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Testing and selecting of the RFoF links for the Noto radio telescope

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This report has been realized in the frame of the activities
of the Laboratory III: Low Frequency Technology and Receivers

Reviewed by: Federico Perini

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Introduction

In 2018, ten optical links were procured for the Noto radio telescope, with six of these already shipped and installed in the antenna following a selection process conducted between June and October 2018. The decision to install four additional links in 2023 led to this selection process.

The first criterion applied in selecting pairs was to identify links with a gain trace close to 0 dB. It was not possible to pursue this criterion on the basis of the measures adopted, as will be explained and shown in this report. Therefore, it was necessary to adjust the approach and identify pairs that were uniform in terms of gain.

The nominal specifications of the optical links are listed below:

Gain(RF@408MHz): Min = 0dB, Typ = 1dB, Max = 2dB

In-band Gain Variation = max +/-1dB;

Input and output Return Loss > 15dB;

NFmax = 38dB;

OIP3 > +30dBm, **OIP2** > +40dBm

unless otherwise indicated, these are in the 100÷2100MHz band at room temperature and with OTX connected to ORX by means of two 1 or 2m long Single Mode Fiber (SMF) SC/APC fibre pigtails each and a 500m SMF G652D fibre reel with SC/APC connectors.

The four optical links are composed of transmitter (OTX) and receiver (ORX) pairs, which were measured in every possible combination to determine which links have the desired performance in terms of gain.

In short (less than 1km) RFoF links with direct intensity modulation and direct detection, like the ones here under consideration, the RF gain mainly depends on the efficiencies of LASER

and the responsivity of the PD and thus on the combinations of OTX and ORX. These measurements aim to identify the four best possible combinations.

The PCB that houses the RX module provides for the control, via wires that can be connected to a terminal board, of a two-colour LED diode (standard 3mm LED) which is GREEN when the power level is higher than a threshold corresponding to -3 dBm and RED when the optical power level is lower.

The four links belong to a batch of ten links which were produced by the company Protech that were tested between June and October 2018. The best six of the ten links tested in 2018 were selected and sent to Noto.

We had to reconstruct the history of the measurements taken in 2018 in order to compare them with those taken in April 2024. The reference report is a document that was never published but was used as an internal report. Unfortunately, some of the information contained in the technical report was missing, so we had to limit our comparison to the measurements of the S parameters taken in 2024.

1. Measurements setup

1.1 S-Parameters

S-Parameters were measured by performing a two-port measurement using Keysight's PNA-X N5249A.

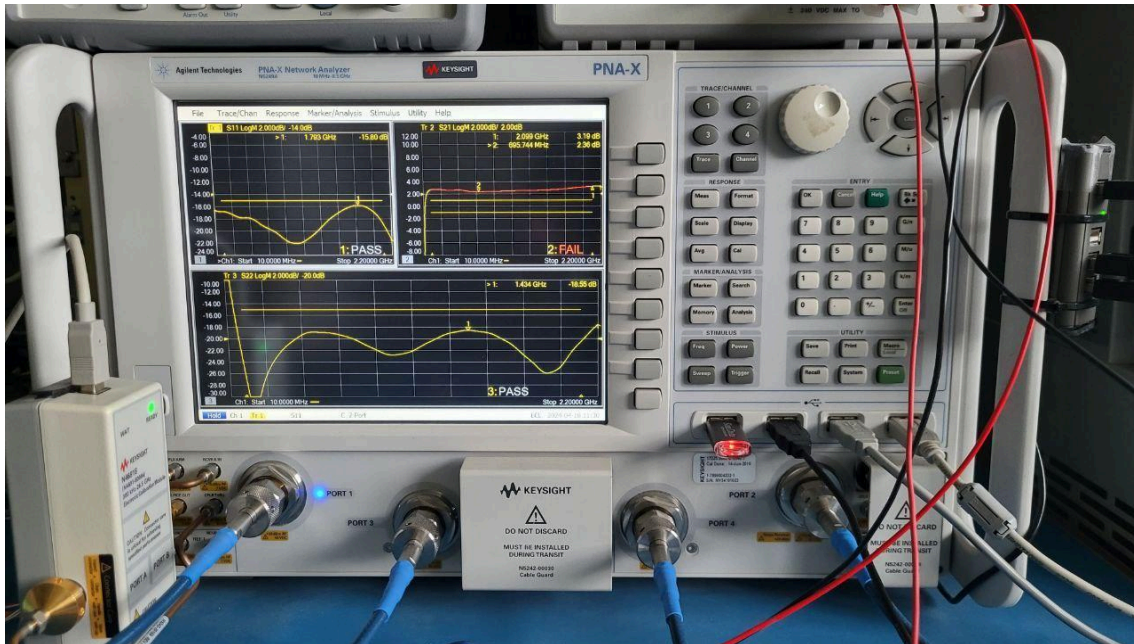


Figure 1: PNA-X

The S-parameters were measured with the following set up:

Calibration file name: S-parameters.csa

Frequency range: 10 MHz - 2.2 GHz

Number of points: 1601

IF Bandwidth: 300 Hz

Calibration was performed using Keysight's E-cal module, model N4431-60008.

The image below illustrates the power settings applied to both Port 1 and Port 2.

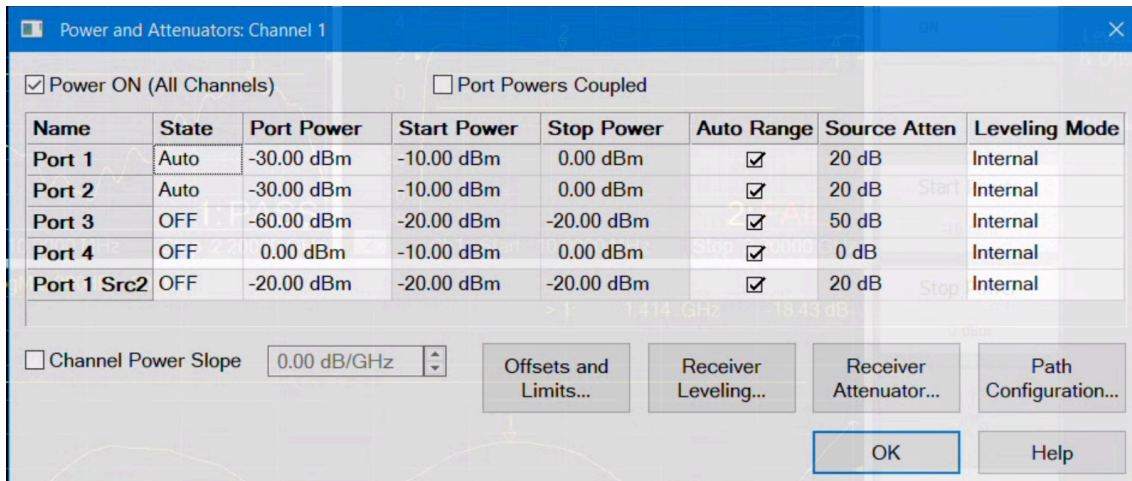


Figure 2: Port power settings

Test bench

In order to measure the two-port S-parameters, the transmitter was connected to Port 1 of the VNA and the receiver to Port 2. The receiver and transmitter were connected directly through a SC/APC-SC/APC adapter.

