Study and Design of **18GHz Wideband Analog Optical Link** and **Fiber Transfer Delay Measurement System** for millimeter-wave VLBI INAF antennas

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DI ASTROFISICA

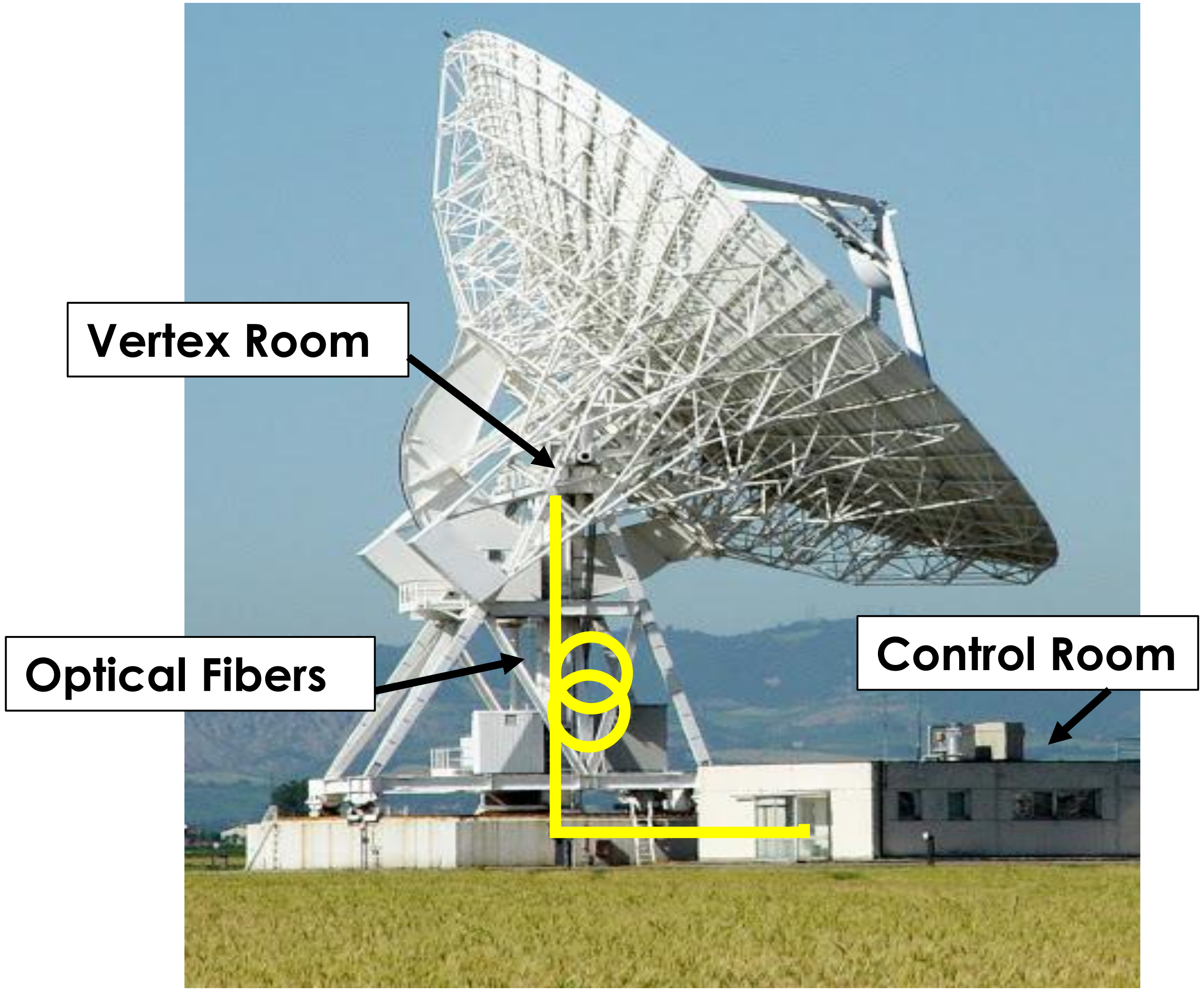
Aim of the talk

To present the joint activities of the microwave photonics group of University of Bologna (UniBo) and IRA-INAF for the realization of a **18GHz wideband analog optical downlink** system of the VLBI antenna in Medicina and a **Fiber transfer delay measurement system (FTDMS)**

Outline

- Introduction to **mm-W VLBI INAF Antennas**
- Design of **18 GHz Analog Optical Fiber Downlink** for INAF VLBI Antennas
- Design of **Antenna Downlink Fiber Transfer Delay Measurement System (FTDMS)**
- Conclusions and perspectives

Current Needs for INAF VLBI antennas



- Recent upgrade of Medicina and Noto INAF dishes to reach **up to 100 GHz operations**
- Installation of Tri-Band IF receivers to perform observation in **K band, Q band and W band**
- Each IF receiver provides **1-18 GHz** output at the Vertex Room
- **Digital Acquisition System** located at the Control Room

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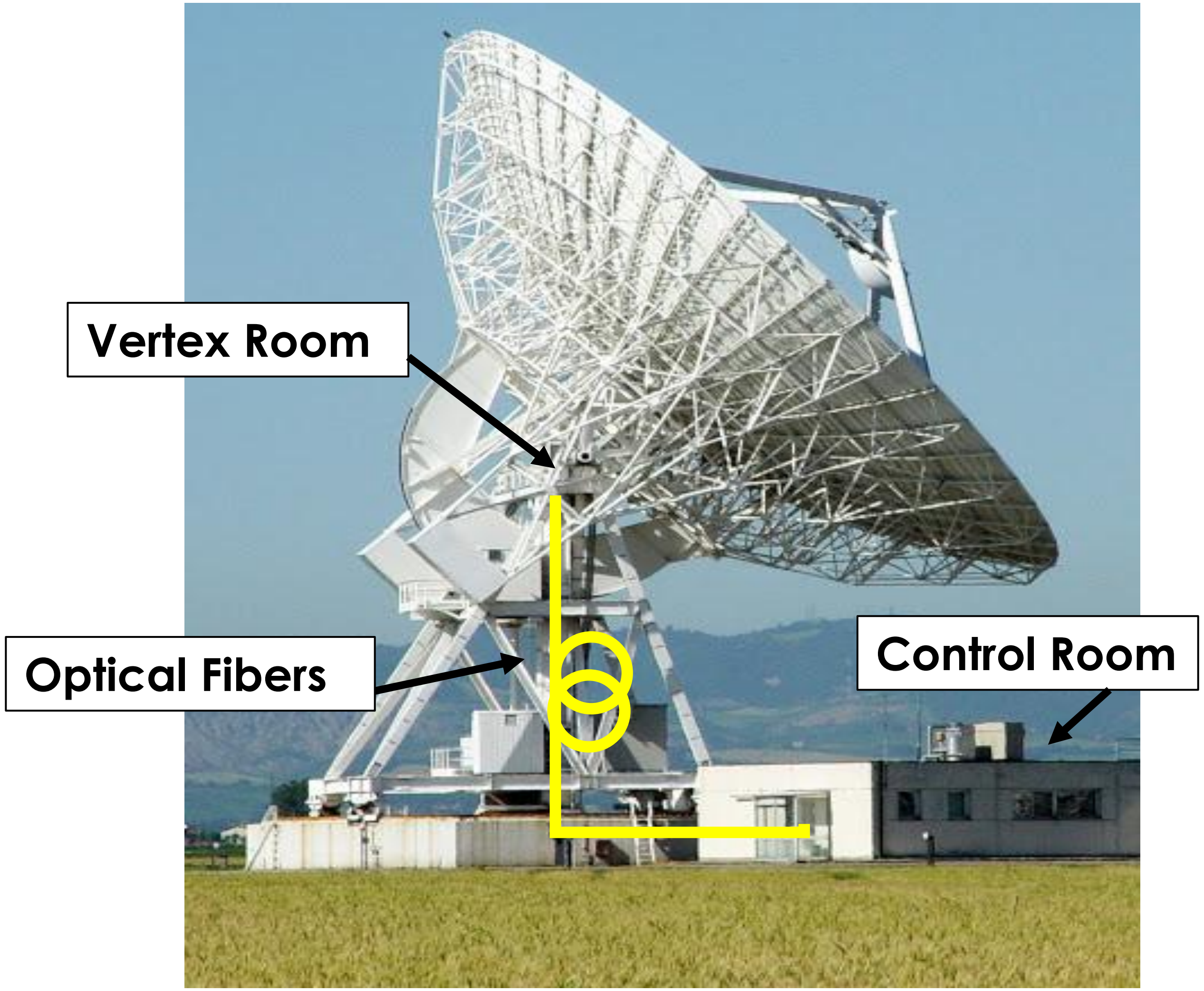

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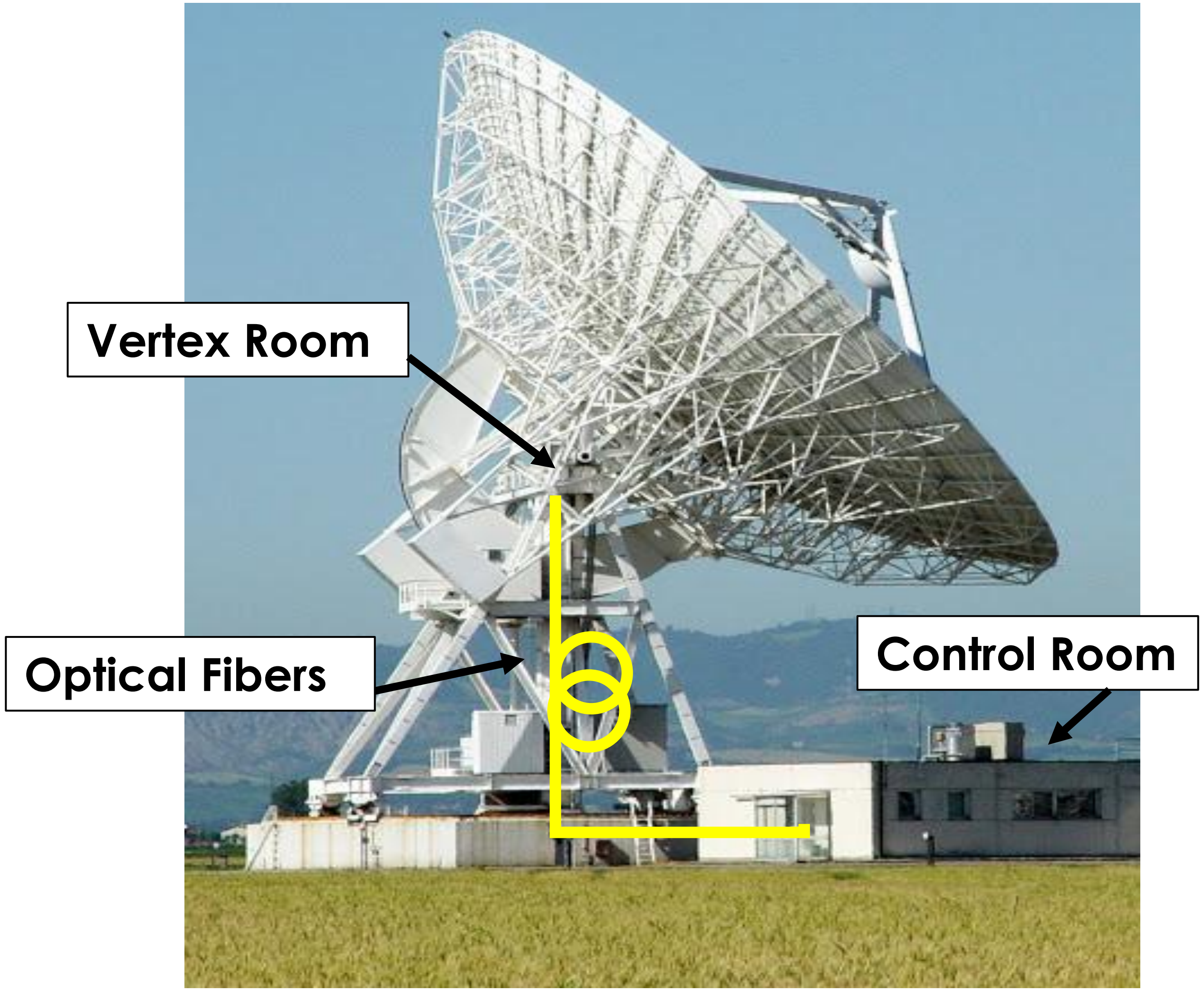

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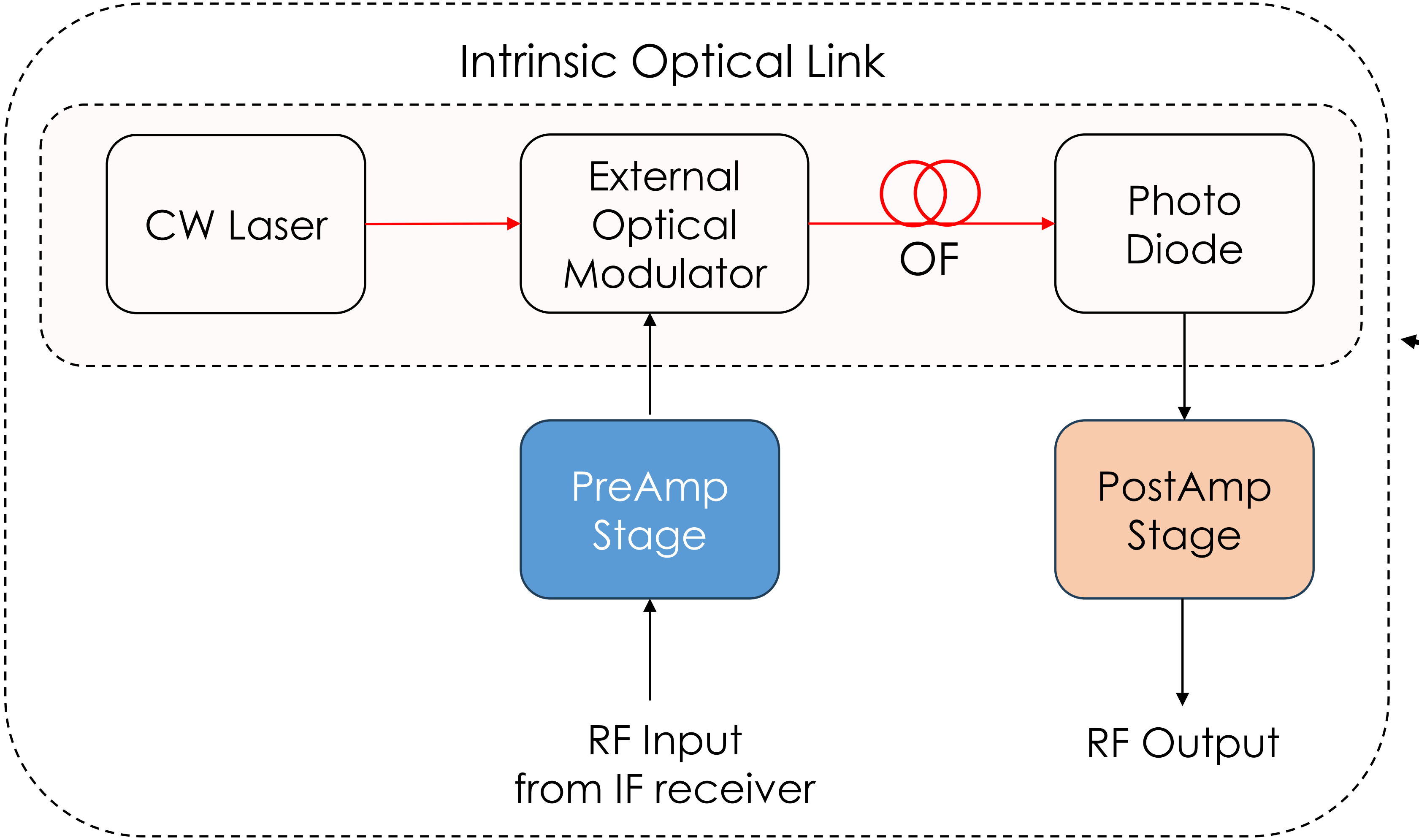
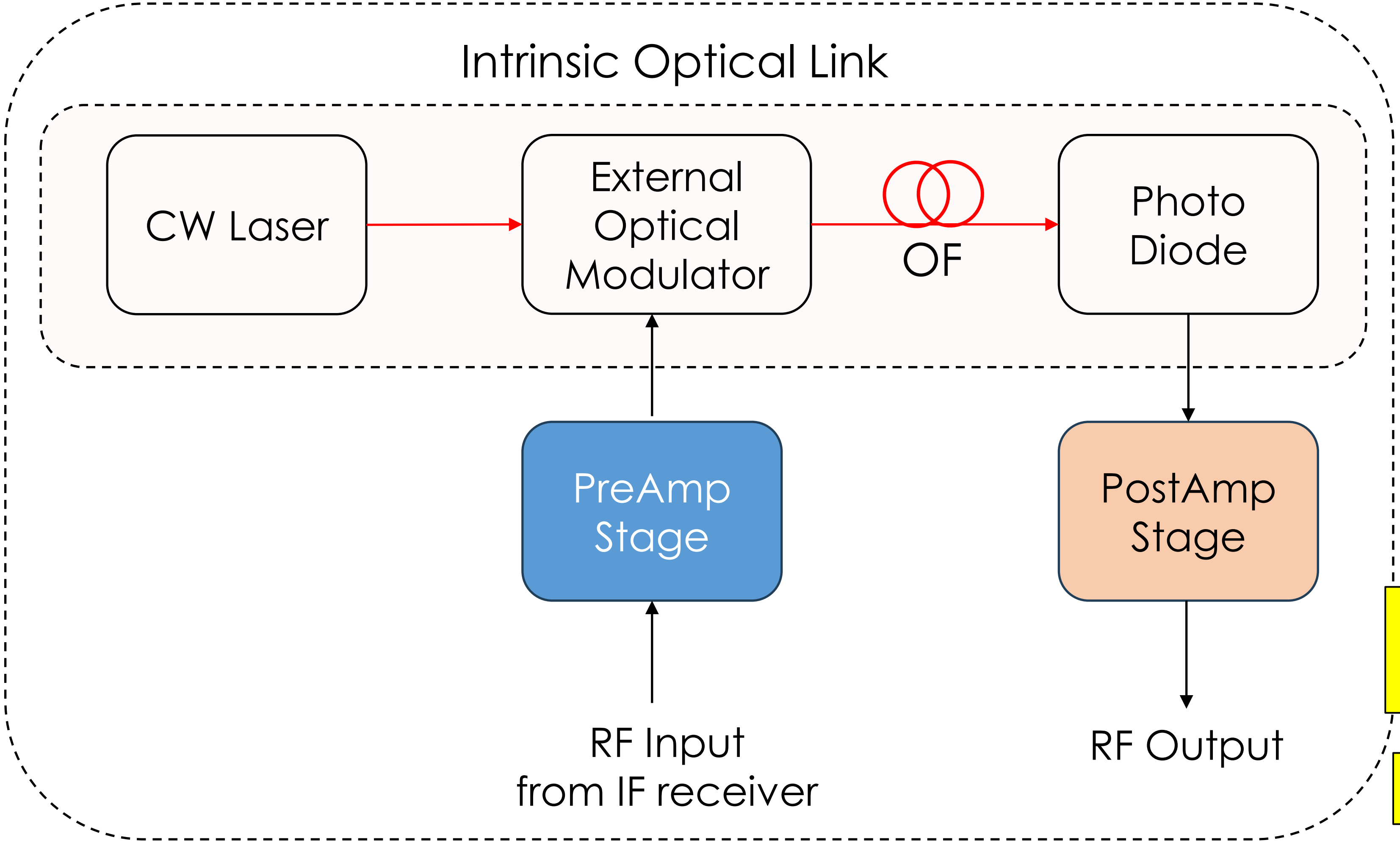
18 GHz Wideband Optical Fiber Link

