



AN ENHANCED NEAR-INFRARED HETERODYNE INTERFEROMETRY TESTBED

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Motivated by discussions with Thomas Schweizer, David Fink, and Razmik Mirzoyan (MAGIC)

MAX-PLANCK-INSTITUT FÜR PHYSIK

STELLAR INTENSITY INTERFEROMETRY WORKSHOP 2026

Santa Cruz de La Palma, La Palma, Spain

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OVERVIEW

1 Introduction

- 1 Motivation for the heterodyne detection approach

2 An Enhanced NIR Heterodyne Interferometer Testbed

- 1 Overview of setup
- 2 Recent improvements

3 Comparison of Signal-to-Noise Ratio in Optical Interferometry

- 1 SNR in intensity interferometry (HBT type)
- 2 SNR in heterodyne interferometry

4 Outreach Demonstration (time permitting, otherwise speak to me after)

5 Summary



MOTIVATION: WHY PHOTON DETECTION MATTERS

Light is the fundamental carrier of astronomical information.

- Photons are the primary messengers that travel cosmic distances and reach our detectors with minimal interference.
- They carry **directional**, **spectral**, and **temporal information** directly from their source.

Challenges in modern astronomy:

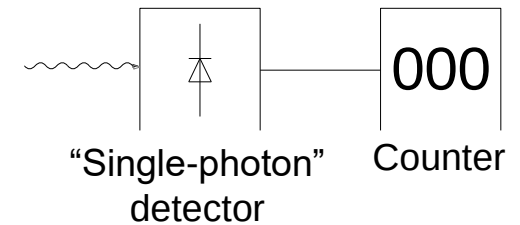
- **Low photon flux** from distant sources
- **Atmospheric turbulence** (i.e. phase disturbance)
- Need for **ultra-high angular resolution**

Motivation: extract the most information from the light that we receive.

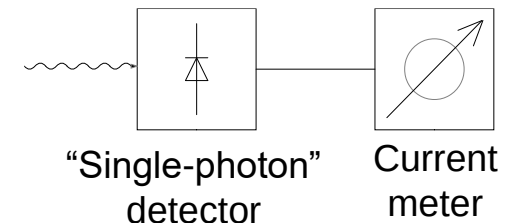
It matters how we detect the incoming light.

Are there additional options to photon counting and flux measurements?

Photon counting:



Photon flux measurement





HETERODYNE DETECTION

Principle: Mix source with a stable local oscillator (e.g. laser).

Beat frequency: down-converts from IR/optical signal (~ 100 s THz) to RF ($\sim$ GHz) for sampling.

Applications are ubiquitous: stellar interferometry, quantum optics, optical data transmission/communications systems.

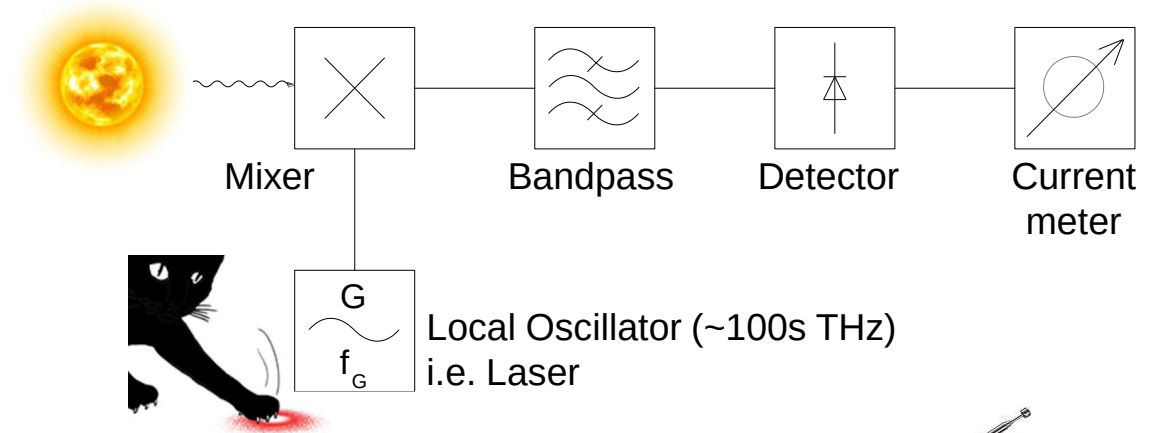
Key advantages for stellar interferometry:

- **Increased sensitivity**
- Enables **digital signal processing** (delays, filtering, correlation)
- Scalable to **km-long baselines**

Large benefits from existing techniques developed in radio astronomy.

Heterodyne Detection Chain

Star (~ 100 s THz) $\rightarrow$ Downconvert $\rightarrow$ $\sim$ GHz



Nothing new!
Heterodyning has been around a long time.