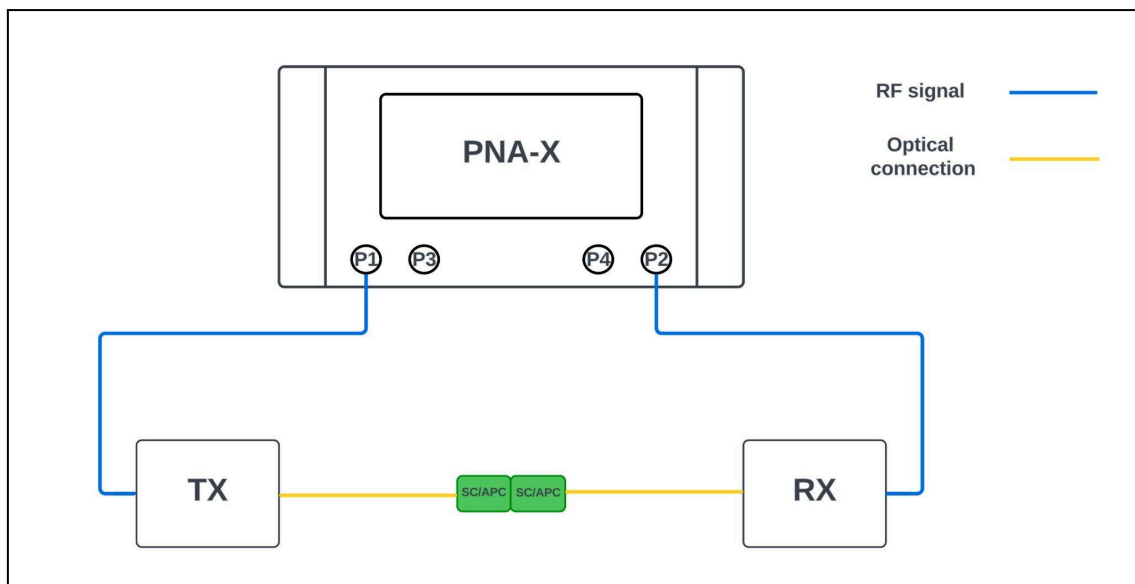


Figure 3: Test bench block diagram

[Note: In the acceptance tests done in 2018, the connection of the links was made with two SC/APC-SC/APC jumpers.]

There are two serial numbers on each OTX and ORX: E00XX refers to the photodiode for receivers and the laser serial number for transmitters, while 3618000X refers to the entire

receiver or transmitter. The last four digits of the transmitter and receiver serial numbers will be used for identification in this report.

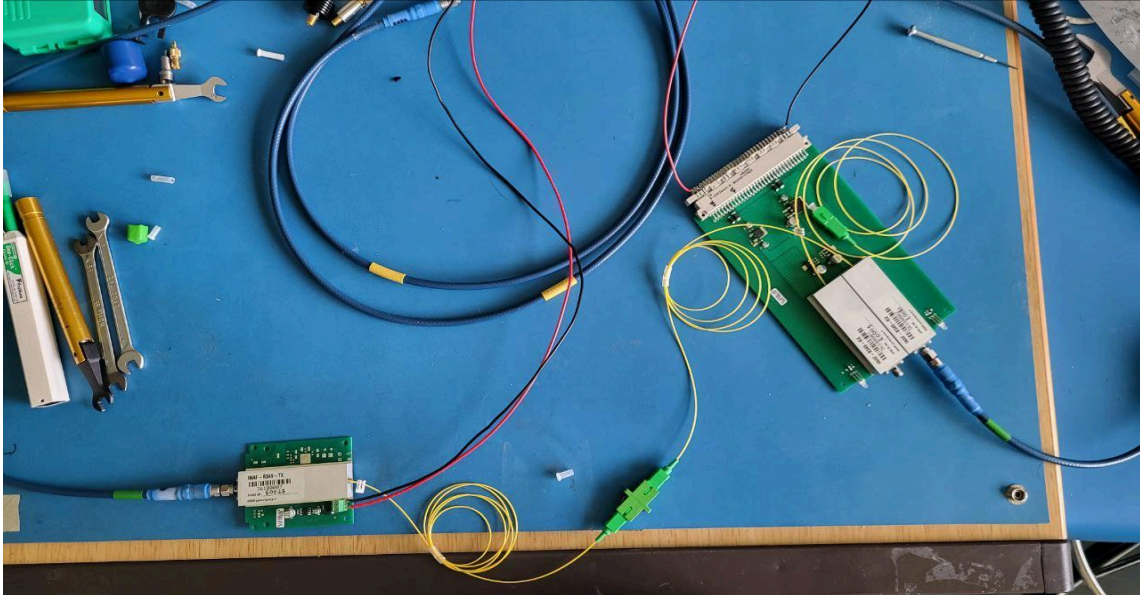


Figure 4: OTX and ORX connected on the test bench

The OTX-ORX pairs that make up the links selected for best gain will be named with the letters A,B,C,D, to easily identify them.

1.2 Noise Figure

The Noise Figure was measured by performing a vectorial noise figure calibration using Keysight's PNA-X N5249A. The E-Cal module used for calibrating the S parameters is the Keysight N4431-60008. The module used as a tuner is the N4691B. The NF receiver calibration was performed using the USB Average Power Sensor model U2004A from Keysight.

Calibration file name: Noise.csa

Frequency range: 10 MHz - 2.2 GHz

Number of points: 1601

☒ Power ON (All Channels) ☐ Port Powers Coupled

Name	State	Port Power	Start Power	Stop Power	Auto Range	Source Atten	Leveling Mode
Port 1	Auto	-10.00 dBm	-30.00 dBm	-30.00 dBm	☒	0 dB	Internal
Port 2	Auto	-10.00 dBm	-10.00 dBm	0.00 dBm	☒	0 dB	Internal
Port 3	Auto	-30.00 dBm	-40.00 dBm	-30.00 dBm	☐	20 dB	Internal
Port 4	Auto	-30.00 dBm	-40.00 dBm	-30.00 dBm	☐	20 dB	Internal
Port 1 Src2	Auto	-30.00 dBm	-30.00 dBm	-30.00 dBm	☐	0 dB	Internal

☐ Channel Power Slope 0.00 dB/GHz

Offsets and Limits... Receiver Leveling... Receiver Attenuator... Path Configuration...

OK Help

Figure 5: Noise Figure calibration power setup

Frequency Power Noise Figure

Bandwidth/Average
 Noise Bandwidth: 4.0 MHz
 Average Number: 16
☒ Average ON
☐ Use Narrowband Compensation (available if noise BW <= 4 MHz)

Noise Receiver
☐ NA Receiver (Port 2)
☒ Noise Receiver Gain Low
☐ External Noise Amplifier -- Sweep Delay 500.00 msec

Source Temperature
 300.00 K
☒ Use 302K for Vector Noise Cal with internal/ECal tuner

Impedance States
 Noise Tuner: N4691-60004 ECal 13646
 Max Acquired Impedance States: 4

OK Annulla Applica ?