Analog Optical Fiber Link



18 GHz Wideband Optical Fiber Link

Analog Optical Fiber Link



System already installed for SRT with an external committment

Requirements? Performances?

Requirements and Current Status: SRT

Specs required for SRT (External Commitment)

Parameter	Value	Unit
Frequency band	1-18	GHz
Gain (mean value in band)	14 ± 2.5	dB
Gain Smoothness	±1 (on 2GHz bandwidth)	dB
Input Return Loss	>10	dB
Output Return Loss	>10	dB
Input P1dB*	***>-11 (-6)***	***dBm***
Input IP3	>-11	dBm
Input IP2	>-11	dBm
NF	***<6***	***dB***
Cost	***<17.5***	***K€***

* -6 dBm was the original specification which has been relaxed to **-11dBm because the spec was not reachable with COST system**

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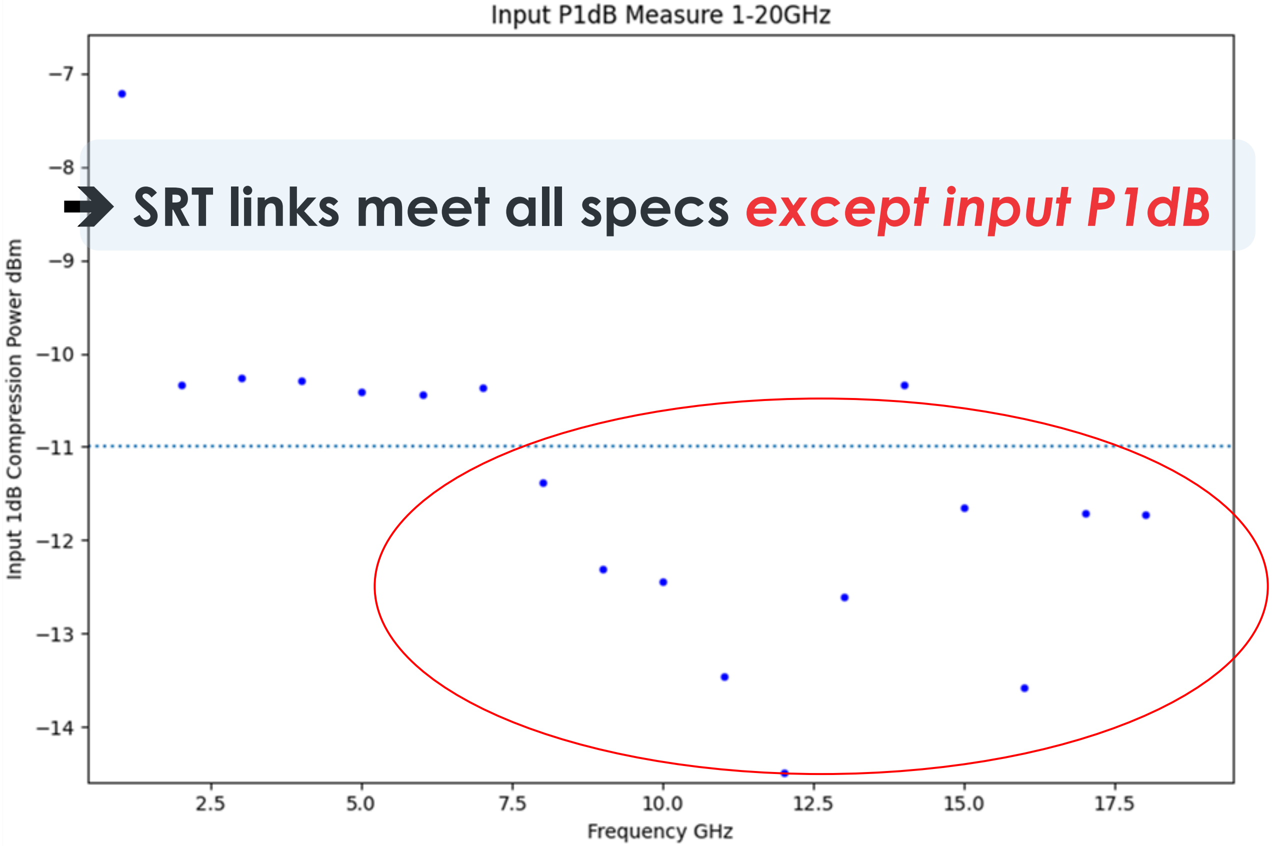
Example of Input P1dB measurement of SRT link no. 1

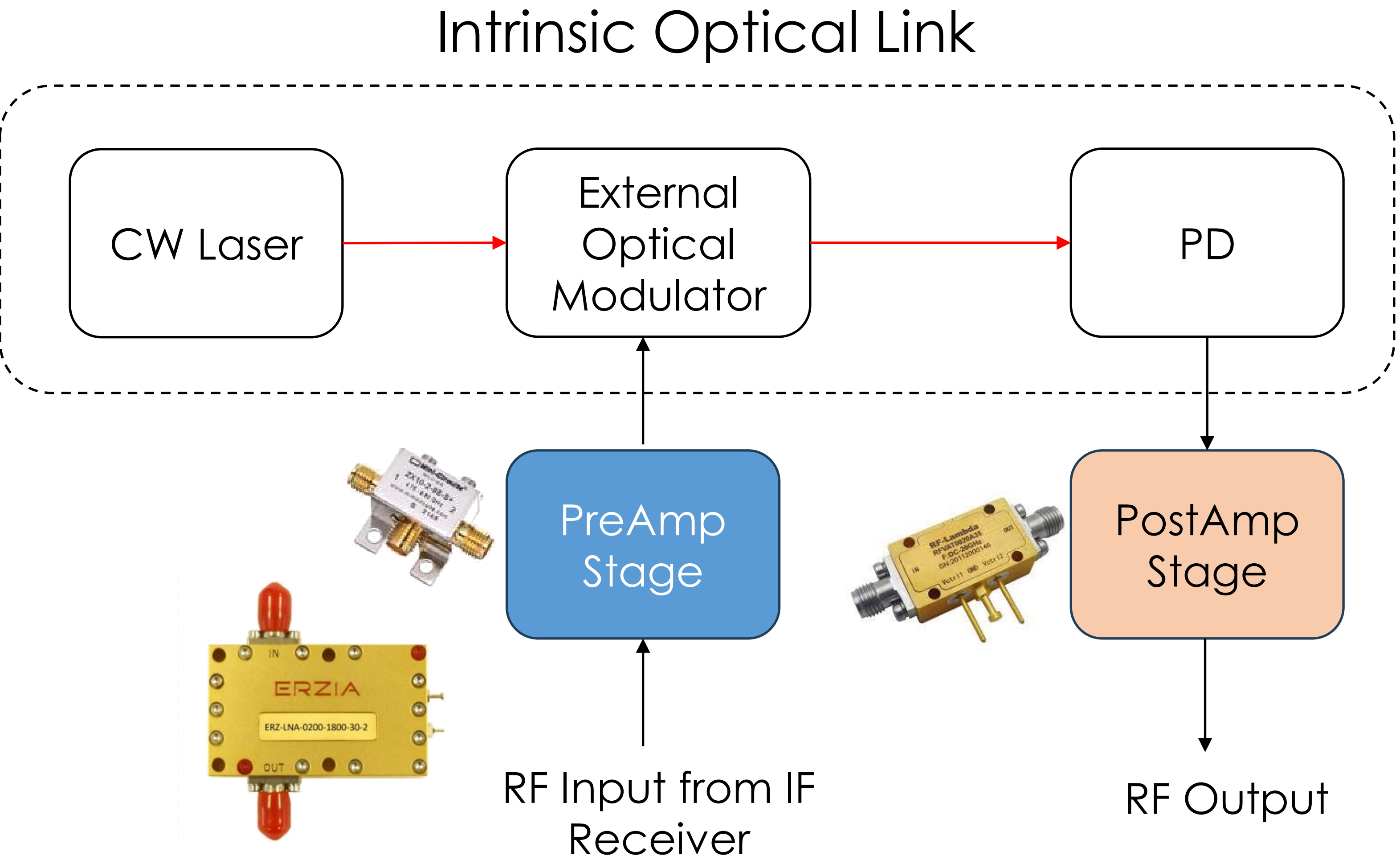


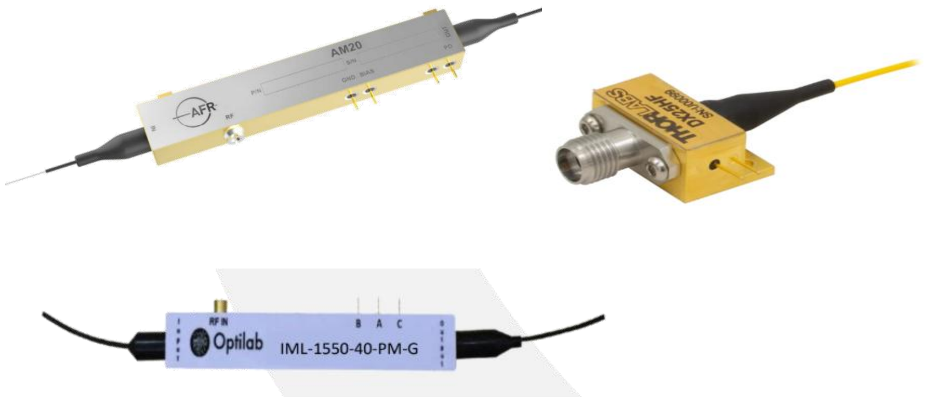
➔ **SRT links meet all specs *except input P1dB***

* -6 dBm was the original specification which has been relaxed to **-11dBm because the spec was not reachable with COST system**

Strong Trade-off NF vs. IP1dB

Design Status: Is it possible to meet the specs with COTS?

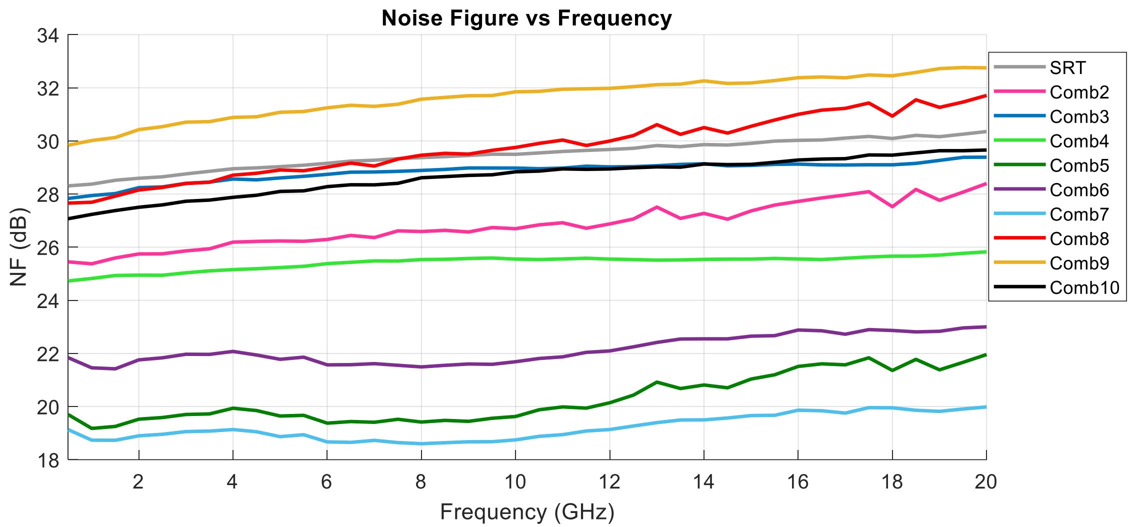


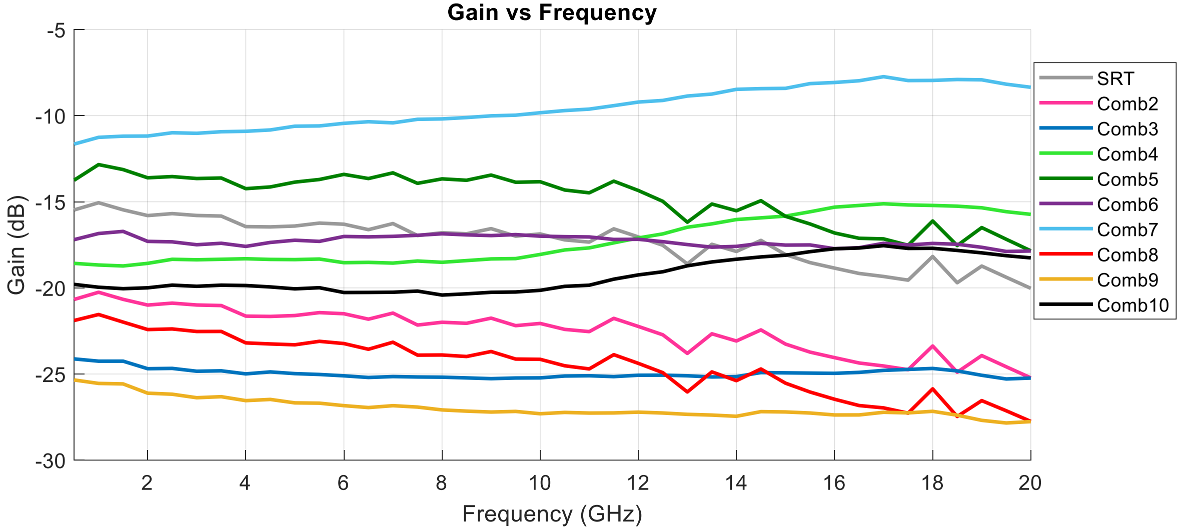


Development of a ad-hoc Simulation tool

Test of all possible combinations of COTS components

Intrinsic Optical Link





1 – AFR AM-20 — **WESTMAG GD45220R(SRT)**
$V_{\pi,DC}$ = 5 V, IL = 3.3dB — $V_{\pi,DC}$ = 5 V, IL = 3.3dB — R = 0.8 A/W

2 – AFR AM-20 — **WESTMAG GD45220R**
$V_{\pi,DC}$ = 5 V, IL = 3.3dB — $V_{\pi,DC}$ = 5 V, IL = 3.3dB — R = 0.8 A/W

3 - AFR AM-20 — **Thorlabs DX25H**
$V_{\pi,DC}$ = 5 V, IL = 3.3dB — R = 0.45 A/W

4 - AFR AM-20 — **Optilab PD30**
$V_{\pi,DC}$ = 5 V, IL = 3.3dB — R = 0.85 A/W

5 -optilab IML-1550-40-PM-G — **WESTMAG GD45220R**
$V_{\pi,DC}$ = 2.5 V, IL = 4 dB typ — $V_{\pi,DC}$ = 5 V, IL = 3.3dB — R = 0.8 A/W