HETERODYNE DETECTION ADVANTAGES



Starlight

$$a_1(t) = A_1 \cos(\omega_1 t)$$

Local oscillator

$$a_2(t) = A_2 \cos(\omega_2 t)$$

Mixing

$$b(t) = (a_1(t) + a_2(t))^2 = a_1(t)^2 + a_2(t)^2 + 2a_1(t)a_2(t)$$

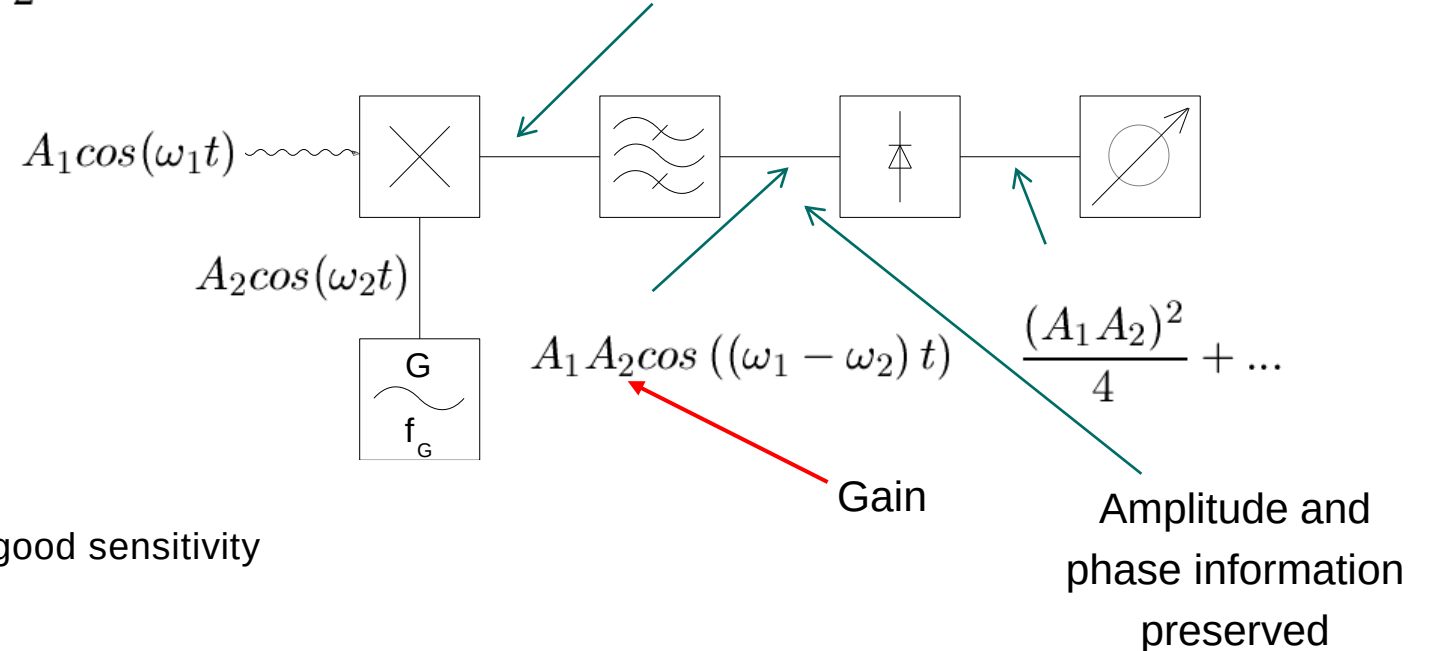
$$b(t) = \frac{A_1^2}{2} (1 + \cos(2\omega_1 t)) + \frac{A_2^2}{2} (1 + \cos(2\omega_2 t)) + A_1 A_2 (\cos((\omega_1 - \omega_2) t) + \cos((\omega_1 + \omega_2) t))$$

Heterodyning

The Photodetector is the “mixer”

Key heterodyne advantages:

- **High gain** (parametric amplification) → very good sensitivity
- **Excellent spectral resolution**
- **Excellent frequency selection** by tuning only the LO frequency



PHOTODETECTOR AS THE MIXER

Reminder: a photodetector is a square-law device: responds to the intensity of the optical field, which is proportional to the square of the E-field amplitude.

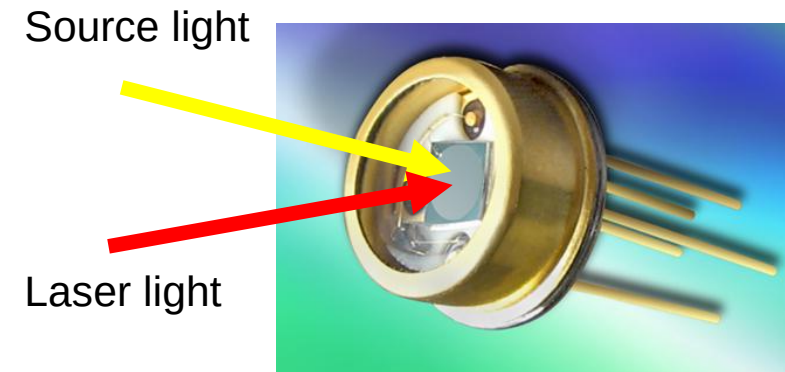
$$\text{Photocurrent: } i(t) \sim P(t) = \frac{|E^2(t)|}{Z_0}$$

Standard photodetectors (Si-diode, InGaAs-diode, Avalanche-diode) have several advantages w.r.t. devices like PMTs and HPDs (in addition to cost, robustness, and compact size).