Figure 6: Noise Figure setup

1.3 Output IP3 and IP2

The two-tone measurement technique is widely used to evaluate the linearity of RF components, by quantifying their tendency to generate intermodulation distortion. In this method, two signals of equal amplitude, at frequencies f_1 and f_2 , are simultaneously applied to the input of the device under test (DUT). The two input tones were generated with the PNA-X, the output is observed

using a spectrum analyzer, which displays not only the fundamental tones at f_1 and f_2 , but also additional spectral components resulting from the device's nonlinear behavior.

Of particular interest are the third-order intermodulation (IM3) products, which appear at frequencies $(2f_1 - f_2)$ and $(2f_2 - f_1)$. These IM3 products are critical because they often fall within the system's operating band and can interfere with desired signals. The severity of the nonlinearity is characterized by the Output Third-Order Intercept Point (OIP3), which is a hypothetical output power level where the extrapolated power of the fundamental output and the IM3 products would intersect. Mathematically, OIP3 is determined using the measured output power of the fundamental tone (P_1 , in dBm) and the IM3 product (P_3 , in dBm), according to the formula:

$$\text{OIP3} = P_1 + (P_1 - P_3)/2$$

This relationship arises because the IM3 products increase at three times the rate of the fundamentals as the input power increases.

To simplify the calculation of the OIP3 measurement, Two power tones were generated to achieve an output power level of the DUT of 0dBm so that the marker could read a single value to be divided by 2 to obtain the measurement. Similarly, the Output Second-Order Intercept Point (OIP2) is used to quantify second-order nonlinearity, which produces intermodulation products at frequencies such as $(f_1 + f_2)$ or $(f_2 - f_1)$, and harmonics at $2f_1$ or $2f_2$. OIP2 is calculated using the measured output power of the fundamental (P_{fund}) and the second-order product (P_{IM2}):

$$\text{OIP2} = P_1 + (P_1 - P_2)$$

For both OIP3 and OIP2 measurements, it is essential to ensure that the spectrum analyzer (Anritsu Spectrum Master MS2726C) is not overloaded, for these measurements, a 30 dB input attenuation was selected to ensure optimal performance. The two-tone method thus provides a quantitative assessment of device linearity, which is crucial for predicting system performance in the presence of multiple signals. In this setup, the two tones were generated by the two sources of the PNA-X and fed into the OTX via Port 1 through the internal combiner of the vector analyser, the spectrum analyser was connected to the ORX output. The following figures show the spectrum analyser acquisition screen of the OIP3 and OIP2 measurements.