6 - Optilab IML-1550-40-PM-G — **Thorlabs DX25H**
$V_{\pi,DC}$ = 2.5 V, IL = 4dB typ — R = 0.45 A/W

7 - Optilab IML-1550-40-PM-G — **Optilab PD30**
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8 - Exail MXAN-LN 1550 — **WESTMAG GD45220R**
$V_{\pi,DC}$ = 6.5V, IL = 3.5dB typ — $V_{\pi,DC}$ = 5 V, IL = 3.3dB — R = 0.8 A/W

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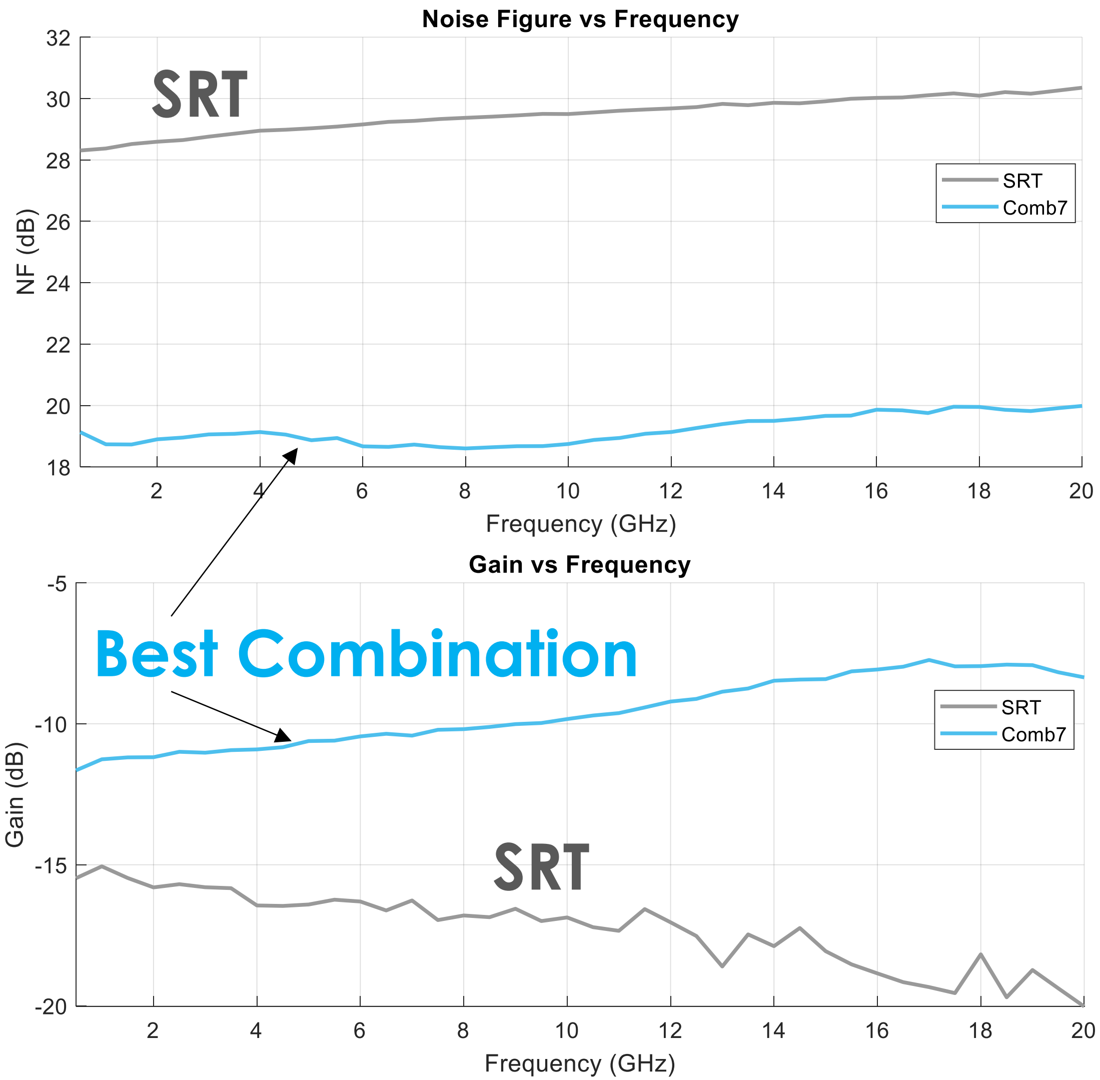
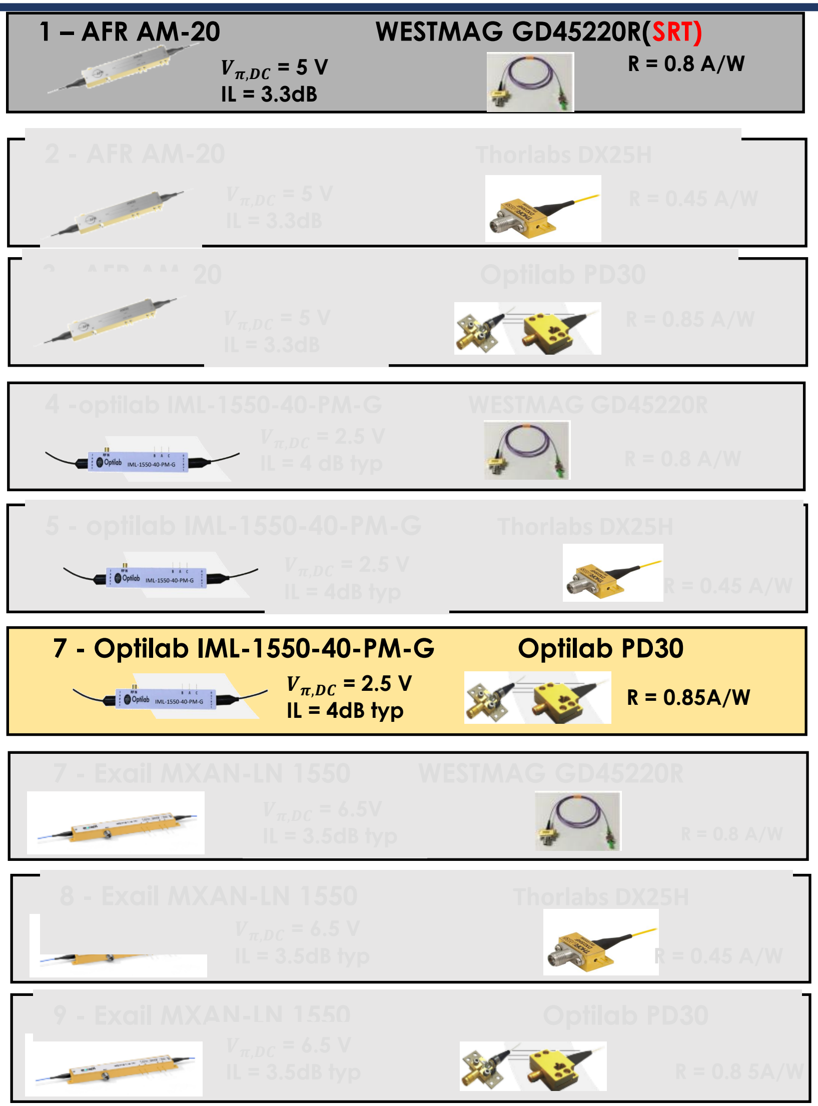
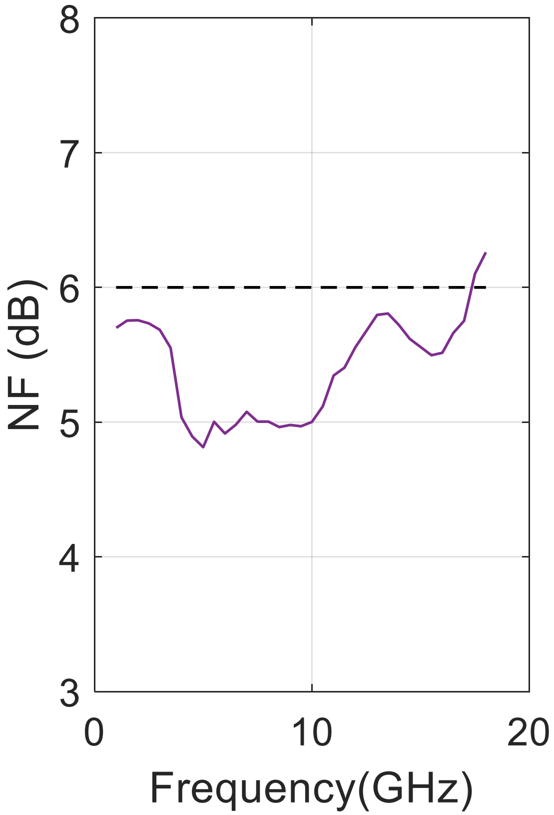
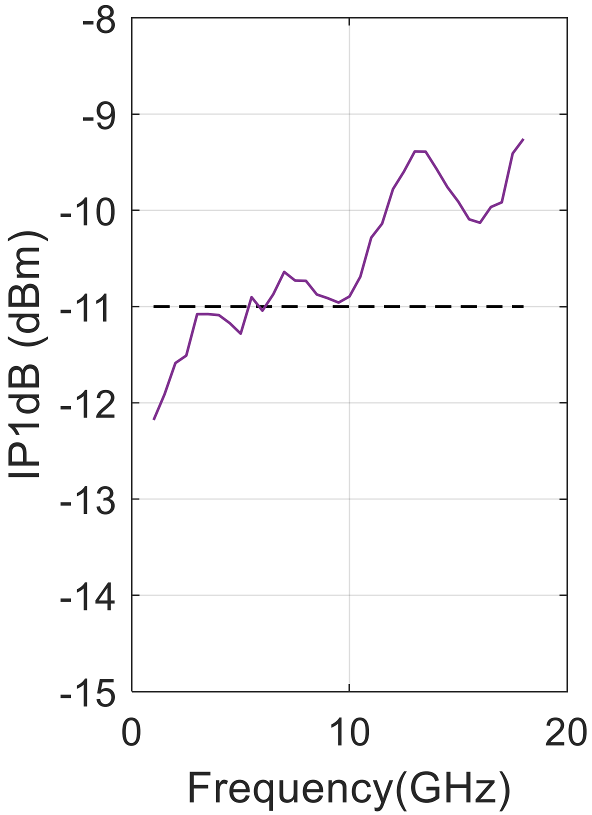
Intrinsic Optical Link

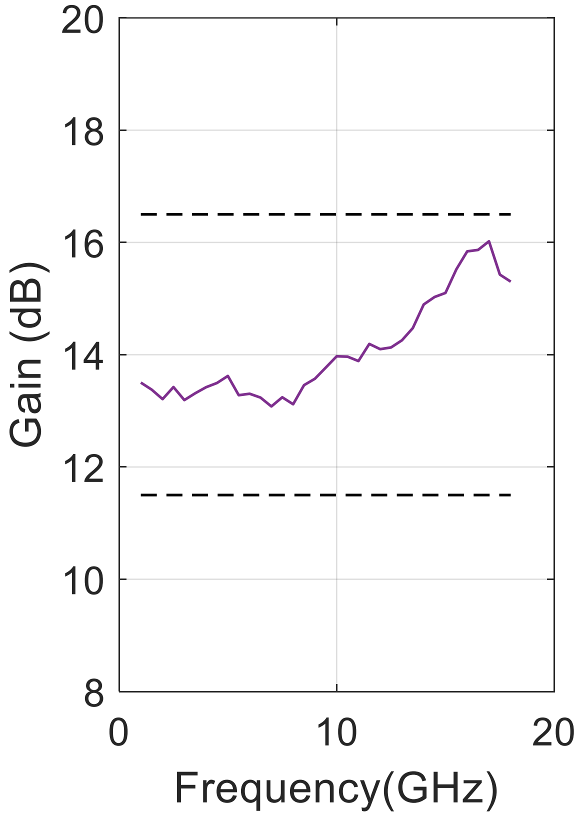


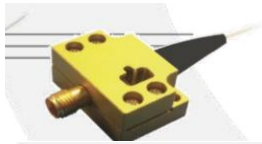


Best Compromise of Full Link Simulation with COTS so far







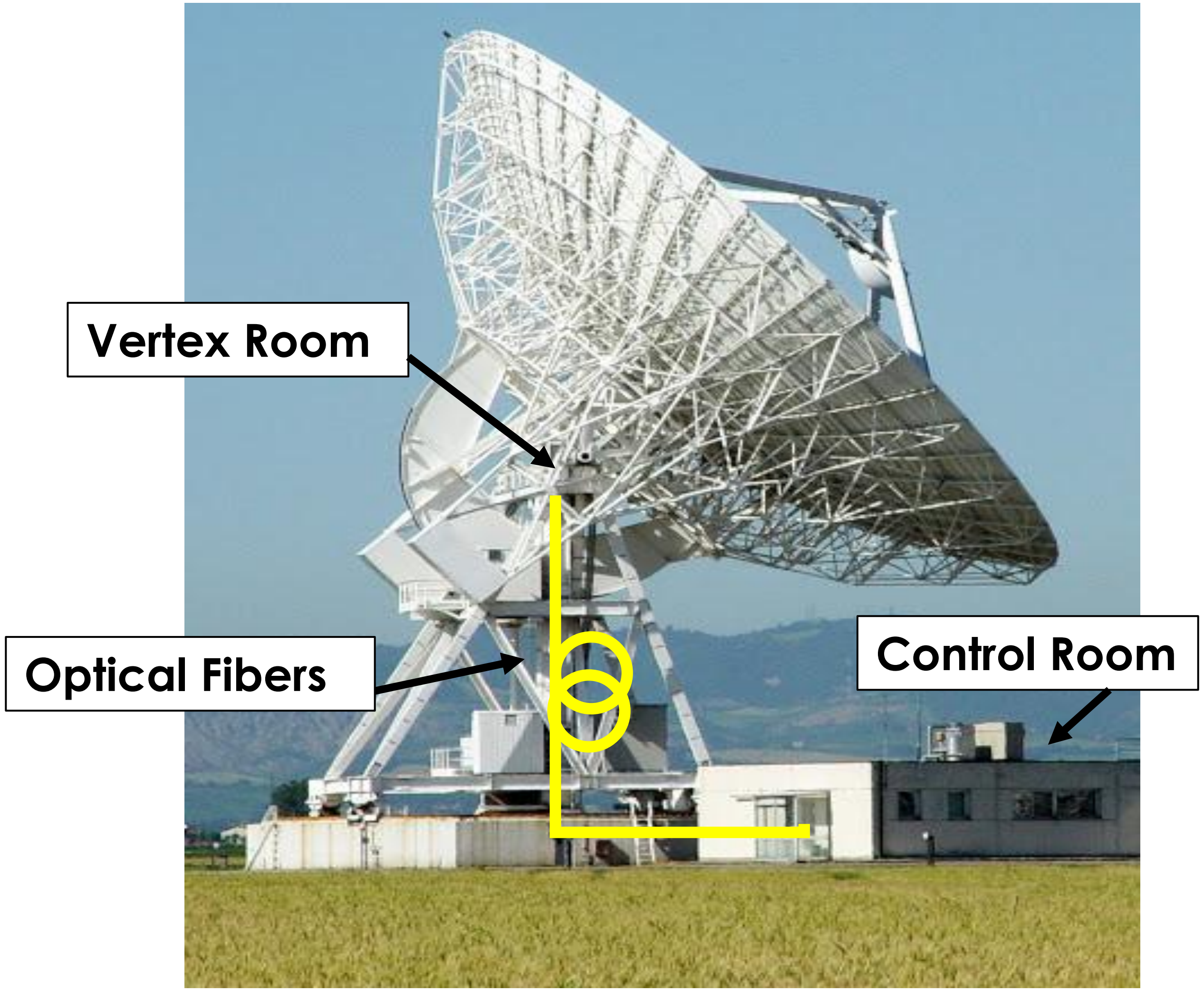


➔ ***Improvement of IP1dB compared to current technology (even with slight worsening of NF)***

