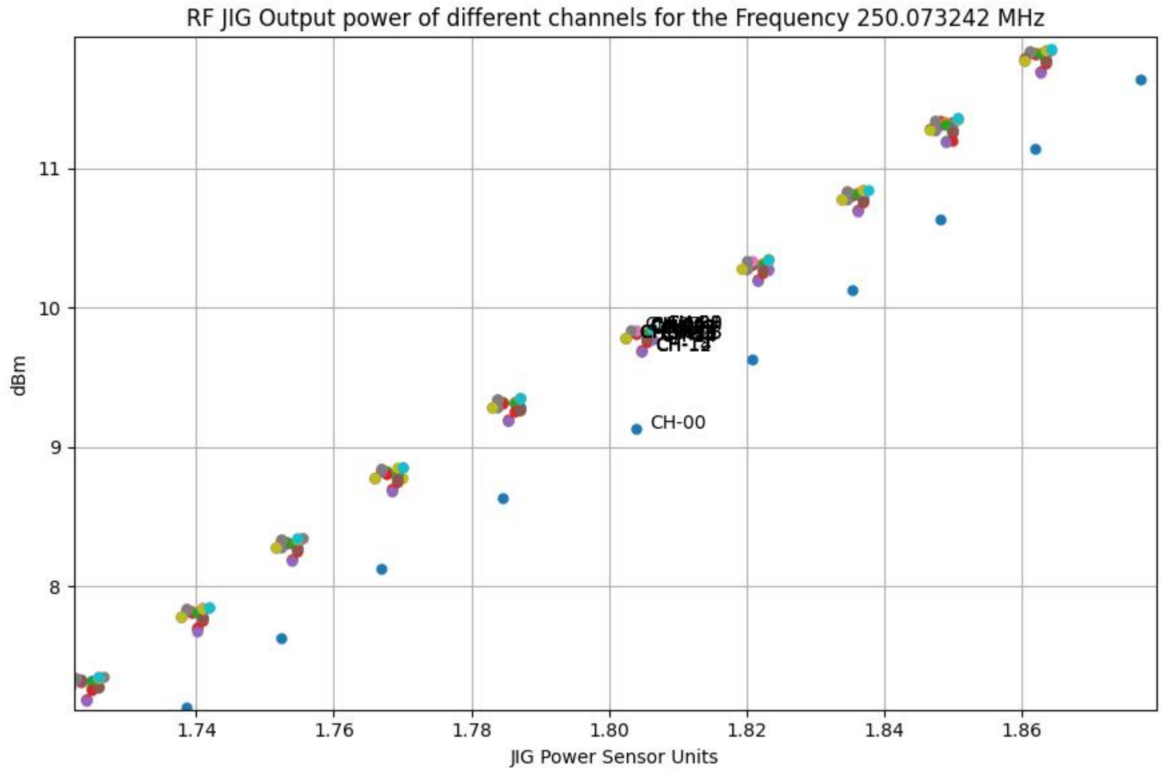

RF JIG Output power of Channel-30 at different frequencies
12.5
12.0
11.5
11.0
10.5
10.0
9.5
dBm
1.72
1.74
1.76
1.78
1.80
1.82
1.84
1.86
JIG Power Sensor Units