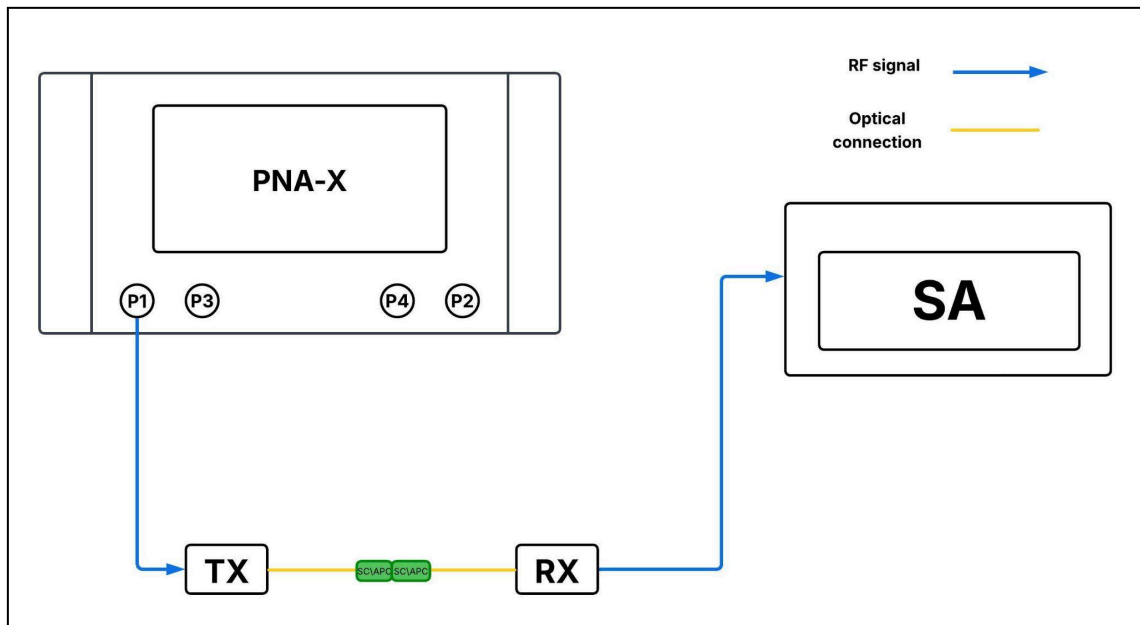


Figure 7: OIP3 and OIP2 measurement setup block diagram

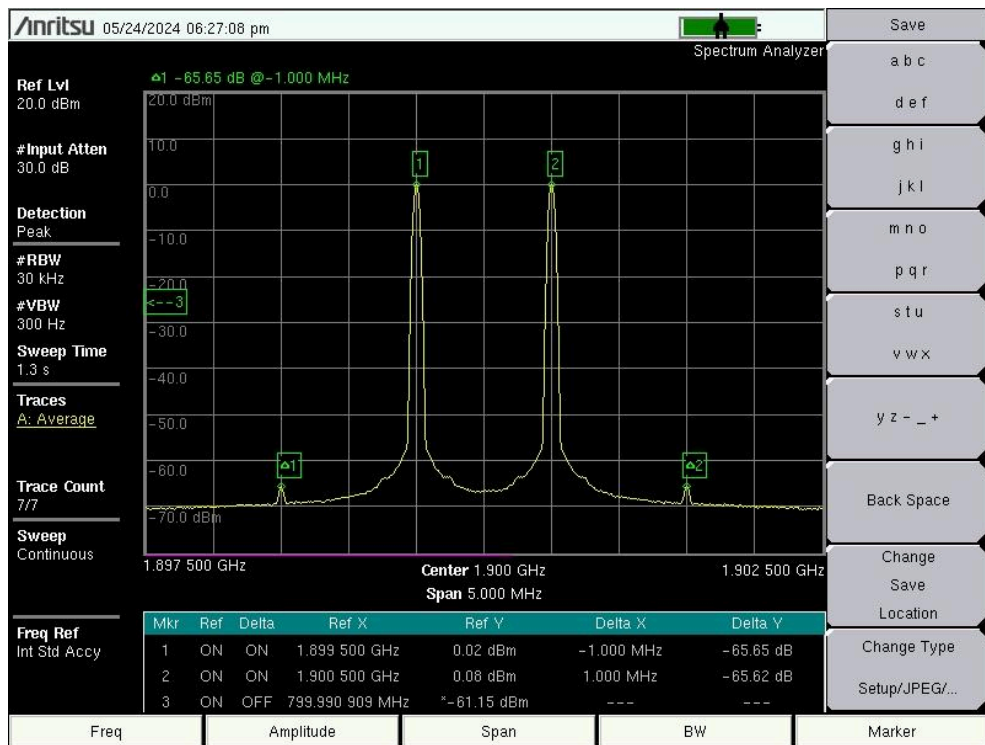


Figure 8: OIP3 measurement on Anritsu Spectrum Master

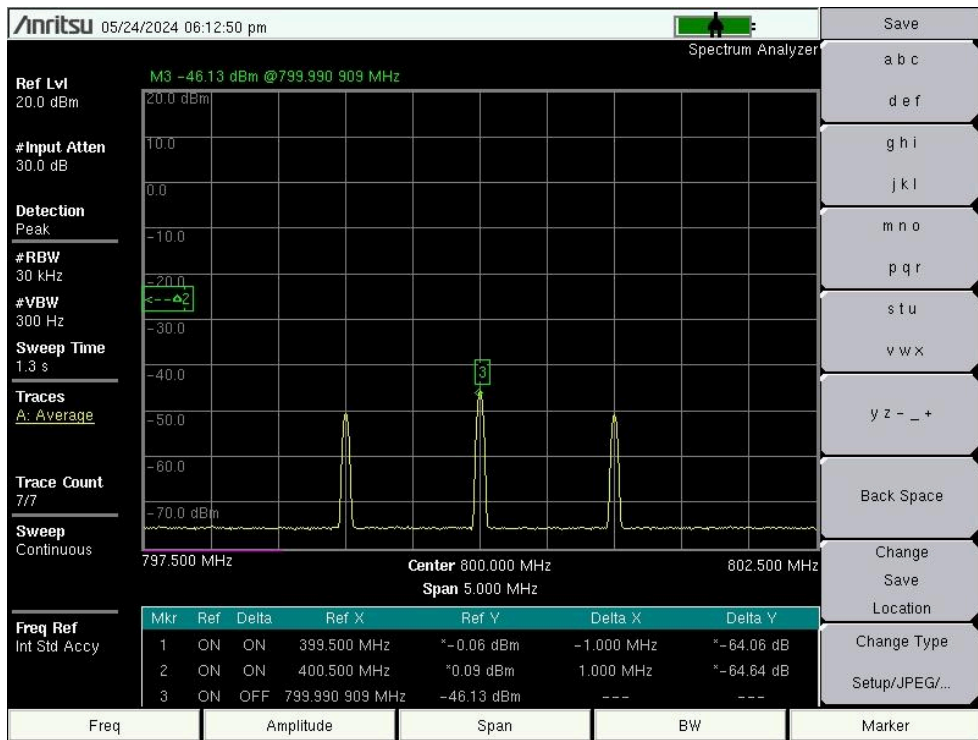


Figure 9: OIP2 measurement on Anritsu Spectrum Master

2. Results

This section provides a comprehensive overview of S-parameter, Noise Figure, OIP3 and OIP2 measurements conducted on the optical links.

2.1 S-Parameters

The plot below shows all the gain measurements of the possible sixteen combinations of OTX and ORX.

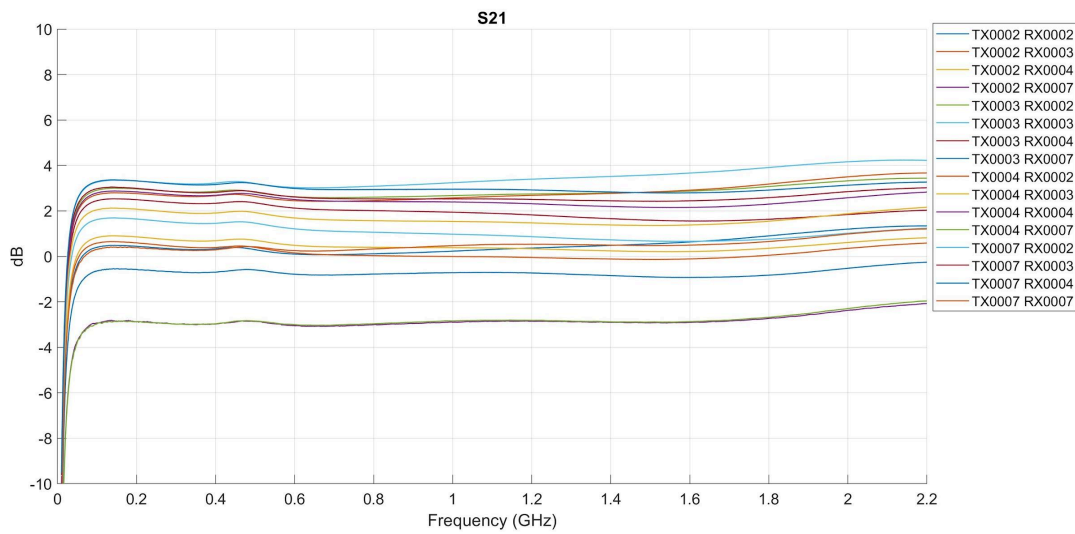


Figure 10: Gain (dB) measurement of allTX-RX combinations

In order to determine the gain of the individual transmitter and receivers, preliminary measurements were carried out by connecting each OTX to the same passive ORX (Andrew TFRY501), and each ORX to an OTX that had been characterised previously (W00780 produced by Protech for INAF).

Results are shown in the following S21 plot.

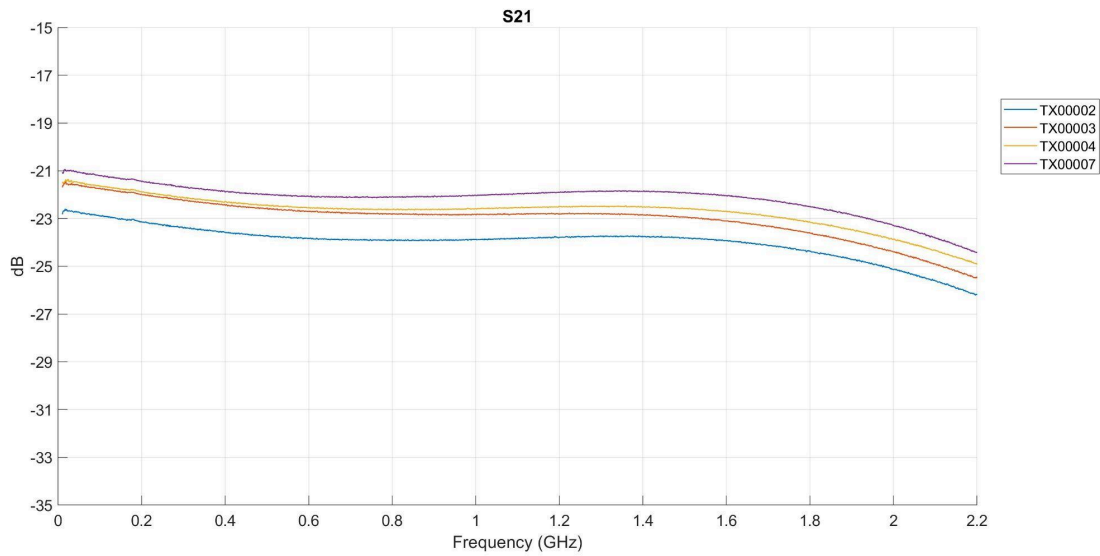


Figure 11: Gain (dB) of TX00xx_TFRY501

The graph in Fig. 11 shows that the optical transmitters have a similar gain curve. The contribution of ORX to the OTX response can be appreciated by considering the peaks at 500 MHz that can be seen in Fig.10 and that are not present in Fig.11 and the general trend of the curves. It can be seen that the offset between the OTX with the highest gain (OTX00007) and the one with the lowest gain (OTX00002) is around 2 dB.