- **Larger intrinsic bandwidth** (up to many GHz)
- Much **lower transit time spread** ($\leq$ femtoseconds)
- **Low operating voltage** (up to 10s of volts)
- **Good dynamic range**

Disadvantages:

- **Normally lower sensitivity** (in standard applications)



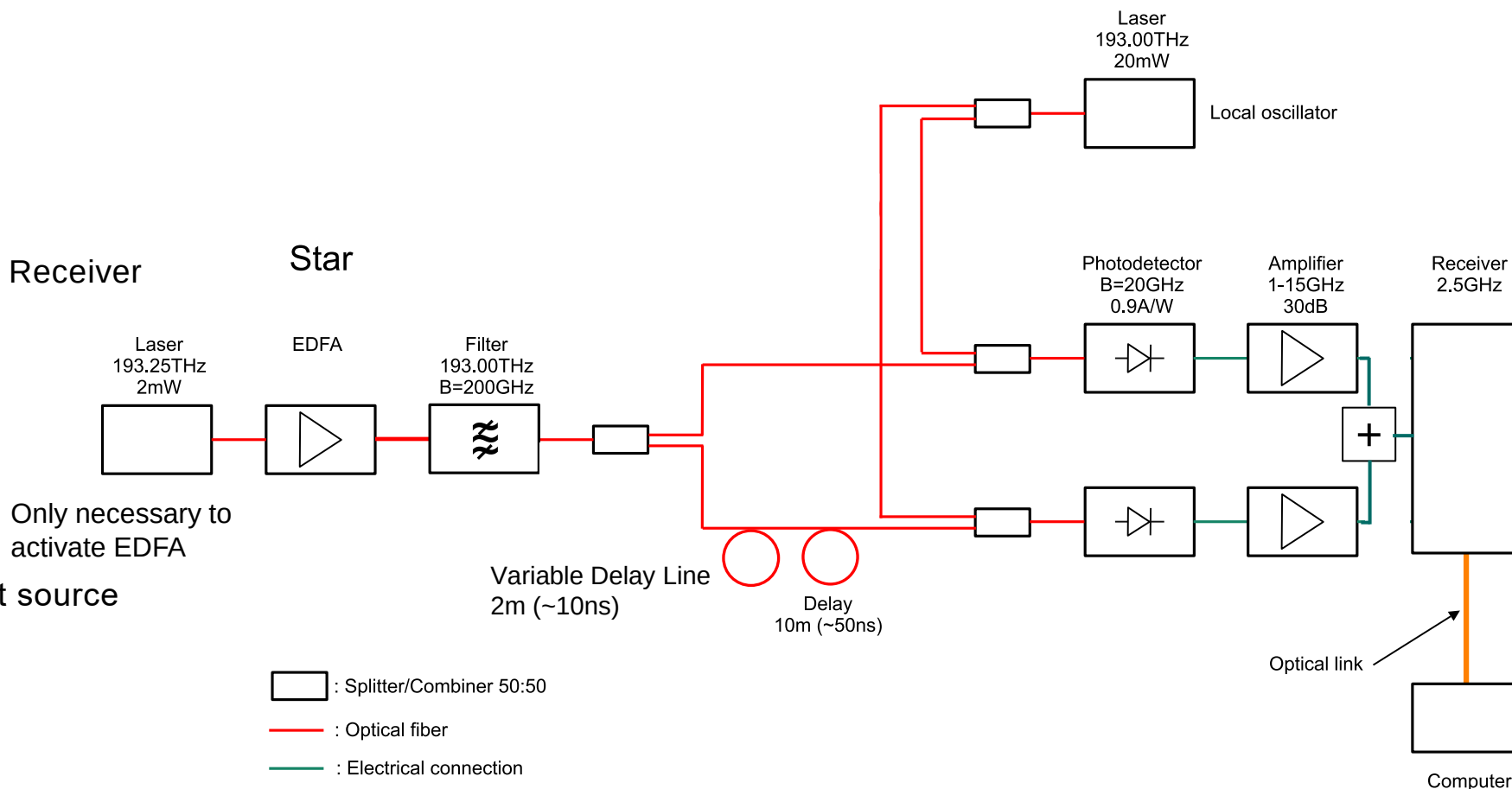
A TABLETOP NIR HETERODYNE INTERFEROMETER TESTBED



We constructed a NIR heterodyne interferometer testbed using (mostly) existing lab equipment:

- Commercial 1550 nm telecommunications components (laser, fibers, filter, etc.)
- EDFA as a white light source
- 20 GHz InGaAs photodetectors
- Low-noise RF amplifiers
- RFSoc 4x2 Software Defined Radio Receiver

Telescopes



Concept:

- Construct a “star” out of a white light source
- Down-convert ~100s THz to ~GHz
- Correlate RF signals

THE LAB SETUP



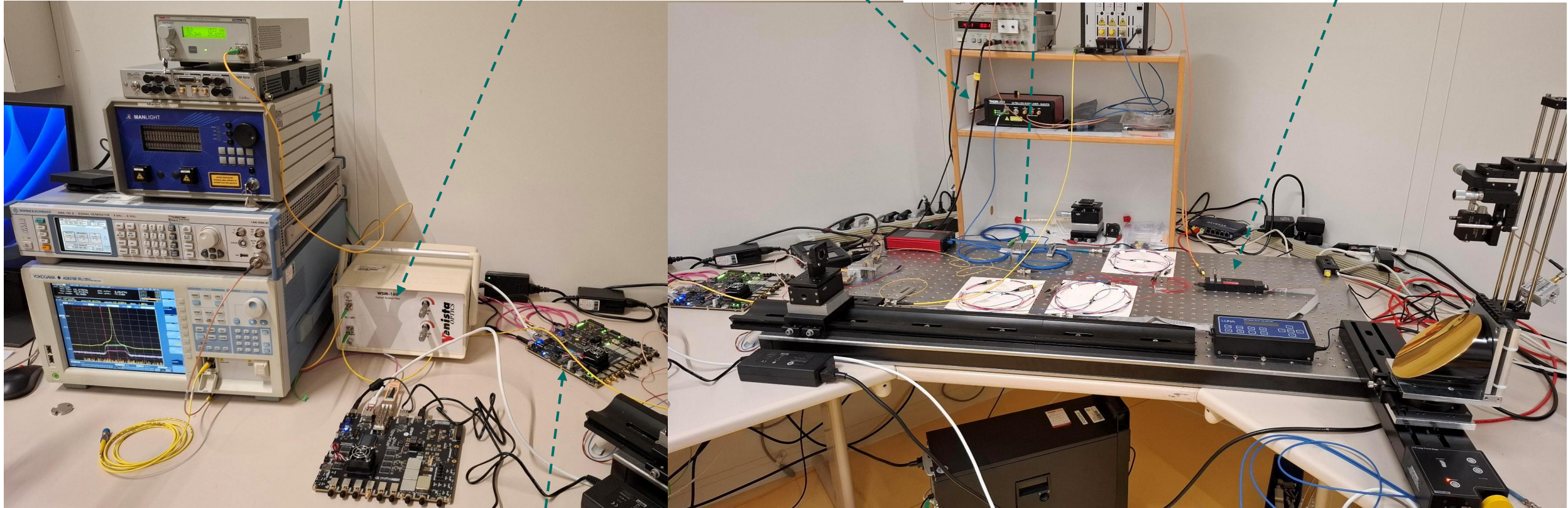
EDFA “star”

Filter

Laser (LO)

Fiber Delay Line
10m (~50ns)

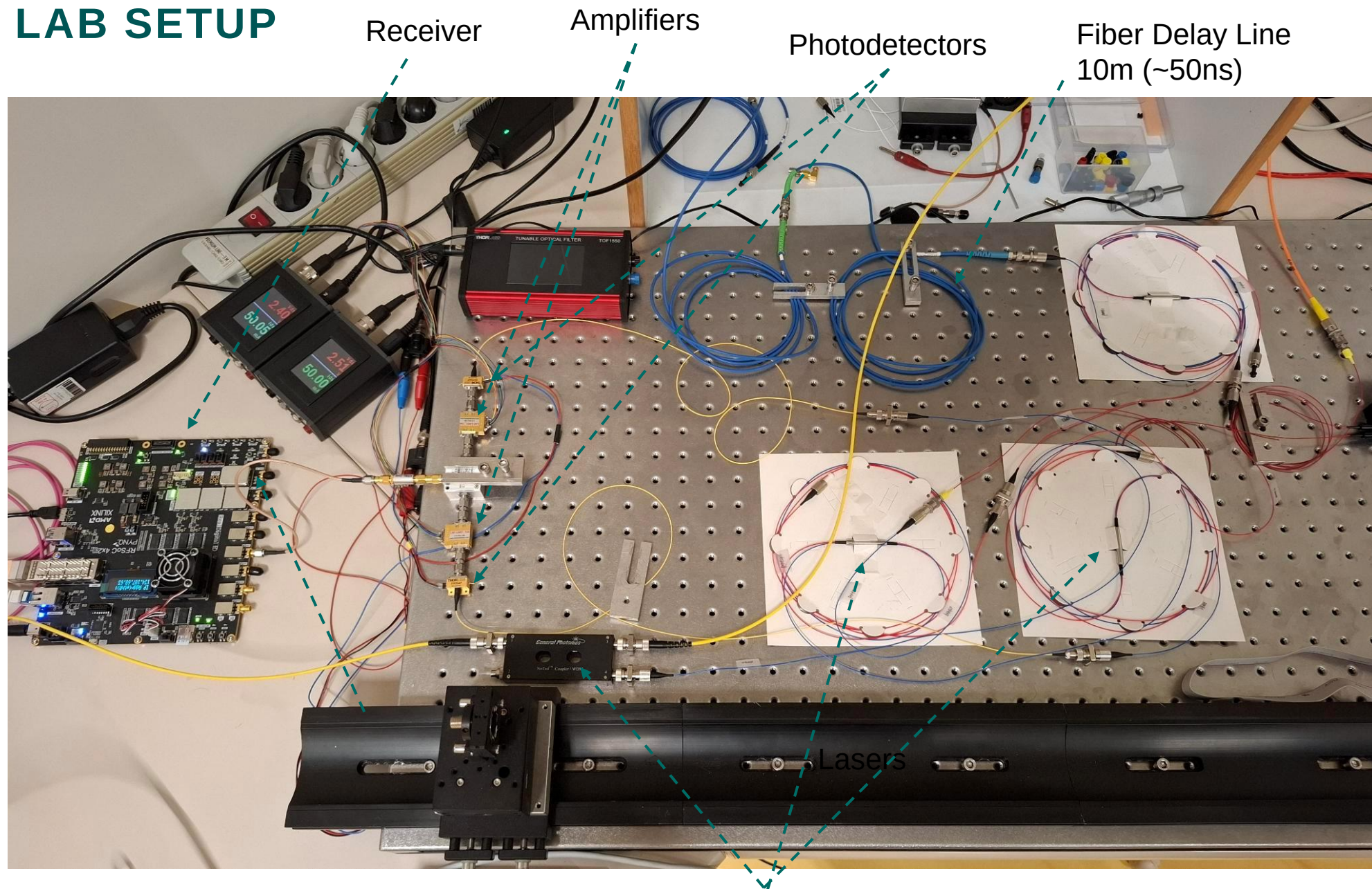
Variable Delay Line
2m (~10ns)