➔ **Next step**: optimization/customization of ***pre- and post-amplifiers.***

➔ ***Next Step: Test of new architectures***

Current Needs for INAF VLBI antennas



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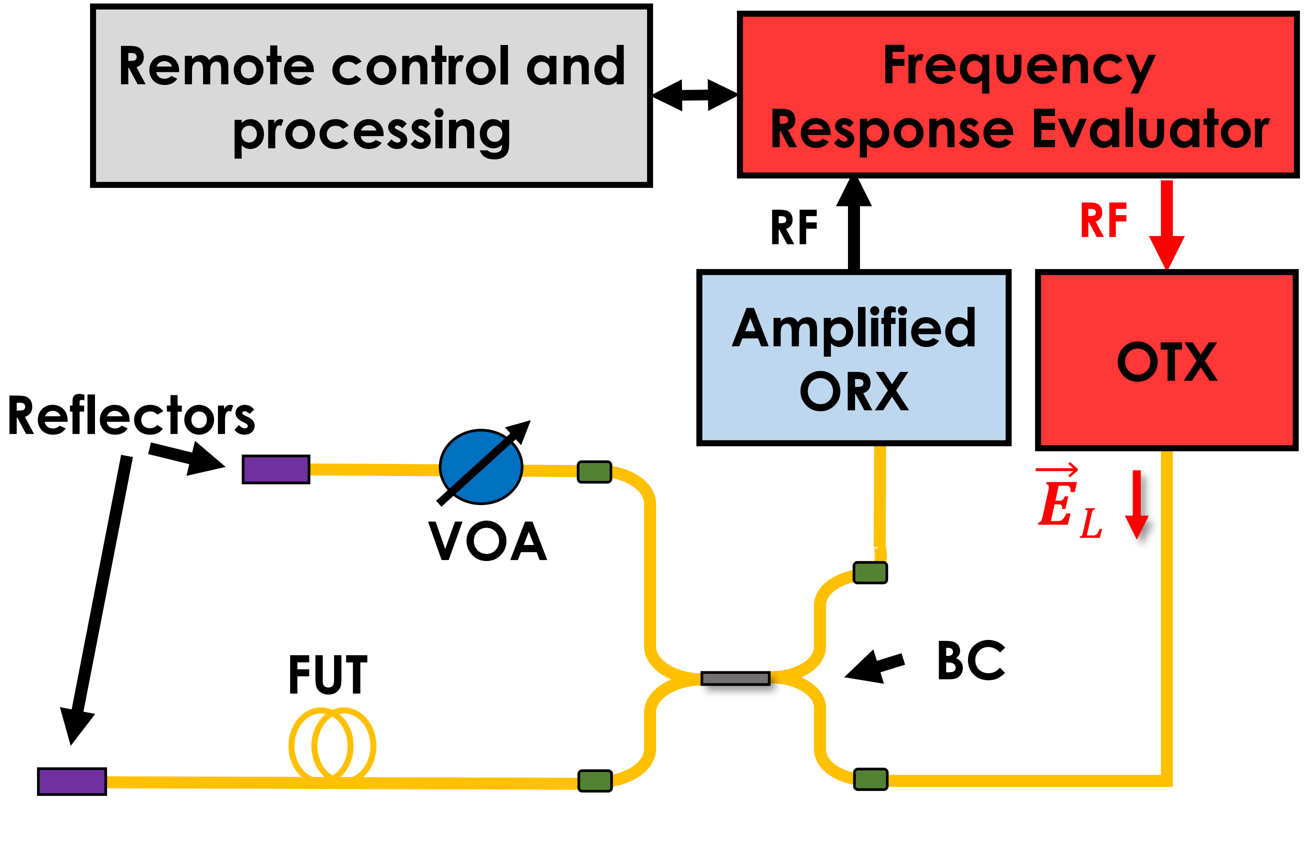
Fiber Transfer Delay Measurement System

- Based on **Michelson's microwave interferometer over optical fiber**

- A **Frequency Response Evaluator (e.g. VNA, NA, etc..)** is used to generate and receive RF tones and measure the **amplitude frequency response**

- The field emitted by **the directly modulated optical transmitter (OTX)** can be expressed in the following form:

$$E_L(t) = E_0\sqrt{1 + m_i \cos(\omega_{RF} t)}\ e^{j\phi(t)}$$



- ω_{RF} : angular RF frequency
- m_i : optical modulation index

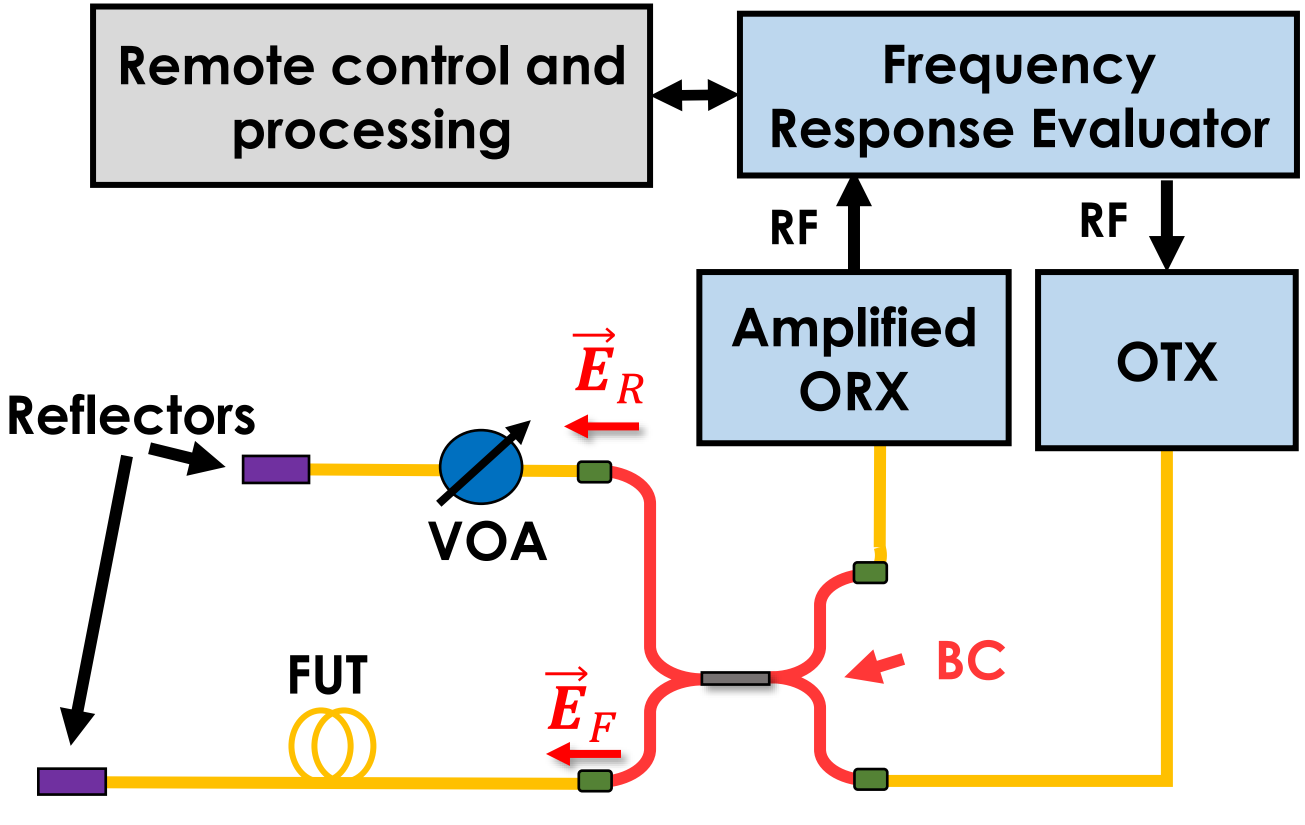
Fiber Transfer Delay Measurement System

- The **Balanced Coupler (BC)** is used to split the field $E_L(t)$ into two fields of equal amplitude $E_F(t)$, $E_R(t)$

⇓

$E_R(t)$ → **Reference fiber**

$E_F(t)$ → **Fiber Under Test (FUT)** of length L

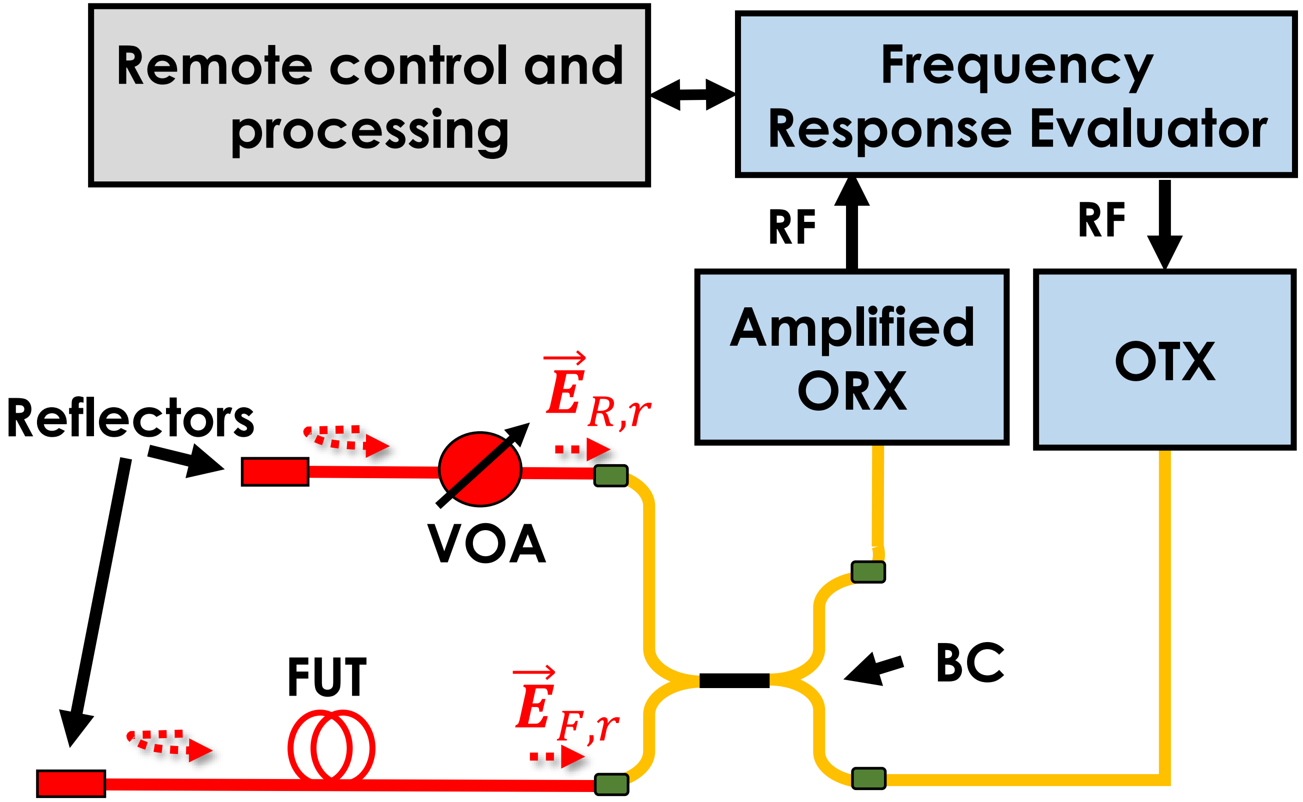


Fiber Transfer Delay Measurement System

- After travelling into the respective path $E_R(t)$ **and** $E_F(t)$ **experience a reflection from a reflector** (Mirror, Grating, PC connector, etc…)

- **A reciprocal delay** τ_F is observed corresponding to the fiber delay (delay on reference path is assumed negligible),

- Adjucting the **Variable Optical Attenuator (VOA)** we can equalize the fields amplitude.



$$E_{R,r}(t) = A\sqrt{1 + m_i\,cos(\omega_{RF}t)}\; e^{j\phi(t)}$$

$$E_{F,r}(t) = A\sqrt{1 + m_i\,cos(\omega_{RF}(t - 2\tau_F))}\; e^{j\phi(t-2\tau_F)}$$

Fiber Transfer Delay Measurement System

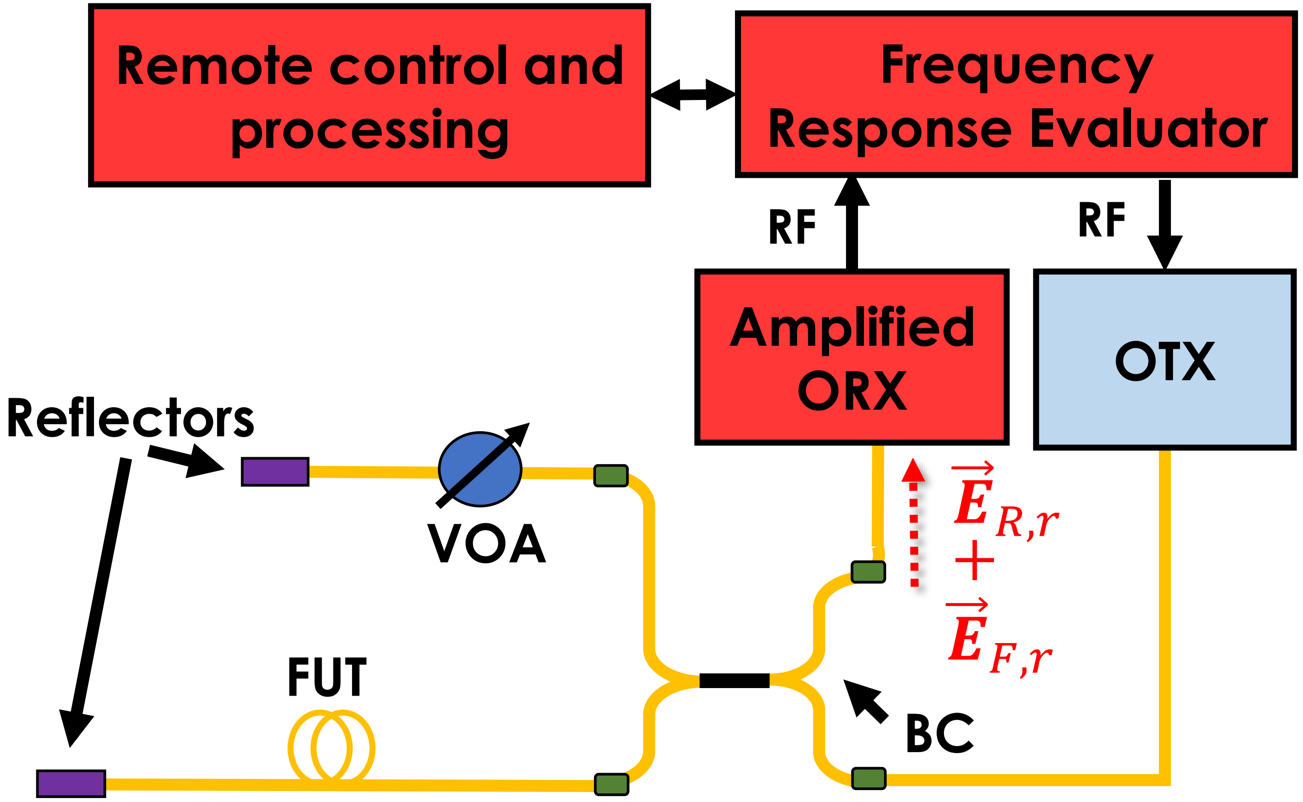
- The detected current i_{PD} results then in

$$i_{PD} \propto \left|E_{F,r}(t) + E_{R,r}(t)\right|^2 =$$
$$= \left|E_{F,r}(t)\right|^2 + \left|E_{R,r}(t)\right|^2 + 2\Re\{E_{F,r}E_{R,r}^*\}$$