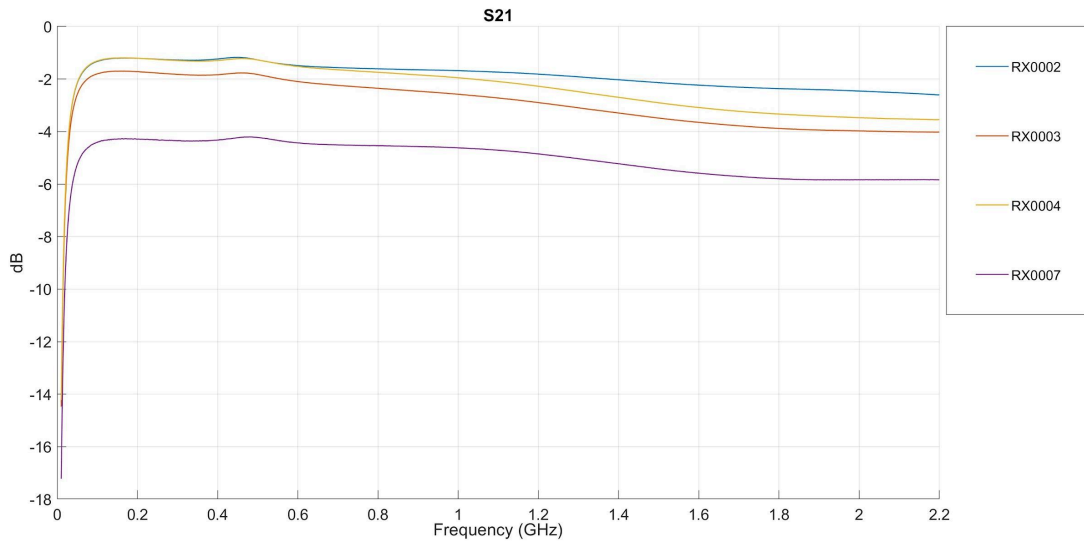


Figure 12: Gain (dB) of W00780_RX00XX

In Fig. 12 the four receivers demonstrate different behaviours. RX00002, RX00003 and RX00004 demonstrate minimal insertion loss (ranging from approximately -2 to -4 dB), while maintaining

a relatively consistent response within the 0.2 to 2 GHz range. In contrast, RX0007 demonstrates a more substantial loss, with values around -6 dB. All receivers show a slight downward slope with frequency.

These data were used to identify the best pairs that make up the RFoF links, as shown in Fig. 13.

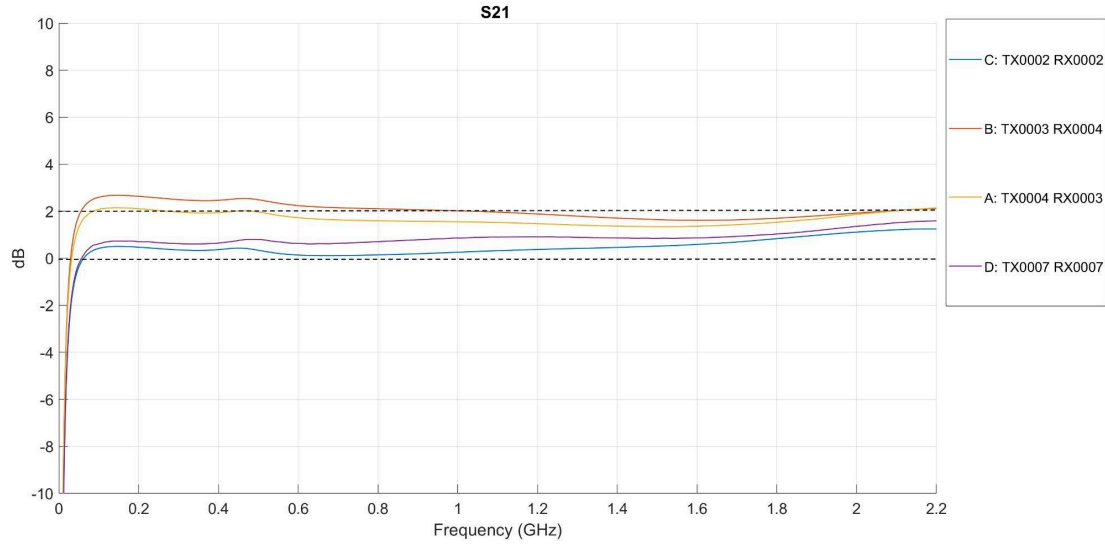


Figure 13: Selected OTX-ORX pairs

The dotted lines in the graph in Fig. 13 indicate the minimum and maximum gain specifications mentioned in the introduction.

It is important to note that the measurements were taken with a direct OTX-ORX connection and without the two jumpers and 500m of fibre in between. According to the calculations we have carried out, the use of three additional adapters would result in an additional loss of about 0.6 dB to be added to the measurements, given the optical losses of 0.1 dB associated with each adapter. Consequently, the measurements are found to be in compliance with the specified range of 0-2 dB.

For all four combinations, the specification for maximum gain variation within the band of ± 1 dB is also met.

A label was applied to each device associating each optical link with a letter as shown in the following Table 1.

RFoF link identification letter	OTX S/N	ORX S/N
A	TX0004	RX0003
B	TX0003	RX0004
C	TX0002	RX0002
D	TX0007	RX0007

Table 1: OTX-ORX pairs

After selecting the pairs based on the gain measurements, the other qualification measurements were performed to verify the specifications of the four selected optical links.

The dotted lines in the graphs in Figs. 14 and 15 indicate the input and output return loss specifications mentioned in the introduction ($|S_{11}| < -15$ dB and $|S_{22}| < -15$ dB).