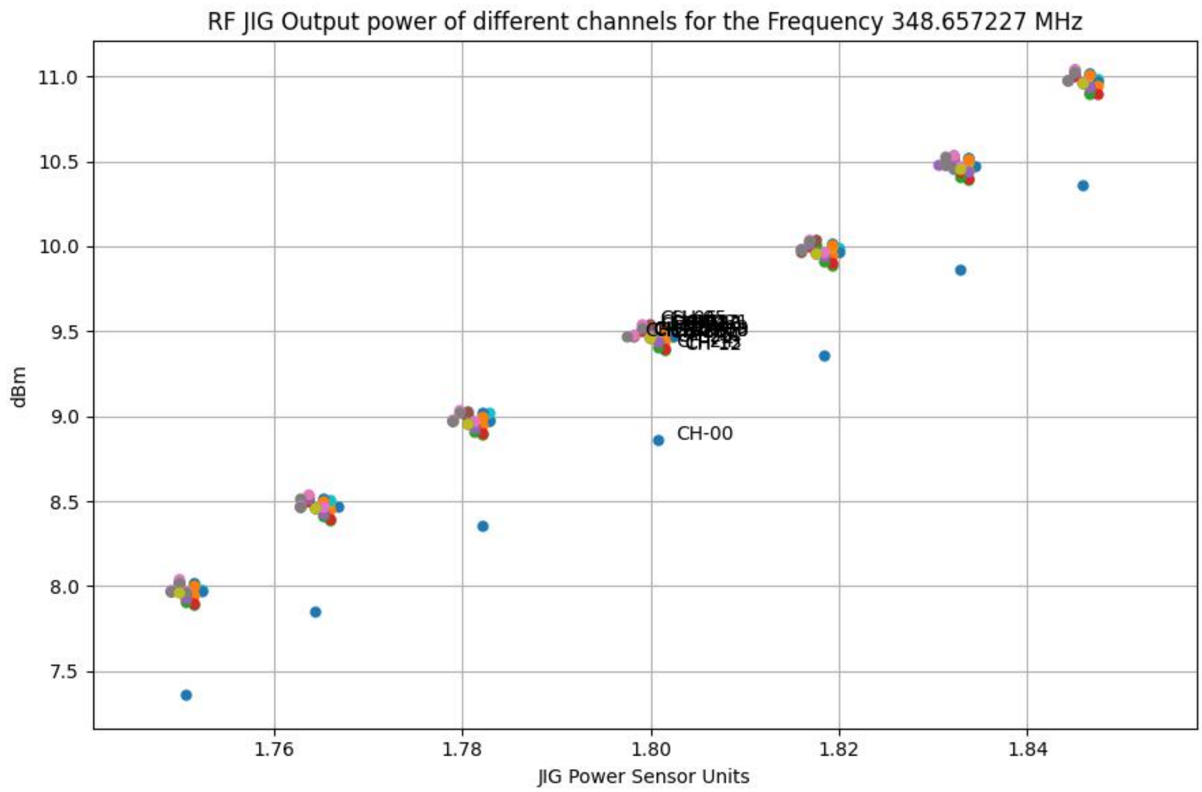
Multi channels analysis

The following plot shows the level measured at different output channels for the frequencies of 50, 100, 250, 350 MHz. They look very similar except for the output channel #0 that is 0.6 dB lower.