Not shown; PC with Control,
Monitoring and Correlator Software

Receiver

THE LAB SETUP





RECENT HARDWARE IMPROVEMENTS

- **Improvements to the NIR tabletop setup**
 - Incorporated atmospheric “turbulence” (phase disturbance) via a variable delay line
 - Better receiver system (RFSoc 4x2) now fully integrated into setup
 - Improved 1550 nm local oscillator laser: Thorlabs ultra low-noise laser system (<250 Hz linewidth)
 - SLD 1550 nm light source (not yet implemented). Our EDFA died in July! ☹

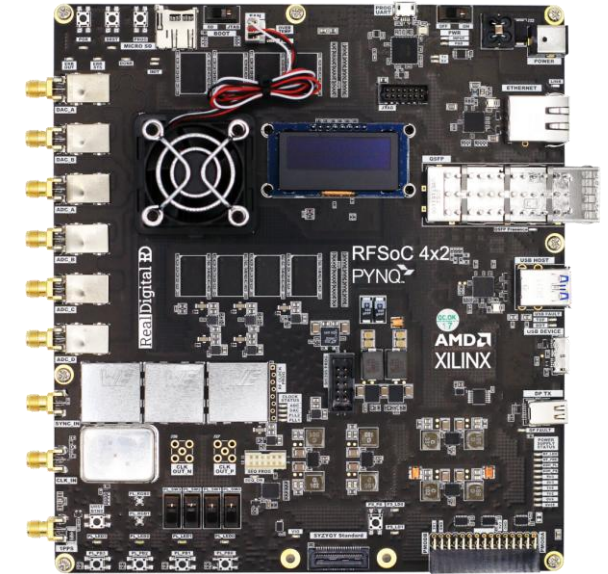
Motorized Variable Delay Line



Ultra Low-Noise 1550 nm (LO) Laser



RFSoc 4x2 SDR Receiver



SLD 1550 nm Light Source



MEASURED INPUT POWER, POWER SPECTRUM, AND CORRELATION

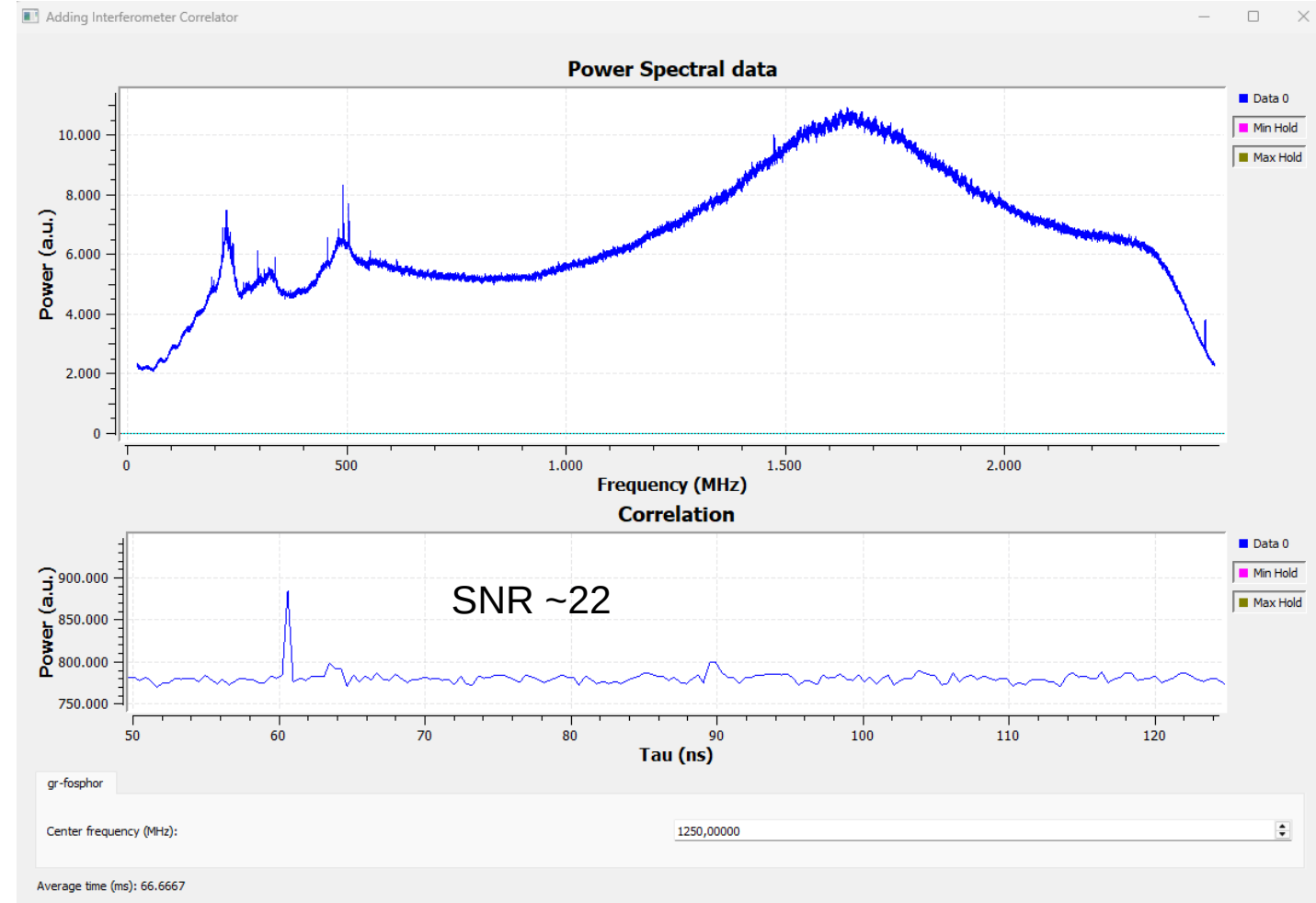
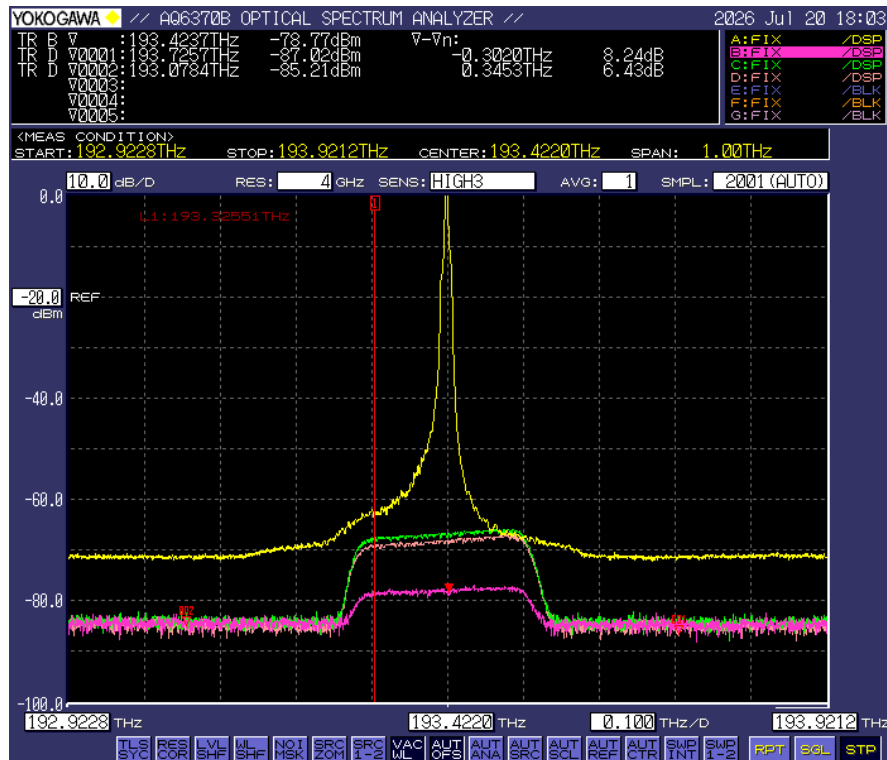