- Fiber length much higher than laser length coherence → **incoherent (optical) process**

$$i_{PD} \propto \left|E_{F,r}(t)\right|^2 + \left|E_{R,r}(t)\right|^2$$

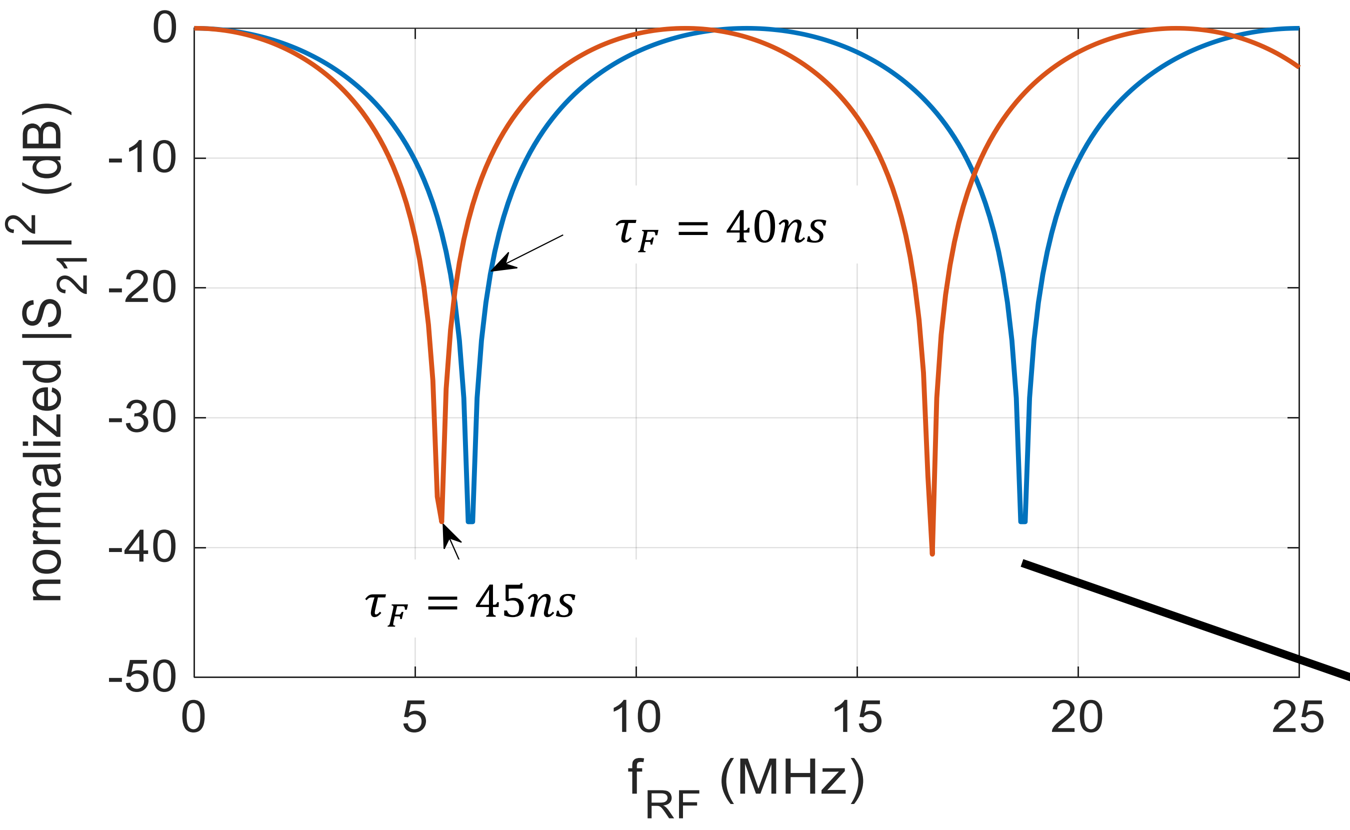
- $|S_{21}(\omega_{RF})|^2$ is function of **the delay difference between Reference and FUT**



$$|S_{21}(\omega_{RF})|^2 \propto |cos(\omega_{RF}\tau_F)|^2$$

Expected behavior

Example of frequency of minimum shifting



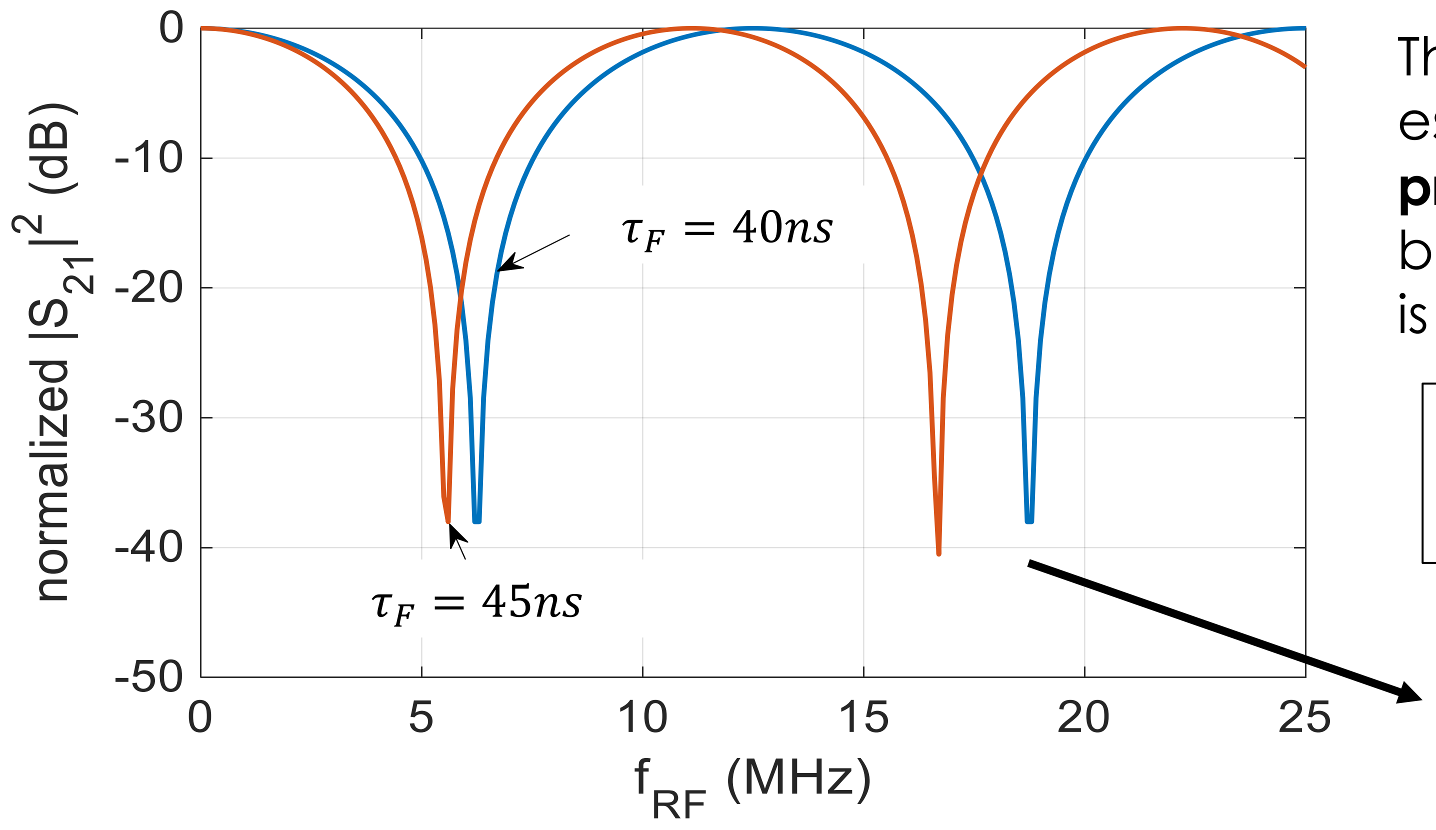
- The value of the delay shift can be then estimated **by tracking one of the minima present in** $|S_{21}|^2$ where the relation between k[th] minimum frequency and $\boldsymbol{\tau_F}$ is the following:

$$f_{RF,min,k} = \frac{2k+1}{4 \cdot \tau_F} \qquad k = 0,1,2,\ldots$$

Higher sensitivity at higher frequency

Expected behavior

Example of shofting of frequency of minimum



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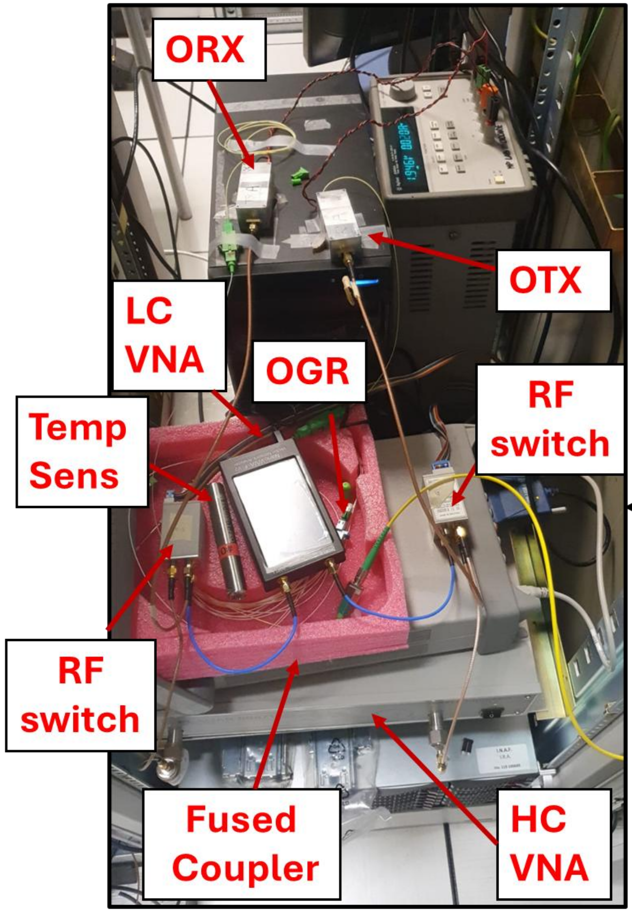
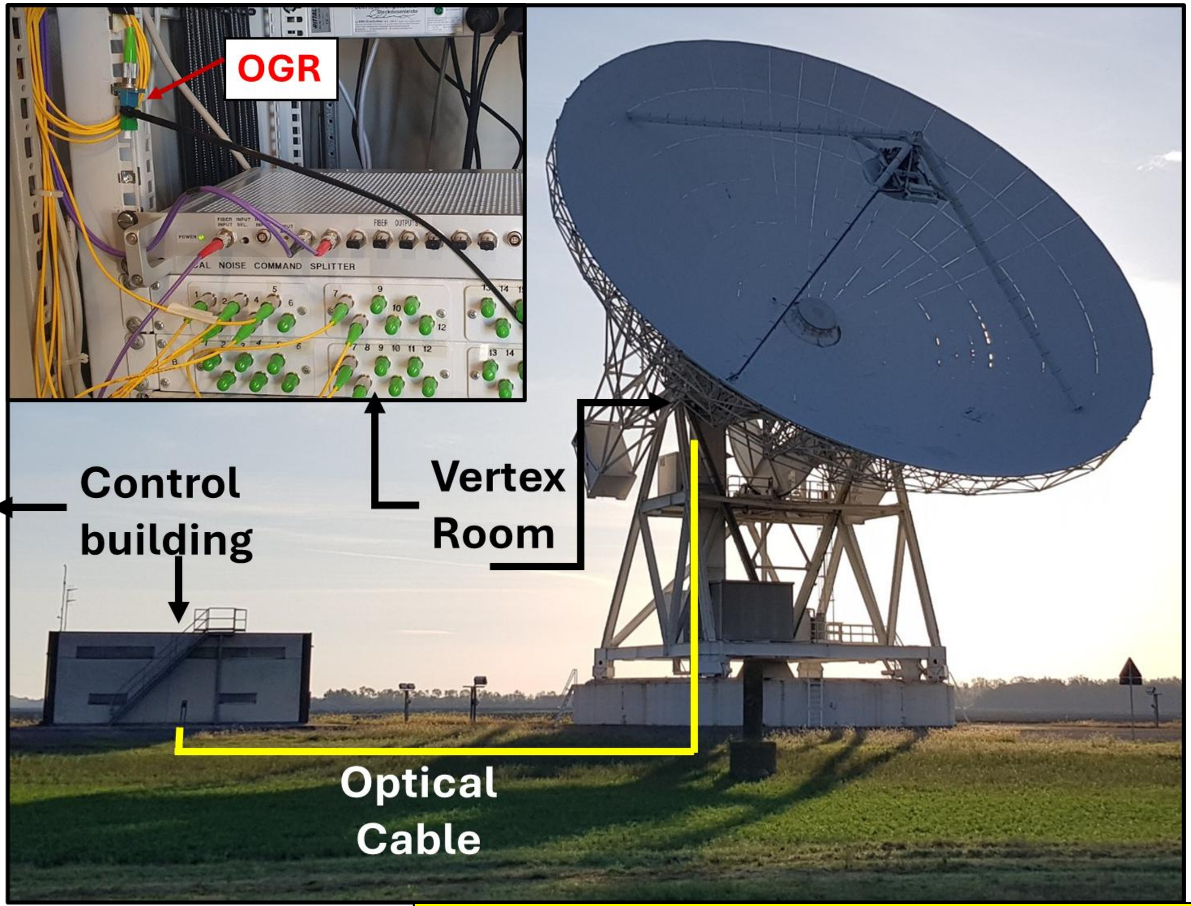
Prototype installation over the INAF VLBI antenna of Medicina

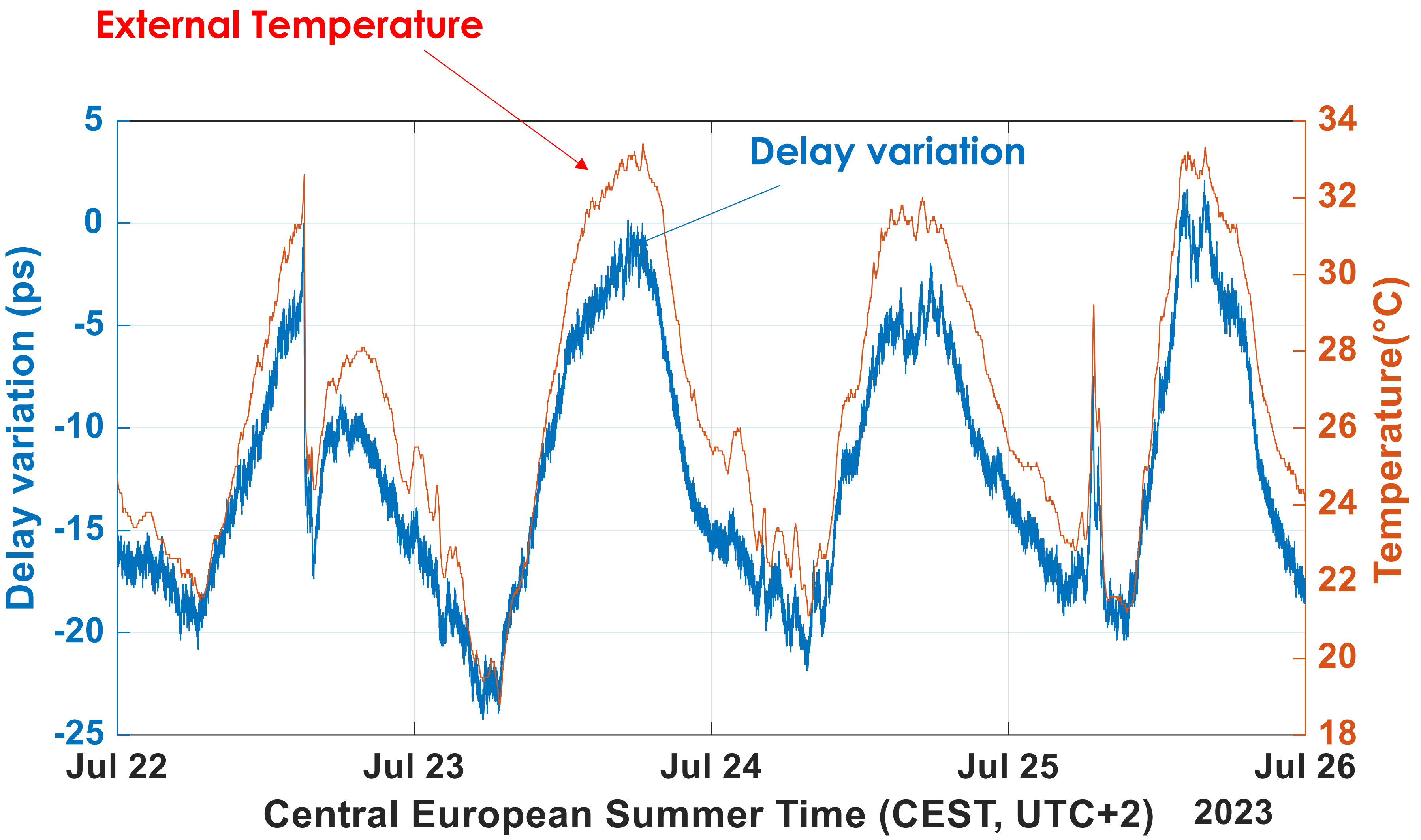
Prototype Installation on the VLBI antenna of Medicina