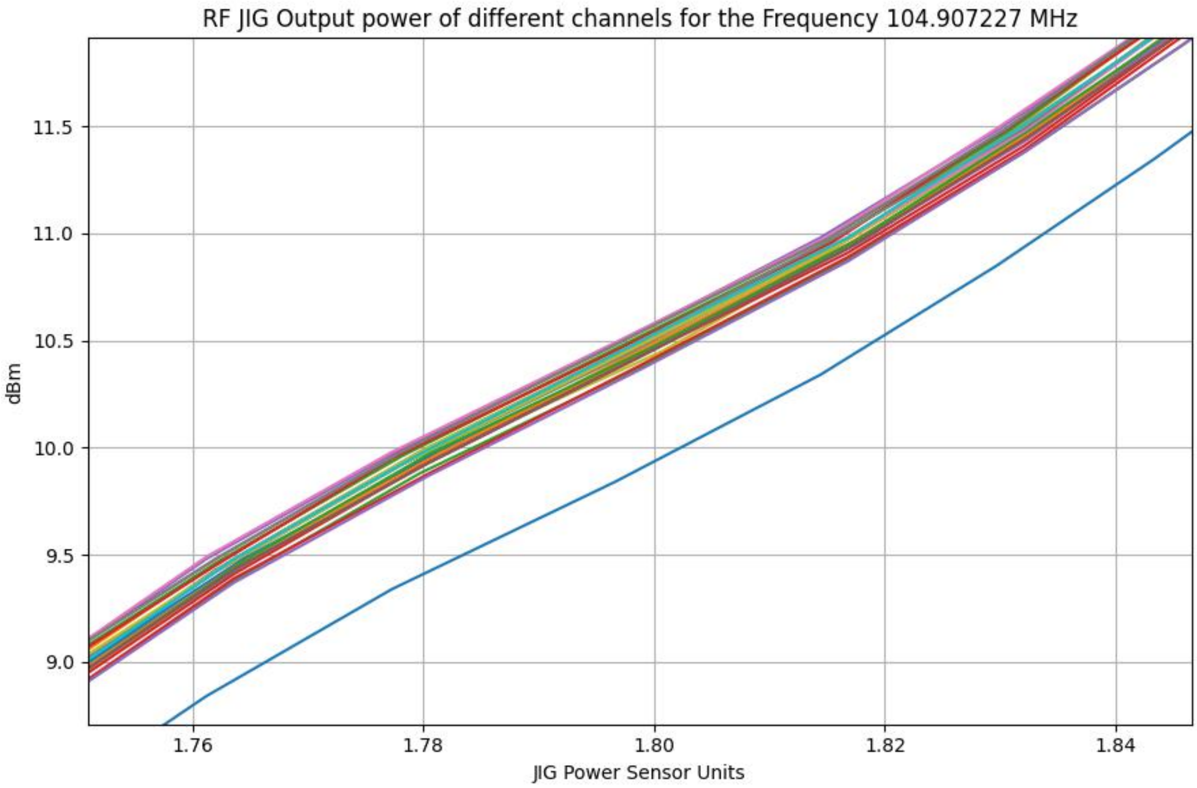


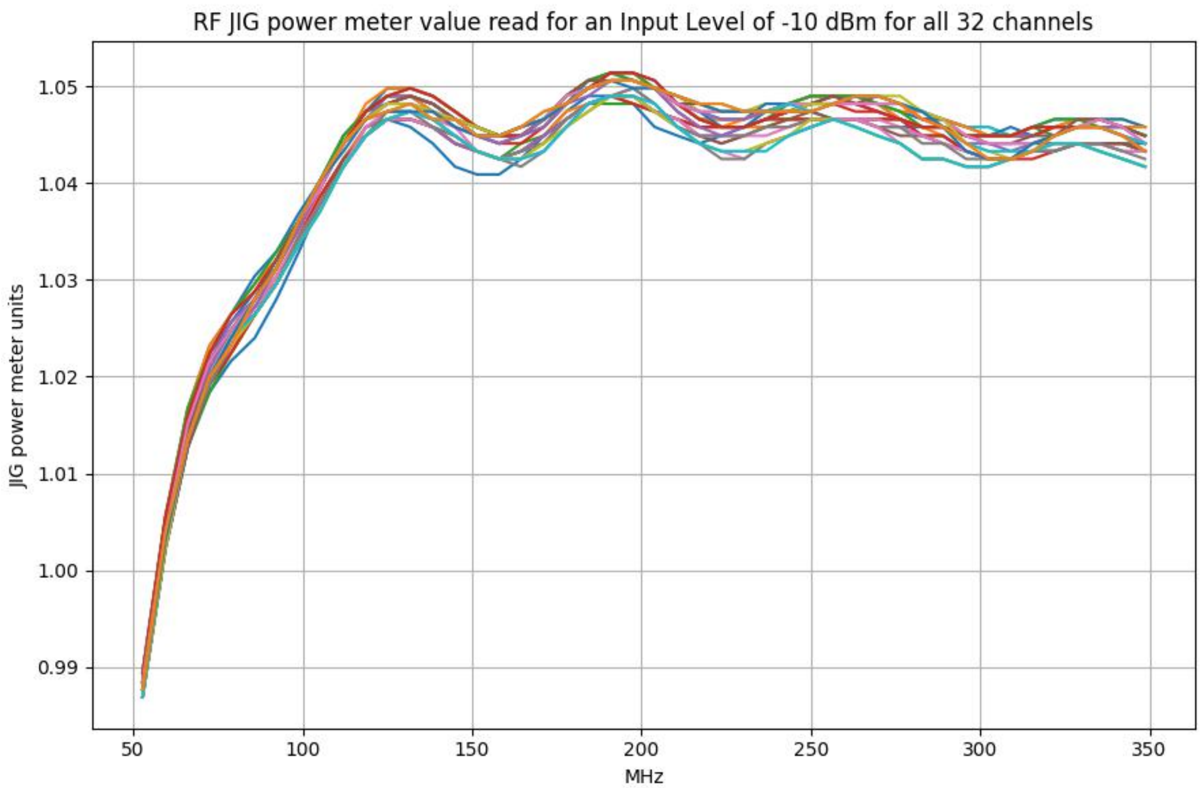


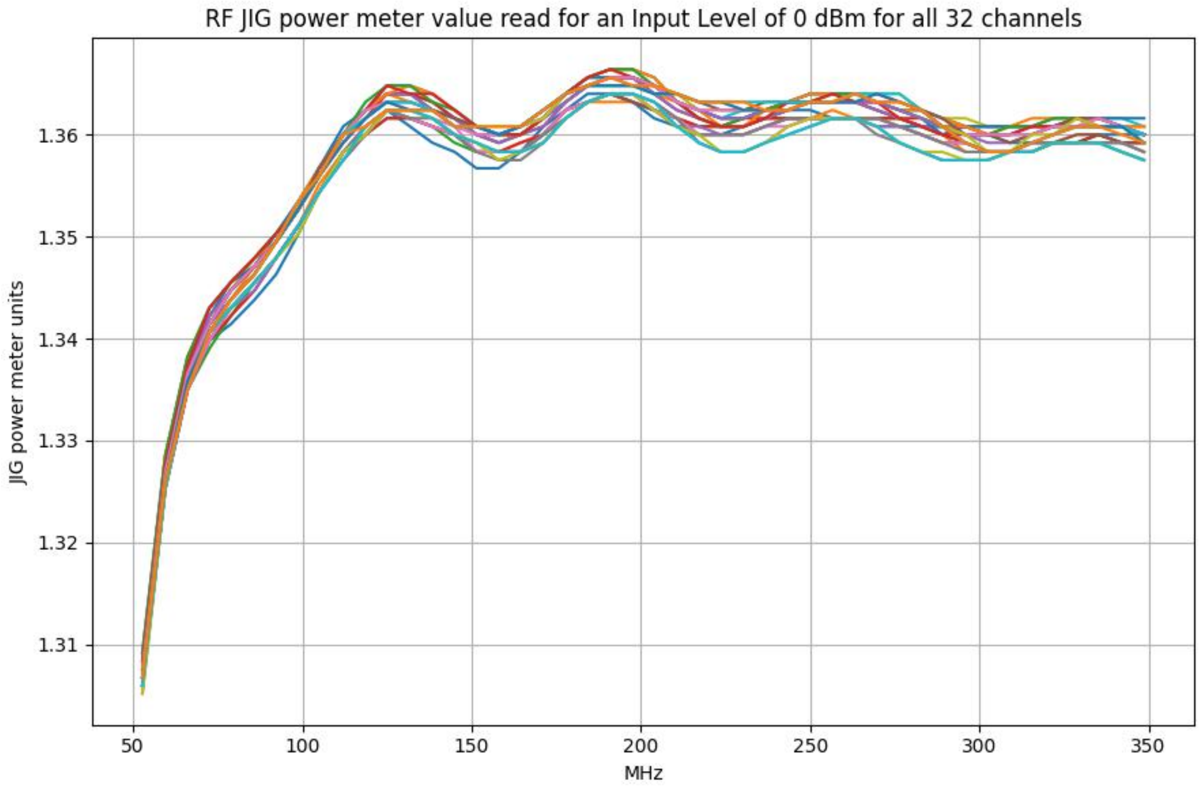

RF JIG Output power of different channels for the Frequency 250.073242 MHz
dBm
JIG Power Sensor Units
CH-00
8
9
10
11
1.74
1.76
1.78
1.80
1.82
1.84
1.86