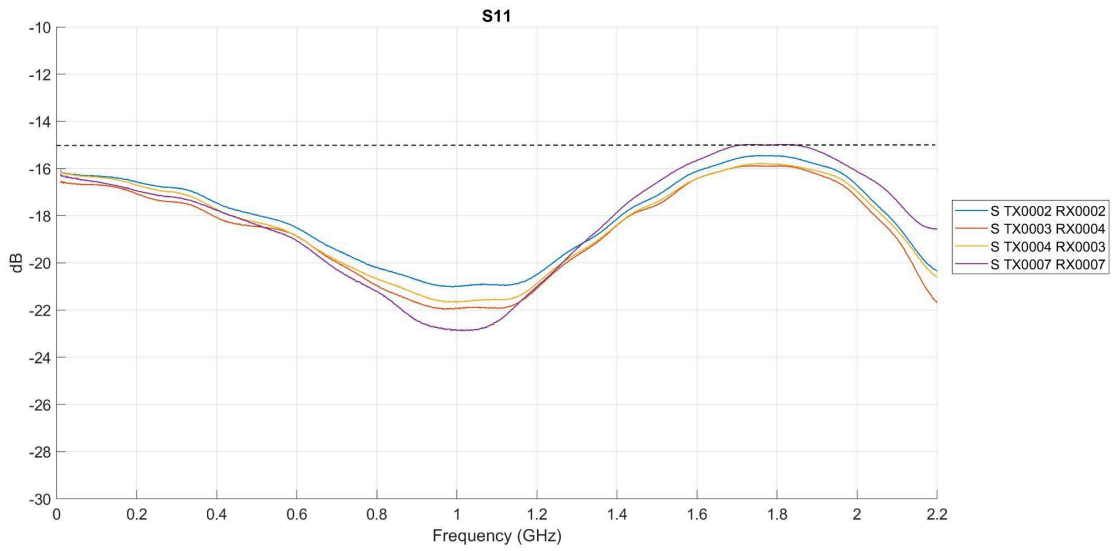


Figure 14: Input Return Loss (dB) of the four selected links

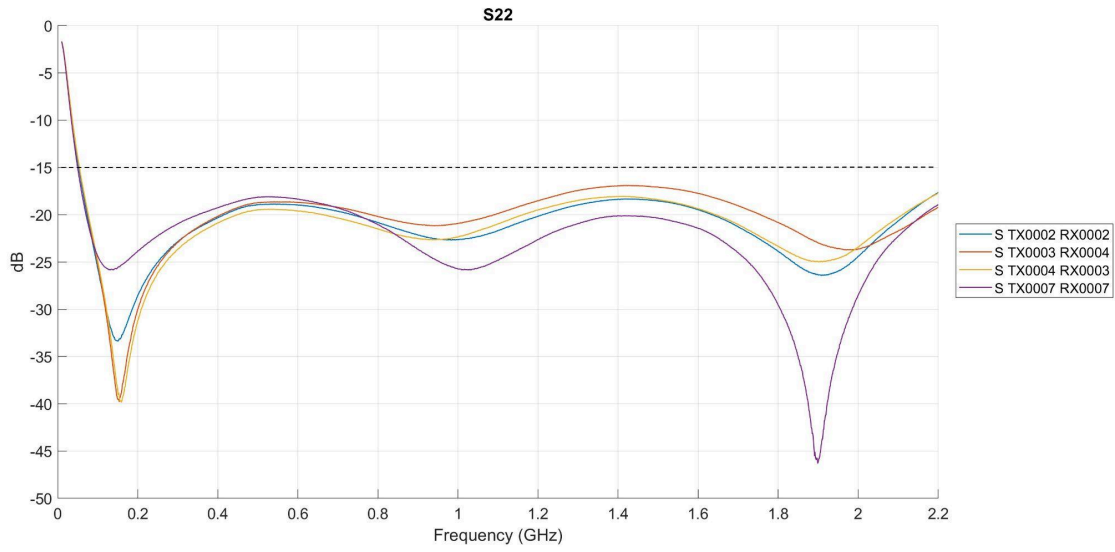


Figure 15: Output Return Loss (dB) of the four selected links

The measurements show that all four links meet the required specifications.

2.2 Noise Figure

The dotted line in the graph in Fig. 16 indicates the requirement for the Noise Figure, which is largely met since all traces are below 38 dB.

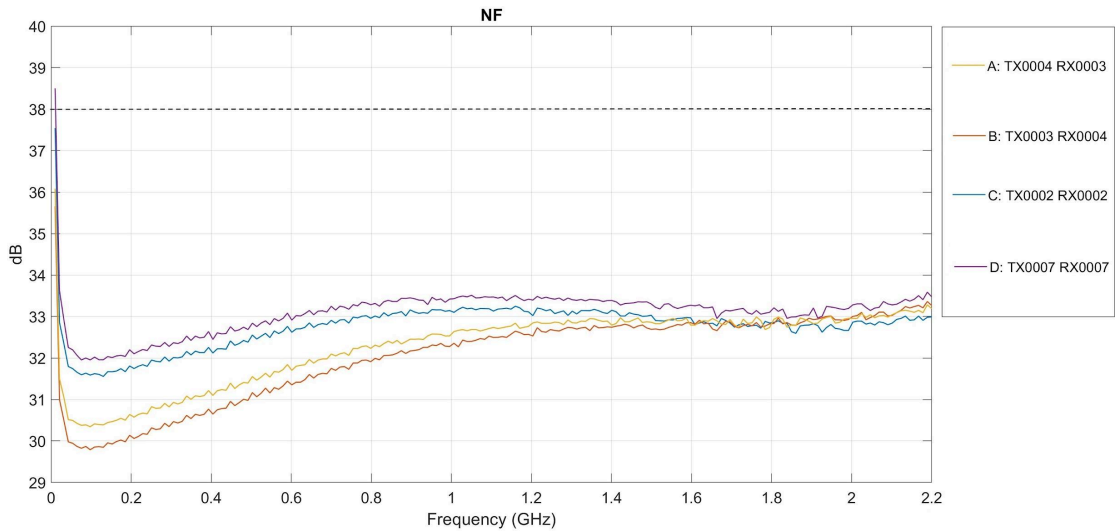


Figure 16: Noise Figure (dB) measurements of the selected optical links

[Note: It has been determined that the optical connection between optical transmitters and receivers affects the repeatability of S21 and Noise Figure measurements. This characteristic is

attributable to the quality of the SC/APC connectors used, although the links still meet the required specifications.]

2.3 Output IP3 and IP2

The OIP3 and OIP2 measurements comply with the specified requirements, as the OIP3 measurements are always greater than +30 dBm and the OIP2 measurements are always greater than +40 dBm.