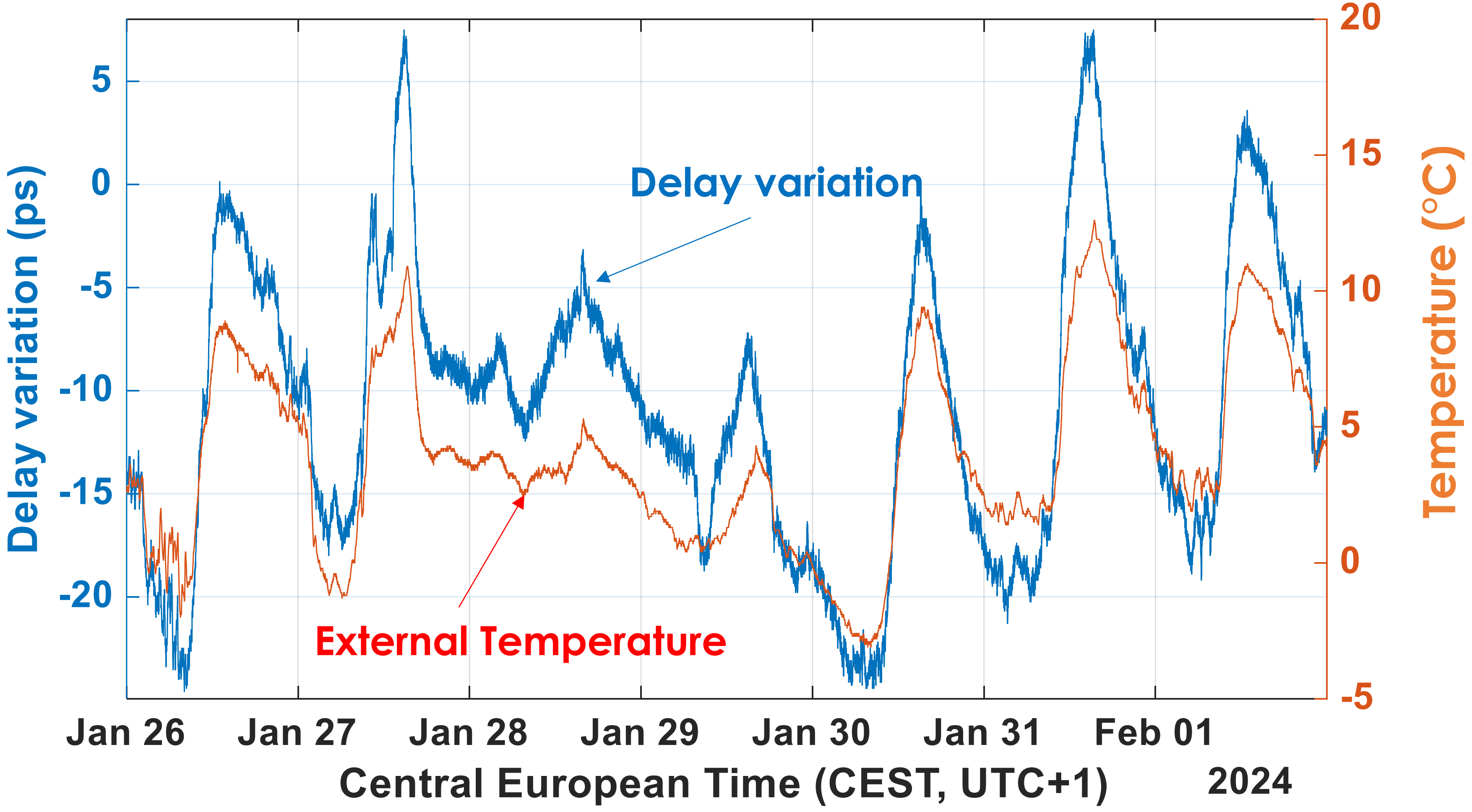


Installation over a spare (unused) optical fiber

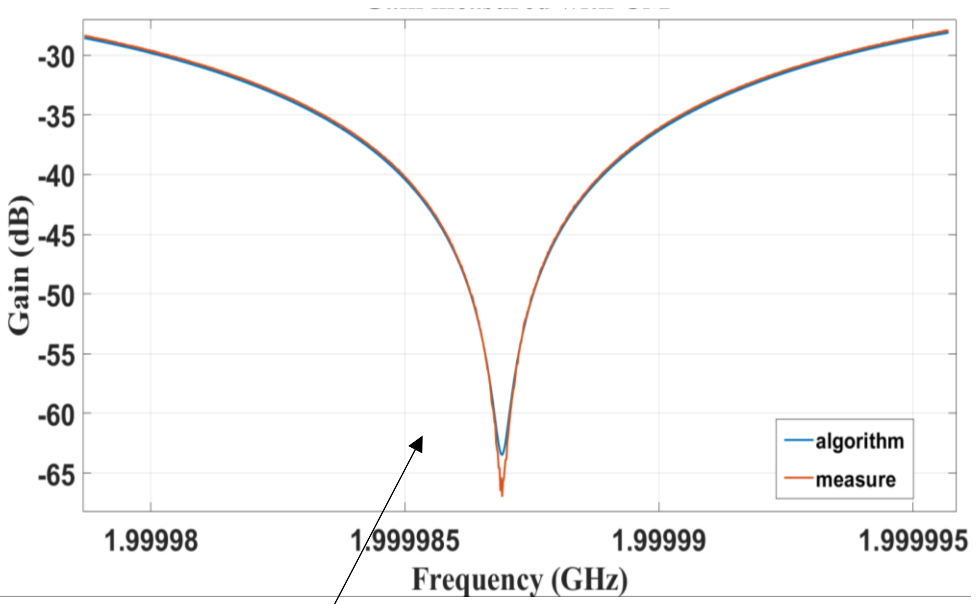
Summer Period Test (Raw Measurements)



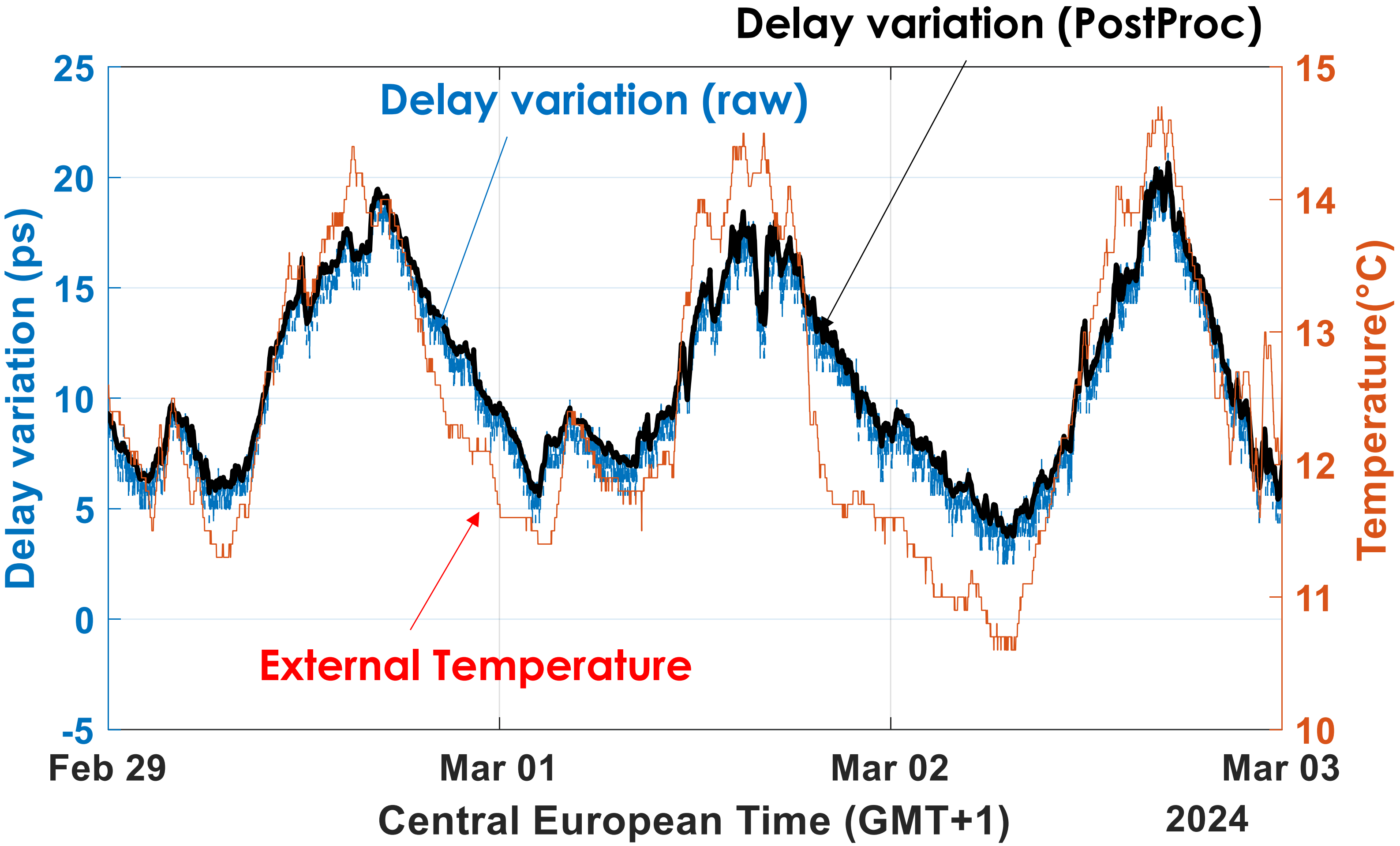
Winter Period Test (Raw Measurements)



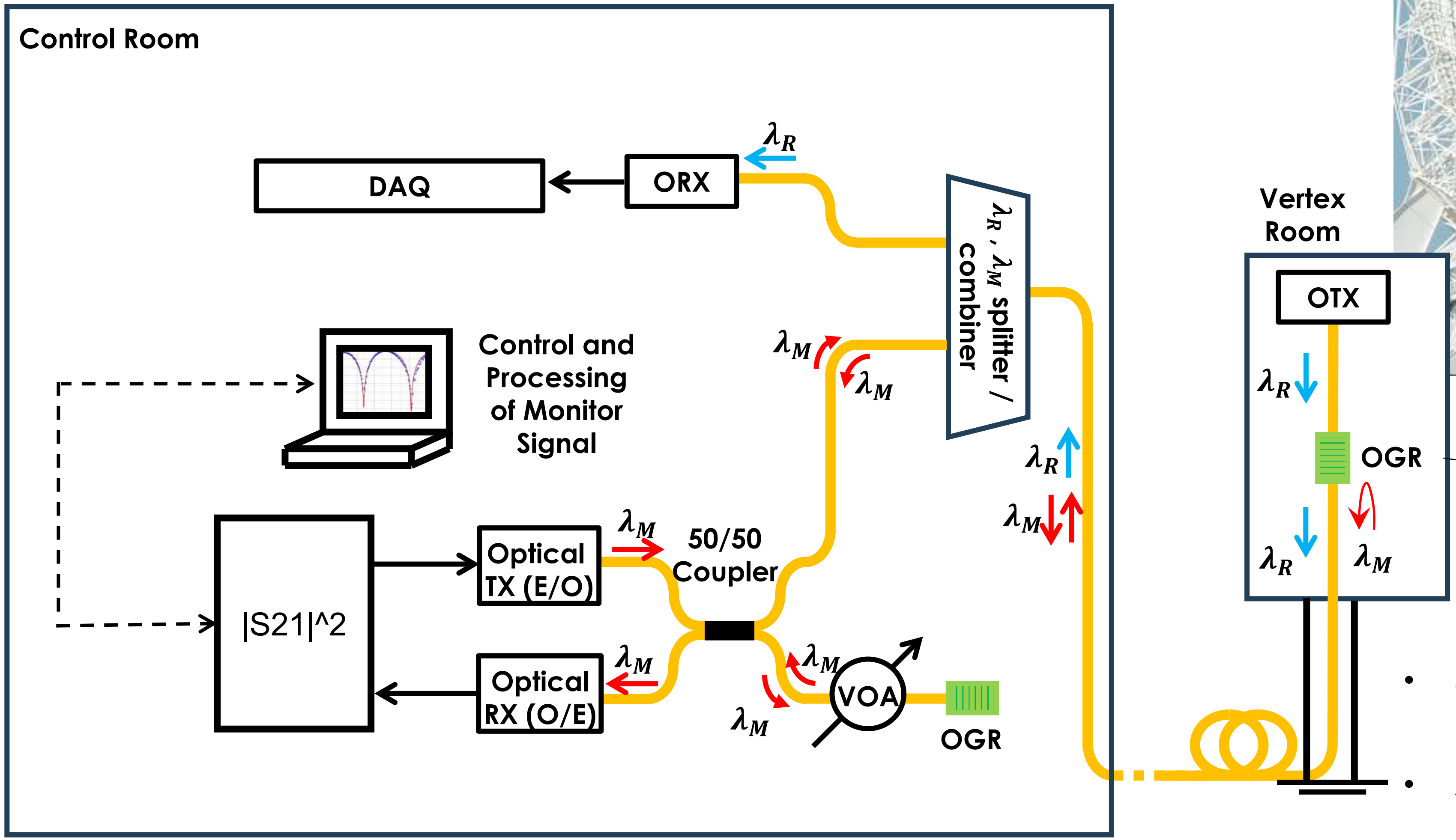
Performance improvement with little postprocessing



Curve fitting using the mathematical model derived



Possible installation over the same fiber used for transmission



- **Selective reflector** based on Distributed Bragg Grating
- λ_M is the only wavelength reflected
- λ_R is transmitted.

Summary and Advantages of the FTDMS proposed

Advantages

- Picosecond-range of precision easily reached
- No Loop is required
- No Optical Frequency Combs lasers
- Simple and effective system with possible integration over the same fiber where the RF signal is carried

Weak point

- Only for monitoring (not direct compensation)

Conclusions and perspectives

Conclusions

- Through the collaboration between UniBo and INAF two "microwave photonics" systems for **mm-W VLBI antenna downlink** are under design:
  - **18 GHz Low Noise and High Dynamic Analog Optical Fiber link**