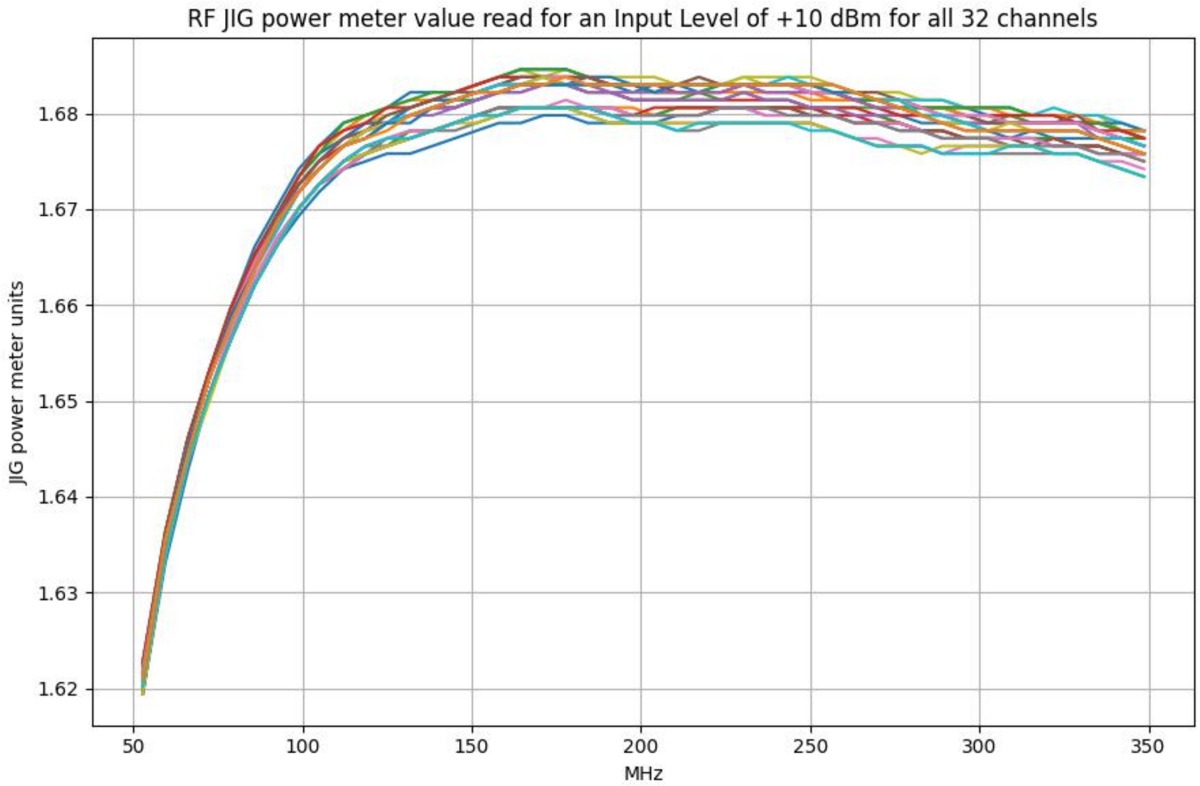

RF JIG Output power of different channels for the Frequency 348.657227 MHz
dBm
JIG Power Sensor Units
CH-00
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
1.76
1.78
1.80
1.82
1.84