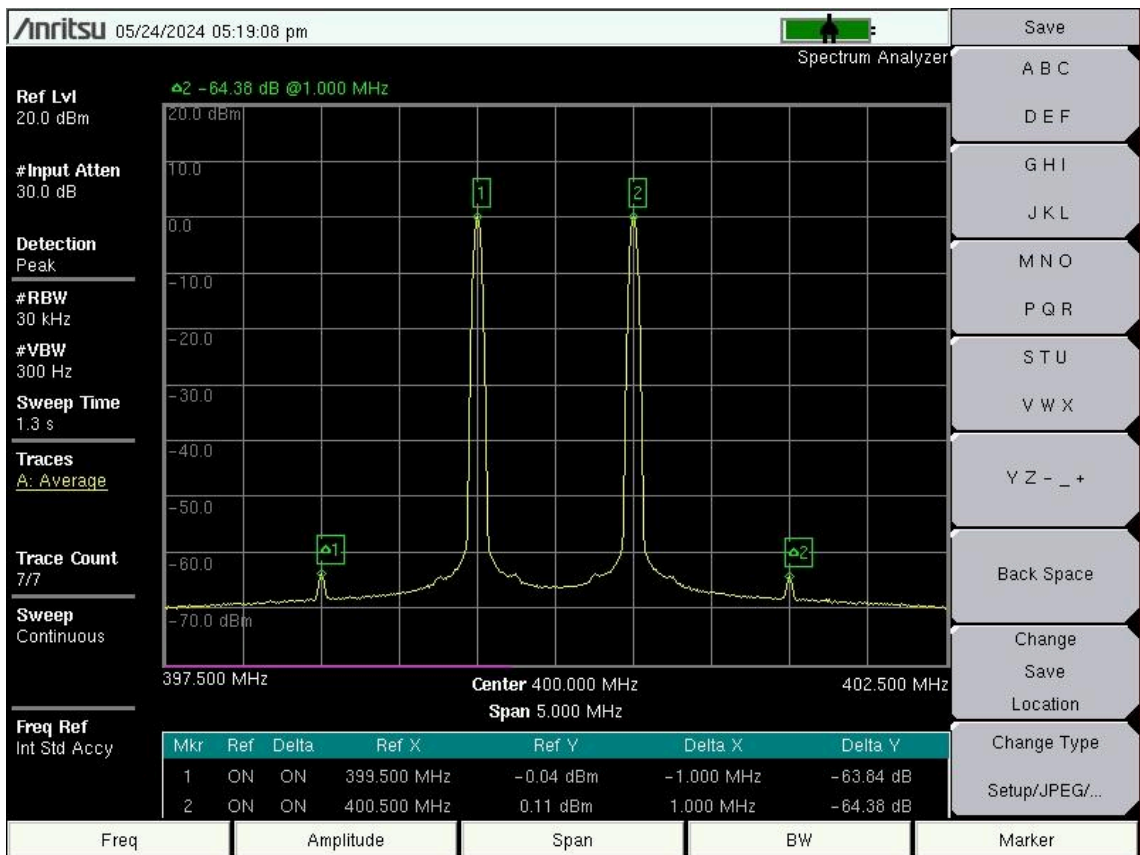


Figure 17: OIP3 measurement with SA of OTX0002_ORX0002 link

As shown in Fig.17 the spectrum analyzer displays two main peaks at 399.5 MHz and 400.5 MHz, which are the fundamental tones injected into the DUT.

At frequencies slightly offset from the fundamentals (here, 398.5 MHz and 401.5 MHz), the smaller peaks are the third-order intermodulation products (IM3). Their presence is due to nonlinearities in the DUT.

Marker 1 (M1) is set on the lower main tone (399.5 MHz), and a delta marker (Δ M1) is used to measure the amplitude of the lower IM3 product at 398.5 MHz.

Marker 2 (M2) does the same for the higher tone (400.5 MHz) and the higher IM3 product at 401.5 MHz.

The OIP3 value is calculated with the formula:

$$\text{OIP3} = P_1 + (P_1 - P_3)/2$$

P₁: Power level of a fundamental tone at the DUT output (set here close to 0 dBm).

P₃: Power level of the IM3 product (read through the delta marker).

When measuring OIP3, it is not always possible for practical reasons to generate or maintain the main tones exactly at 0 dBm. However, it is still possible to perform an accurate measurement by applying the above formula, because the values taken into consideration differ from each other by values in the order of tenths of a dBm, which does not affect the accuracy of the measurement.

From Fig. 17, Marker 1 at 399.5 MHz reads -0.04 dBm, and the IM3 at 398.5 MHz is -63.84 dBm. The same process is repeated with Marker 2. Applying the formula gives an OIP3 value of approximately +32 dBm.

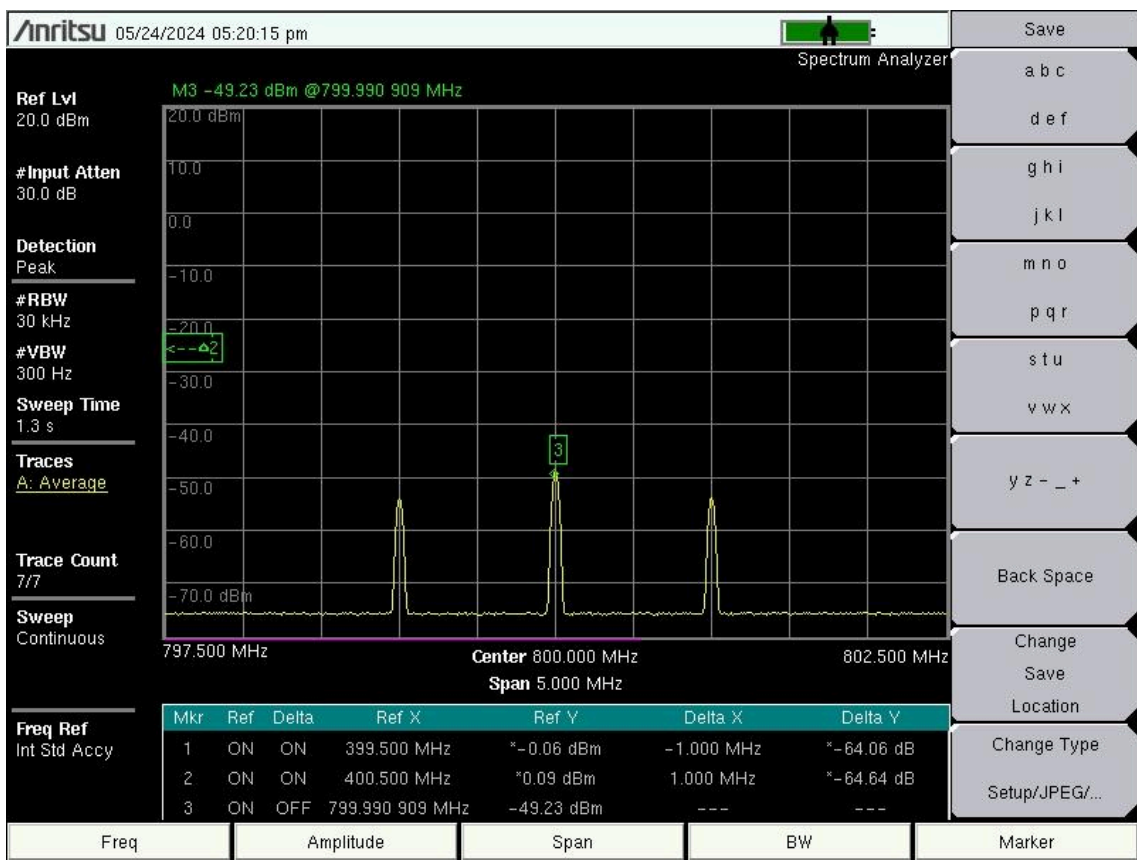


Figure 18: OIP2 measurement with SA of OTX0002_ORX0002 link

Figure 18 shows the OIP2 measurement. Marker 3 is used to read the P2 value (at 800 MHz) used in the following formula:

$$\text{OIP2} = P_1 + (P_1 - P_2)$$

As we already know, P1 in this case is approximately 0 dBm, so the OIP2 value is approximately +49.2 dBm.