-78.77 dBm measured optical power (2 polarizations) in 4 GHz bandwidth at input to photodetector

2.5 GHz receiver bandwidth

Center frequency: 193.4 THz

66.66 ms averaging time





NEXT STEPS

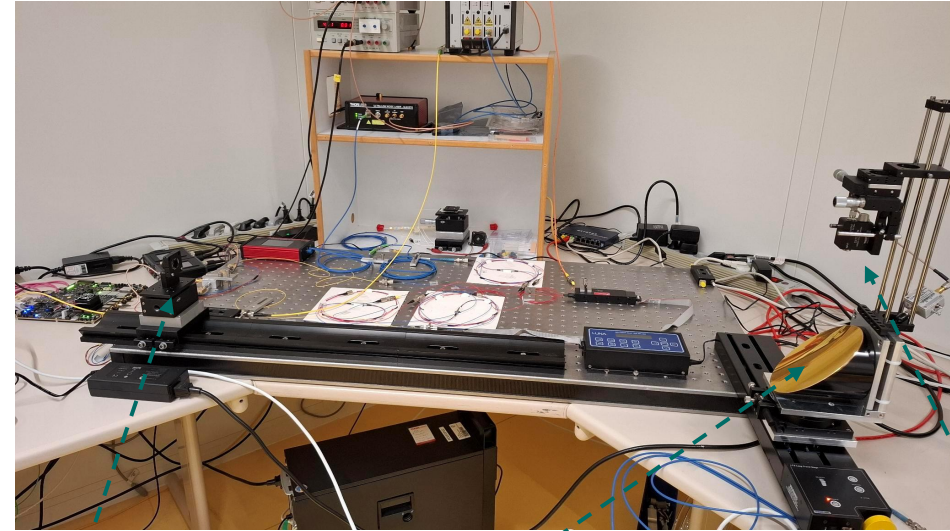
- **Near-term Plans**

- Measure effects with variable delay line
- Go to 10 cm free space star system with two telescopes in the lab
- Adapt system to larger telescopes with multiple baselines and aim to measure real stars (e.g. from the rooftop)

- **Longer-term Plans: Go to VIS (green light)**

- Some first steps already taken in this direction
- 7 GHz free-space photodetector already in lab
- Investigate limitations w.r.t. signal to noise
- Limited by available equipment in VIS

NIR Free-space setup



Fiber to free space coupling

10 cm mirror

Detector



7 GHz VIS free-space photodetector



Signal-to-Noise Ratio Comparison



SIGNAL-TO-NOISE RATIO: COMPARISON OF DIFFERENT SYSTEMS

- Signal-to-noise ratio (SNR) gives the fundamental limit of what an astronomical instrument can observe and measure.
- Sensitivity threshold gives the faintest target (faintest apparent magnitude) an instrument can observe given a statistical confidence level.
- We compare the Spectral Flux Density (S) of 3 instruments using reference values from the MPP-II measurements; **a statistical confidence level of 11 sigma, averaging time of 20 minutes, and an effective area (1 dish) of 1 m².**

MPP-II: Munich Intensity Interferometer (reference measurement)... See poster by Carina Haider and talk by Thomas Schweizer on Friday for more details

MPP-HI: Munich Infrared Heterodyne Interferometer (this system)

HB: Hanbury Brown and Twiss Intensity Interferometer [1]

[1] Hanbury Brown, R., *The Intensity Interferometer, its Application to Astronomy*, John Wiley & Sons Inc., New York, Toronto, 1st edition, 1974