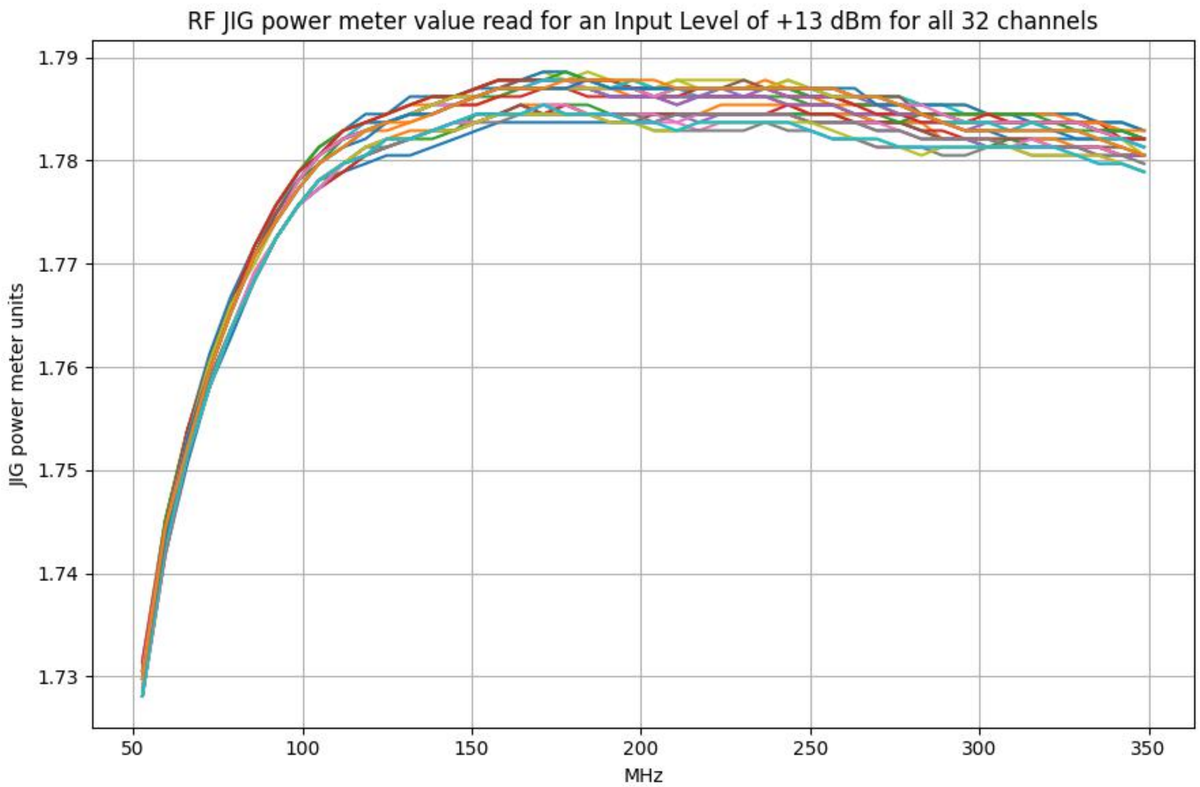
The same behavior by using lines is shown in the next plot.






RF JIG power meter value read for an Input Level of 0 dBm for all 32 channels
JIG power meter units
1.36
1.35
1.34
1.33
1.32
1.31
50
100
150
200
250
300
350
MHz


RF JIG power meter value read for an Input Level of +10 dBm for all 32 channels
JIG power meter units
1.68
1.67
1.66
1.65
1.64
1.63
1.62
50
100
150
200
250
300
350
MHz


RF JIG power meter value read for an Input Level of +13 dBm for all 32 channels
JIG power meter units
1.79
1.78
1.77
1.76
1.75
1.74
1.73
50
100
150
200
250
300
350
MHz

Conclusions

This activity provides the calibration curves for each input channel to compensate for the JIG behavior at different frequencies and input power levels.

Measurements have highlighted that the very first channel (CH-00) has less power than the others (~0.6 dB) and this is due to the different path in the JIG PCB.

The JIG power meter response changes a little bit in the frequency range 50-350 MHz, per input, and per levels. To calibrate this feature single calibration curves are provided for each frequency point.

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