    → NF/P1dB Trade-off reduced compared to current technology

    → **Next Step**: Test of Custom devices + New architectures

  - **Simple and high-precision Fiber Transfer Delay Monitoring System**

    → Consolidated technology

    → **Next step:** feedback from users → system improvement/realization

Thank you for your attention

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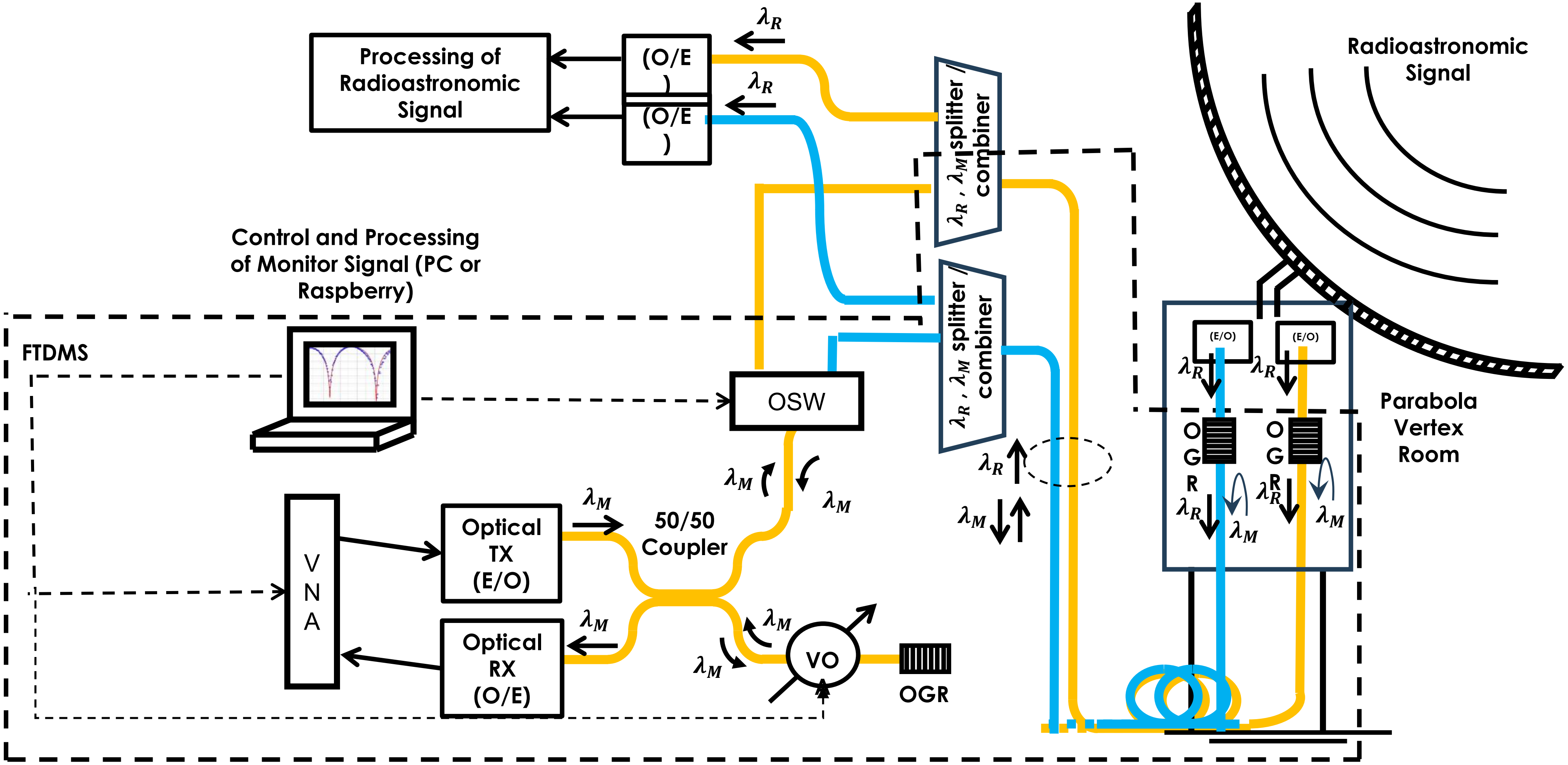
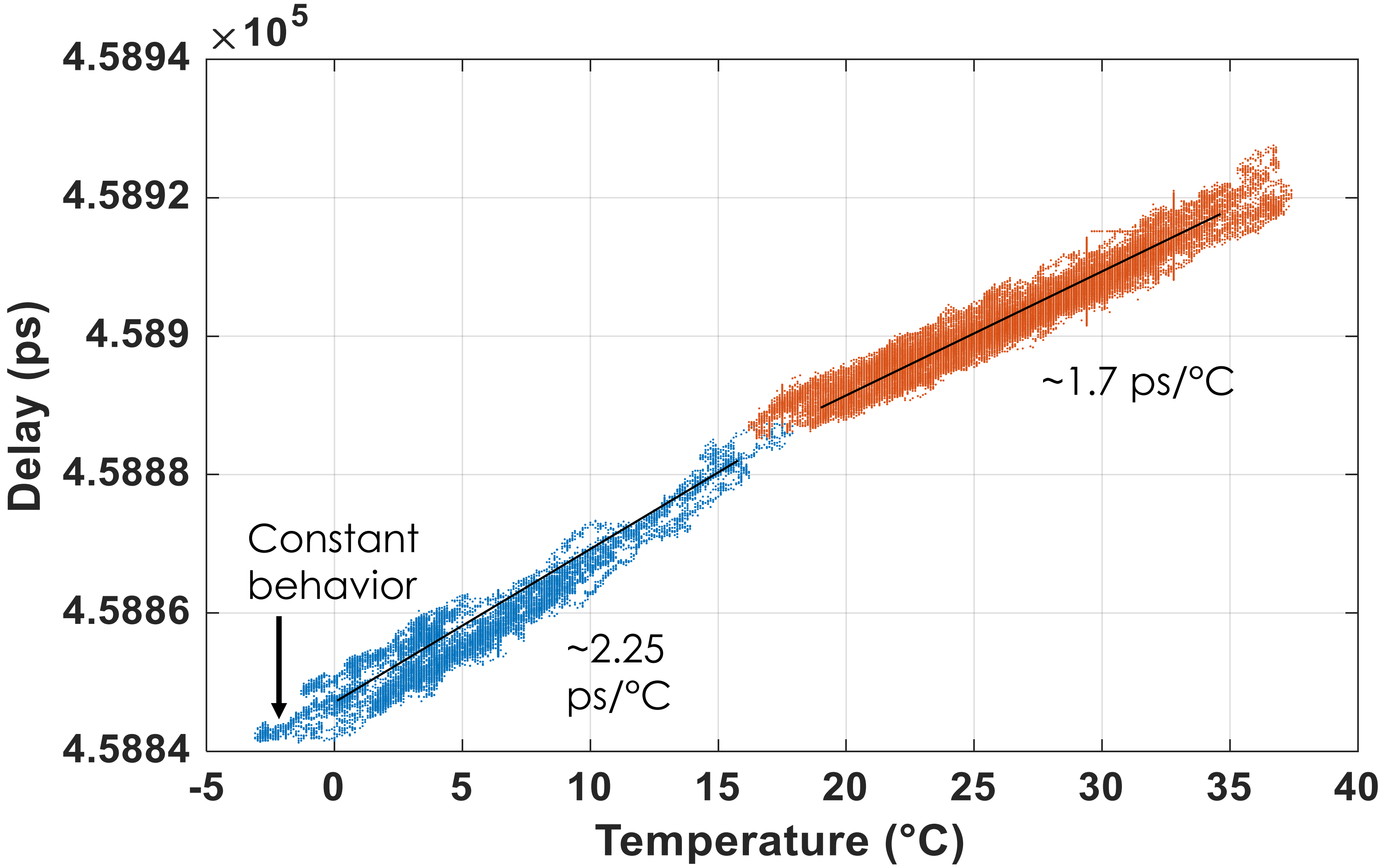
Backup Slides

Extension to more fibers using Optical Switch (example of 2 fibers)

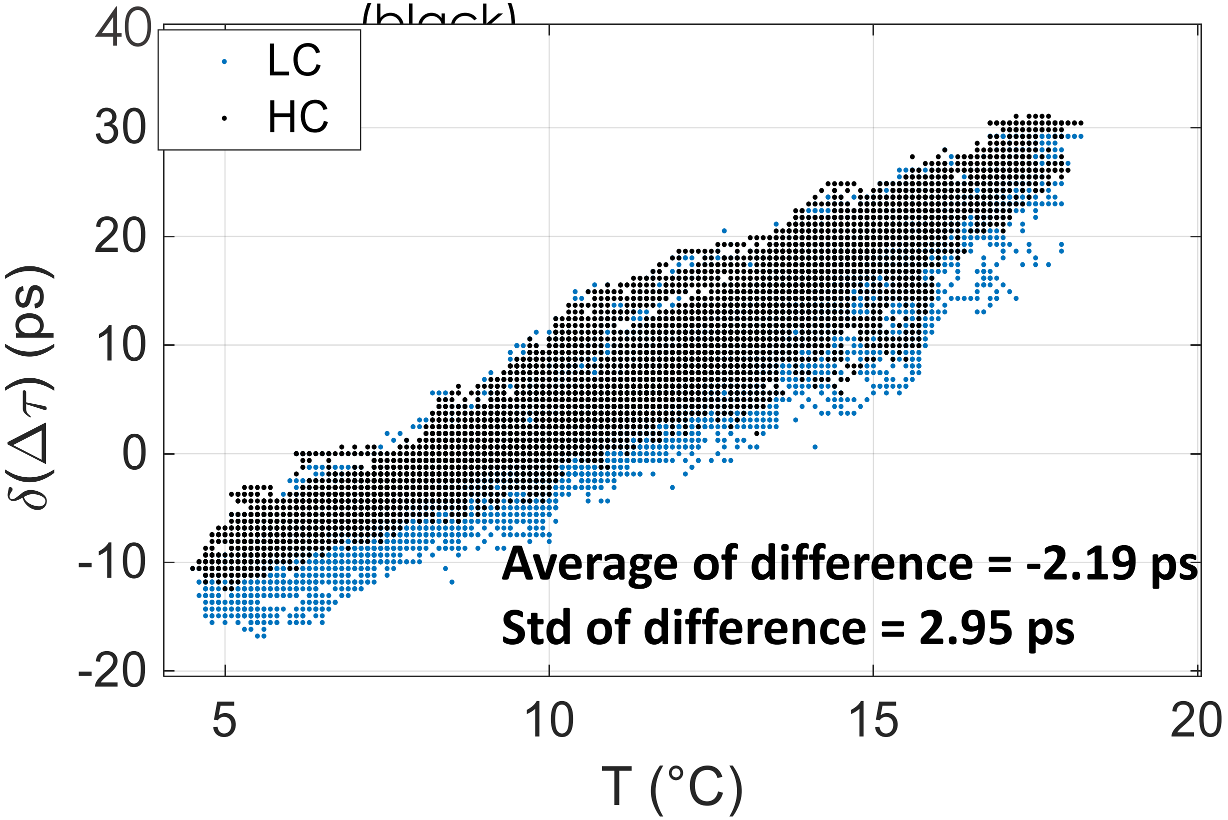


Comparison Summer-Winter period

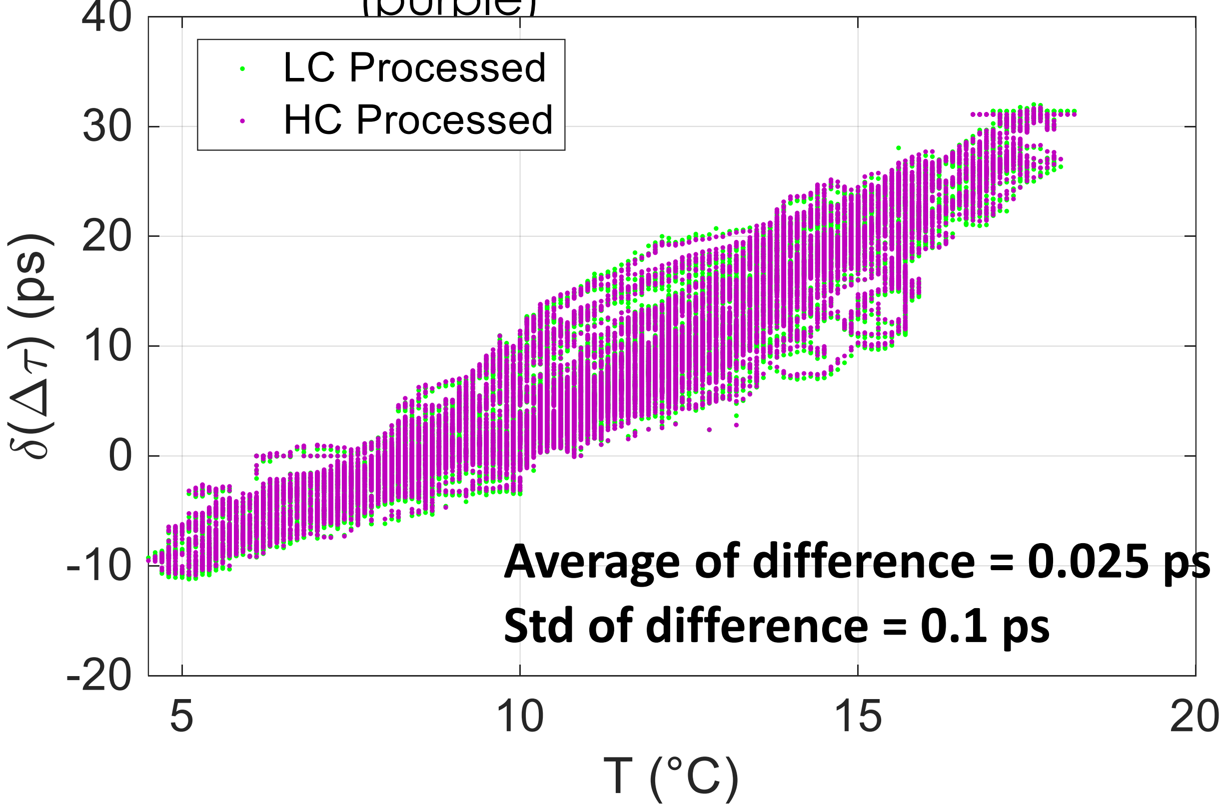


PostProcessing over Temperature

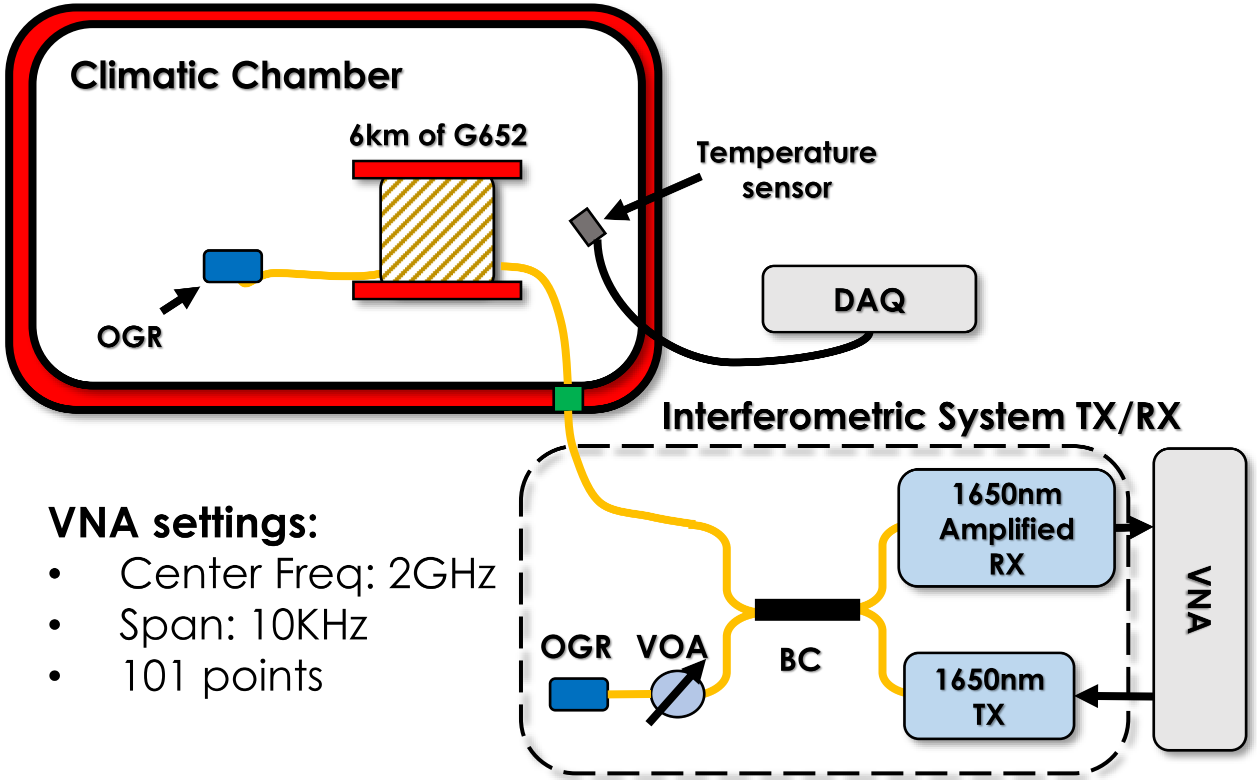
NanoVNA Raw (blue) vs Copper Mountain Raw (black)



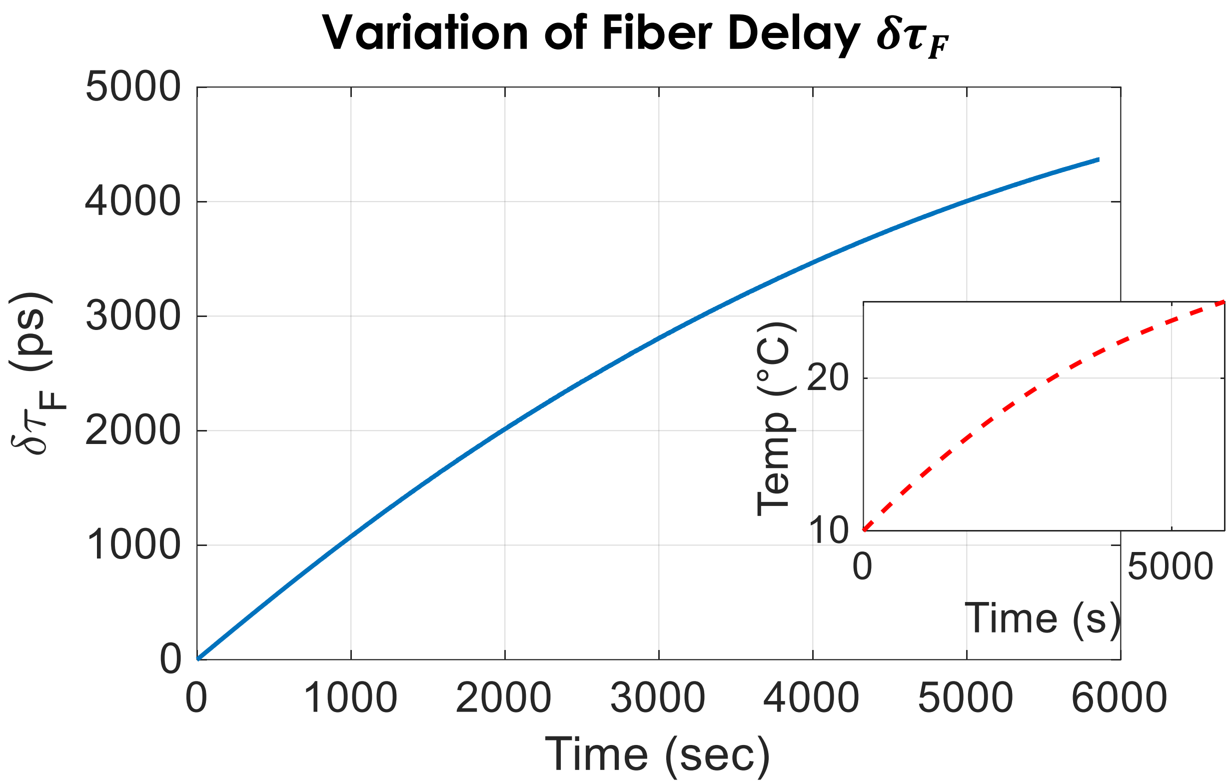
NanoVNA PostProc (green) vs Copper Mountain PostProc (purple)