The values of all measurements performed are shown in Table 1 for OIP3 values and Table 2 for OIP2 values.

Freq (MHz)	TX0004_RX0003 (dBm)	TX0003_RX0004 (dBm)	TX0002_RX0002 (dBm)	TX0007_RX0007 (dBm)
400	32.8	32.5	32	30.2
1900	33.5	32.8	31	30

Table 2: OIP3 (dBm) measurements of the selected optical links

Freq (MHz)	TX0004_RX0003 (dBm)	TX0003_RX0004 (dBm)	TX0002_RX0002 (dBm)	TX0007_RX0007 (dBm)
400	57.8	46.1	49.2	54.1

Table 3: OIP2 (dBm) measurements of the selected optical links

Following the selection of the OTX-ORX pairs, they were identified using special labels in order to avoid errors in their installation and connection, as shown in Figures 19 and 20.

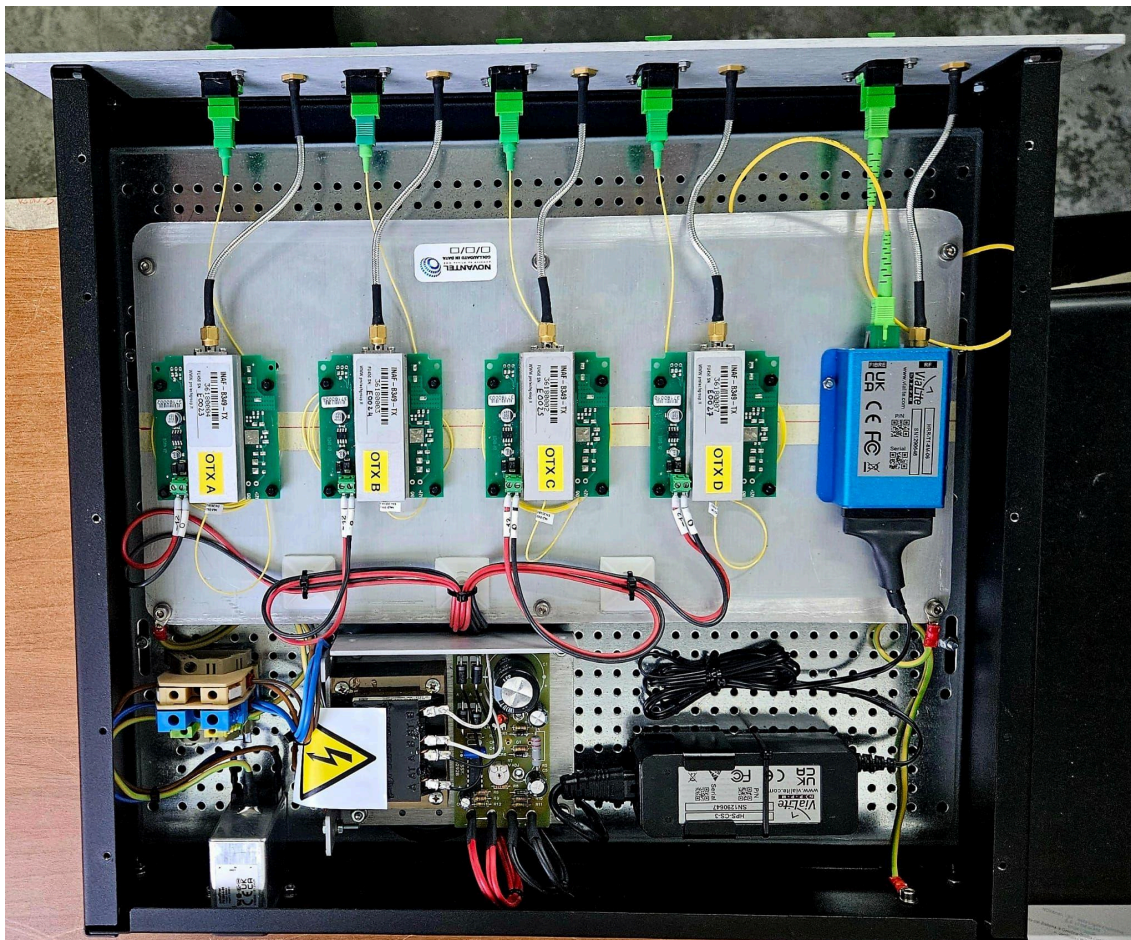


Figure 19: OTX with labels

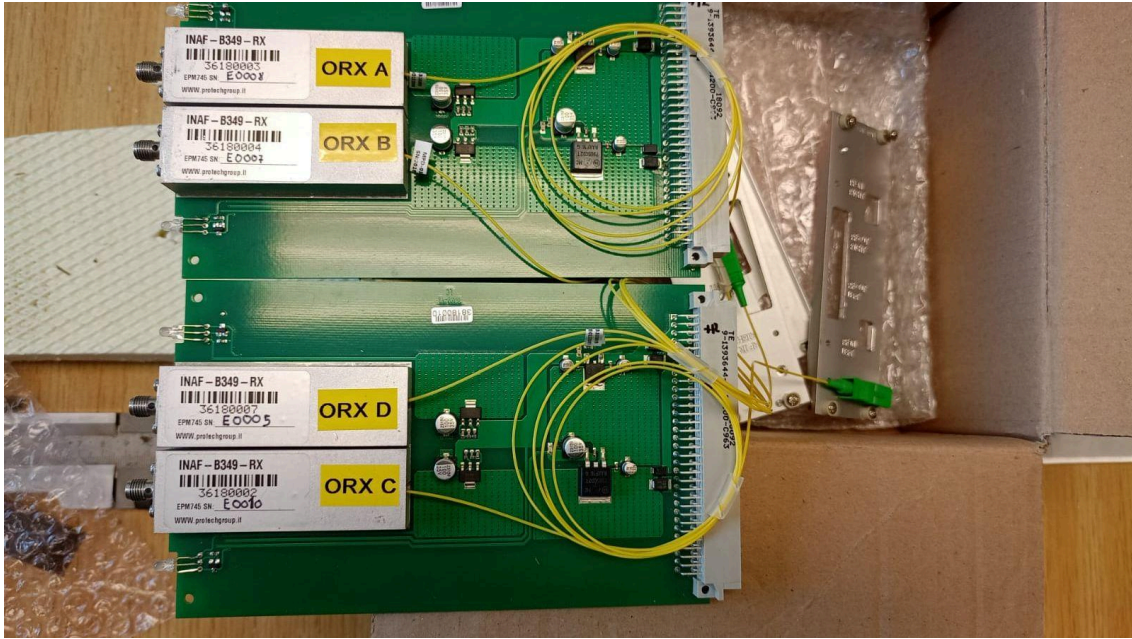


Figure 20: ORX with labels

Conclusions

The primary objective of these measurements was to identify the four most effective OTX-ORX combinations to facilitate the completion of the installation at the Noto radio astronomy station. Measurements confirmed that the four links met the required specifications, so delivery and installation proceeded in Noto.