Lab test performances



VNA settings:
- Center Freq: 2GHz
- Span: 10KHz
- 101 points



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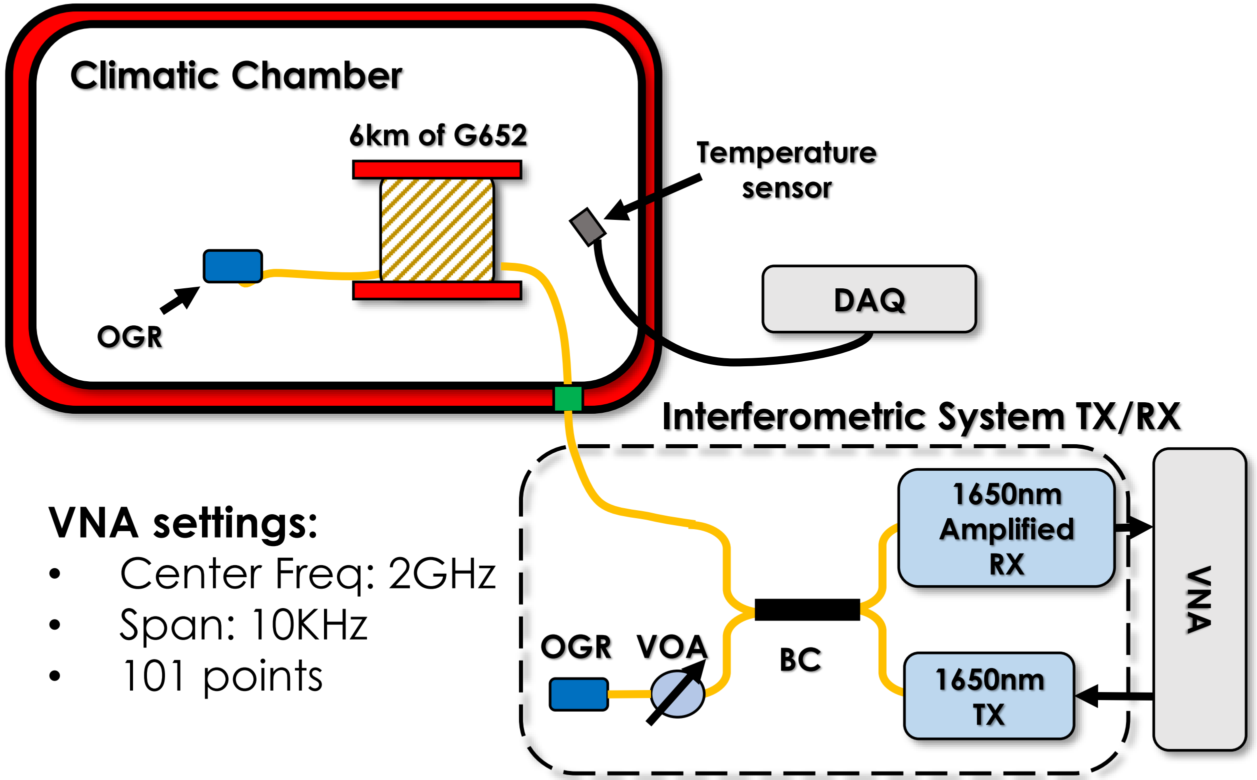

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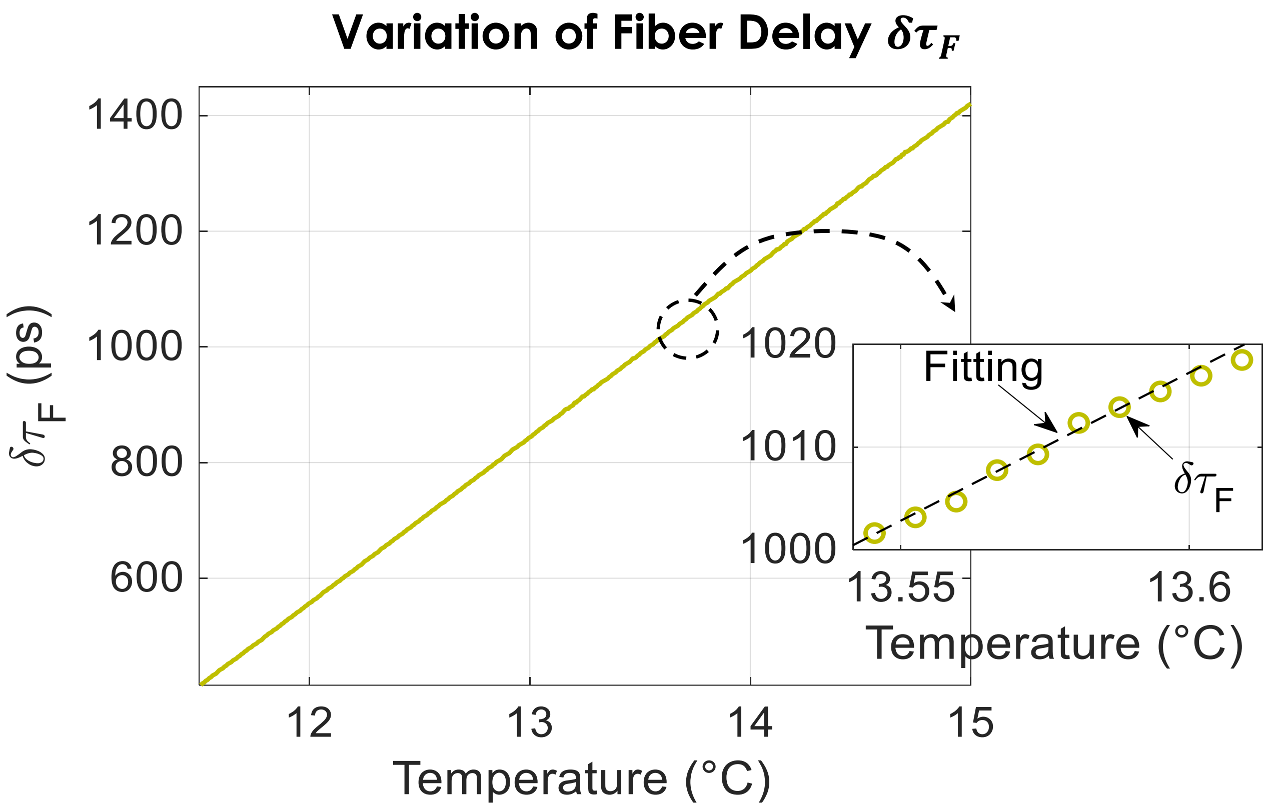
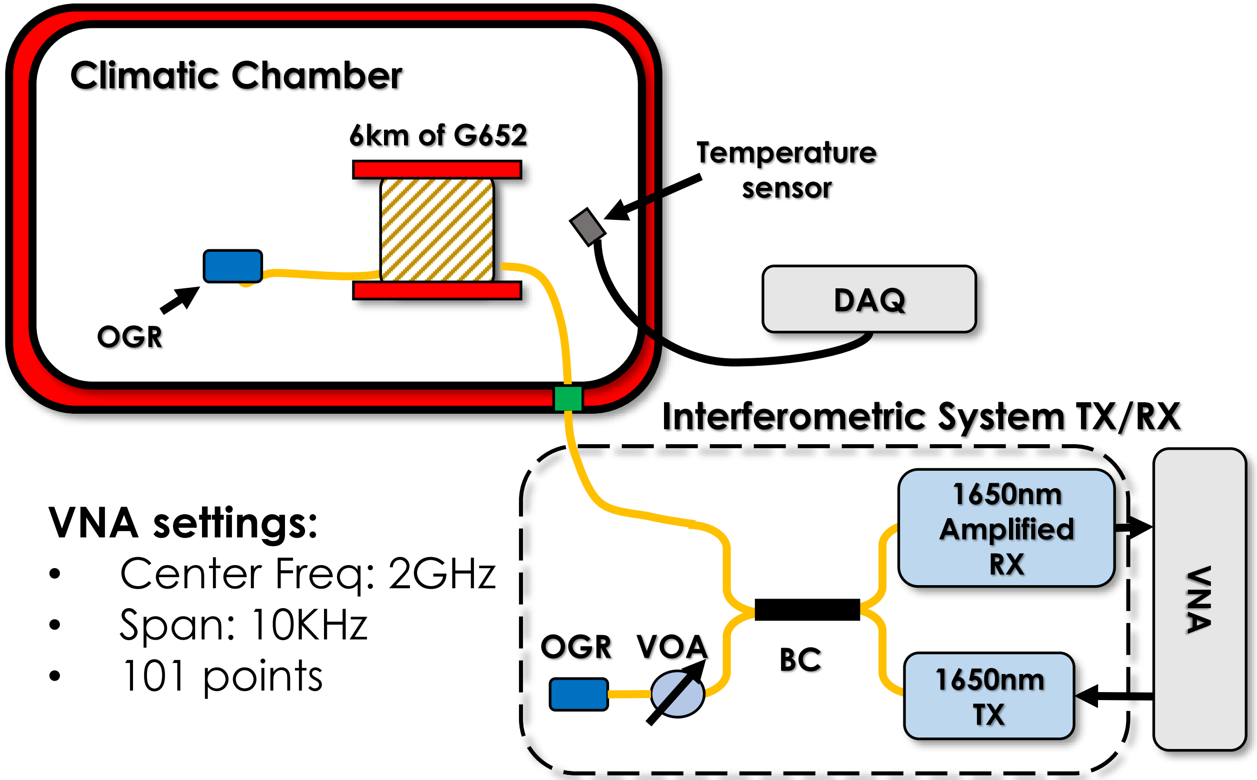


→ About 2 picoseconds of precision achieved

Lab test performances



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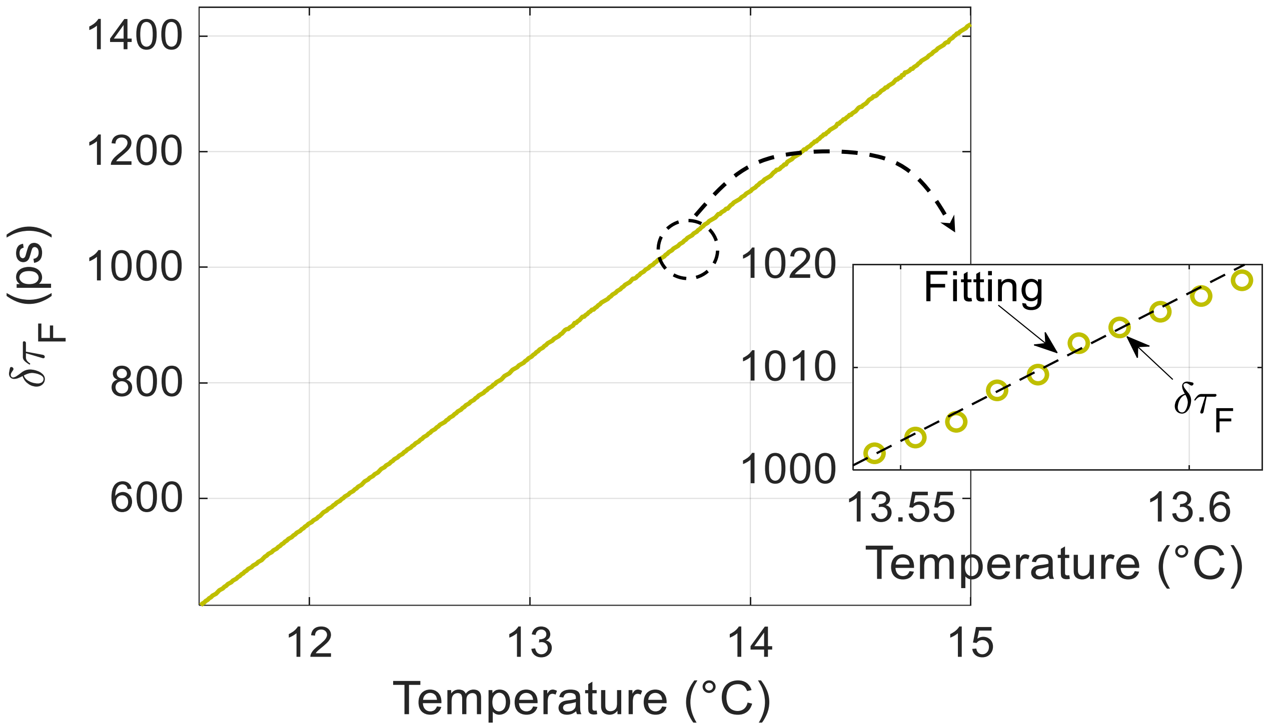
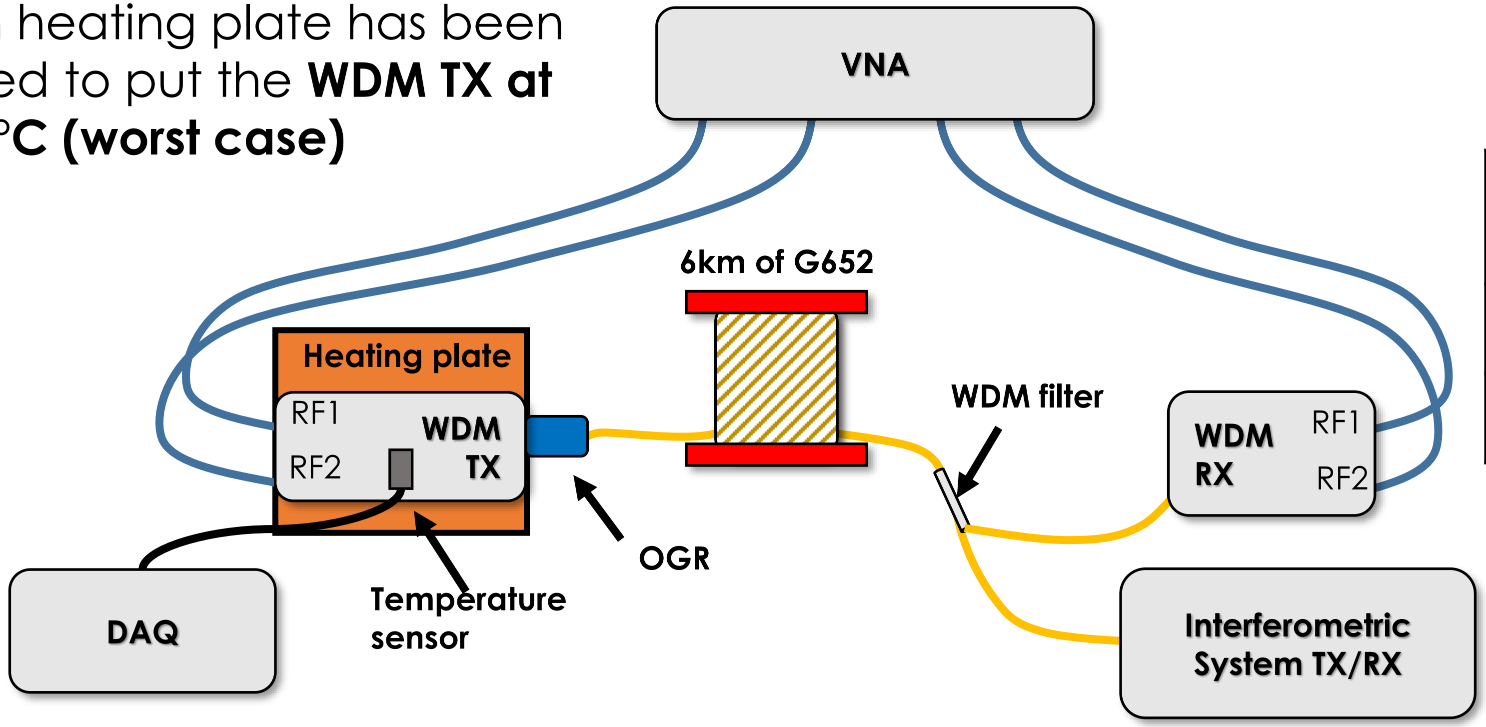


→ About 2 picoseconds of precision achieved

→ What about the insertion impact of the system in the antenna downlink transmission system?

Insertion impact of the FDMS

- An heating plate has been used to put the **WDM TX at 65°C (worst case)**



Performances measured at WDM TX temp of 65 °C

λ (nm)	without FDMS		with FDMS	
	Gain (dB)	NF (dB)	Gain (dB)	NF (dB)
1330	53.3	17.8	51.7	18.7
1270	48.9	20.8	47.5	21.8

→ The insertion of the delay monitoring system affects the **RF gain of less than 1.5dB** and the **noise figure of maximum 1 dB**

→ Acceptable insertion impact for typical systems

→ In case of SKA-Low, **the system is still respecting the requirements**