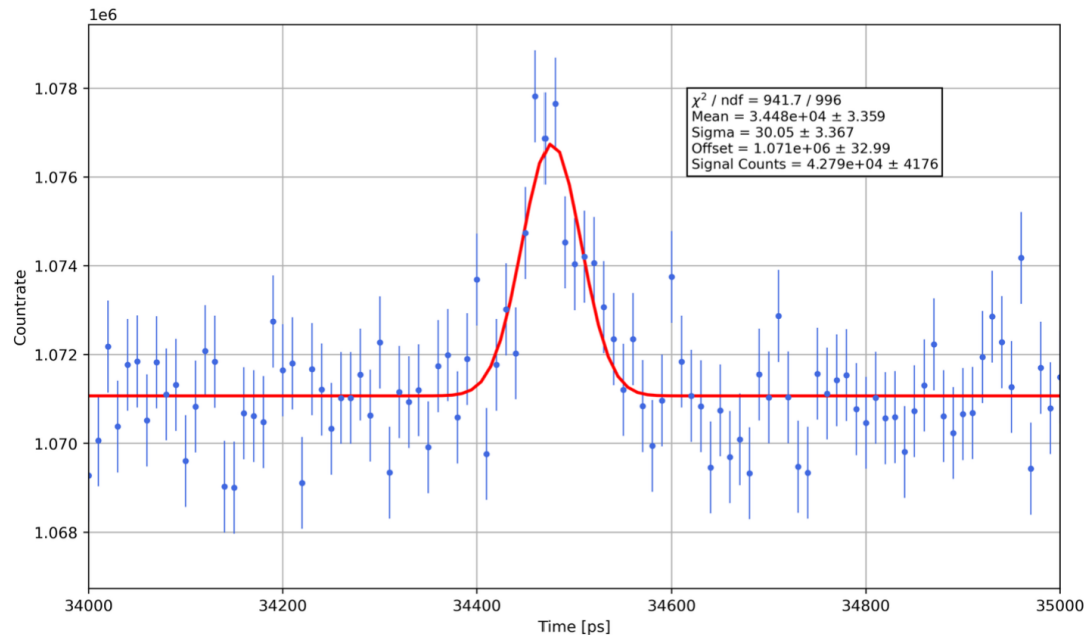


MPP-II SPECTRAL PHOTON DENSITY CALCULATIONS

- MCP-PMT reference measurement from C. Haider and T. Schweizer

With polarization filter

T = 20 min, R1 = 1.22e7, R2 = 0.74e7



- From measurement:

- SNR = 11
- Averaging time $T_A = 20\text{min}$
- Rate $R \approx 10\text{MHz}$; trigger-rate at one counter input
- $\Delta\nu = 1.9\text{THz}$; effective optical signal bandwidth at the photo detector input

$$n_{eff} = \frac{R_{eff}}{A_{eff} \Delta\nu} = \frac{10\text{MHz}}{1\text{m}^2 \cdot 1.9\text{THz}} = 5.3 \cdot 10^{-6} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}$$

- n is unknown, estimate with numbers from HBT ($\alpha=0.2$, $\Sigma=0.2$ [1], $\beta_0=2$, visibility $V^2=0.5$ because of the lens size gives

$$n = \frac{1}{V^2 \beta_0} \frac{n_{eff}}{\alpha \Sigma} \approx \frac{5.3 \cdot 10^{-6} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}}{0.5 \cdot 2 \cdot 0.2 \cdot 0.2} = 1.3 \cdot 10^{-4} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}$$



MPP-HI SPECTRAL PHOTON DENSITY CALCULATIONS

- **MPP Heterodyne measurements**

- $\nu = 193.4\text{THz}$; optical center frequency
- Averaging time $T_A = 66.66\text{ms}$
- $\Delta\nu_M = 4\text{GHz}$; filter bandwidth of the optical spectrum analyzer (form factor ignored)
- $P_M = -78.77\text{dBm}$; measured optical power at photodetector input in two polarization (-3 dB for one pol.)
- Spectral flux density S_M normalized to $A_{\text{eff}} = 1\text{m}^2$ is

$$S_M = \frac{P_M}{A_{\text{eff}} \Delta\nu_M} = \frac{1\text{mW} \cdot 10^{\frac{-81.77\text{dBm}}{10\text{dBm}}}}{1\text{m}^2 \cdot 4\text{GHz}} \approx 1.7 \cdot 10^{-21} \text{Wm}^{-2} \text{Hz}^{-1}$$

- And the corresponding spectral photon flux density n_M is

$$n_M = \frac{S_M}{h \nu} \approx 1.3 \cdot 10^{-2} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}$$

$$S = n h \nu \approx 620 \text{Jy}$$

- Renormalization from $T_{AM} = 66.66\text{ms}$ to the reference value $T_A = 20\text{min} (=1200\text{s})$ gives

$$n_{M20} = n_M \sqrt{\frac{T_{AM}}{T_A}} = 1.3 \cdot 10^{-2} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1} \sqrt{\frac{66.66\text{ms}}{1200\text{s}}} \approx 9.6 \cdot 10^{-5} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}$$

- Rescaling by factor $\Delta s \approx 2$ to account for higher SNR in the HI-measurement (22) w.r.t. the reference value (11) gives the spectral photon flux density n

$$n = \frac{n_{M20}}{\Delta s} = \frac{9.6 \cdot 10^{-5} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}}{2} \approx 4.8 \cdot 10^{-5} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}$$



HBT SPECTRAL PHOTON DENSITY CALCULATIONS

- **Data taken from [1], page 50 for the Narrabri stellar interferometer**

- $\nu = 697.2\text{THz}$; optical center frequency (430 nm wavelength)
- $\Delta f = 100\text{ MHz}$; filter bandwidth of the electrical system
- With $A_{\text{eff}} = 1\text{m}^2$, $T_A = 20\text{min}$ ($=1200\text{s}$), quantum effic. $\alpha = 0.2$, and system effic. $\Sigma = 0.2$ using equ. 4.30 [1]

$$n = \frac{s}{\alpha \Sigma A_{\text{eff}} \sqrt{\Delta f T_A/2}} = \frac{11}{0.2 \cdot 0.2 \cdot 1\text{m}^2 \sqrt{100\text{MHz} \cdot 1200\text{s}/2}} \approx 1.1 \cdot 10^{-3} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}$$

$$S = n h \nu \approx 51.9 \cdot 10^3 \text{Jy}$$

- The effective spectral photon flux density n_{eff} is (with $n_0 = n$ because $\beta_0 = 1$ and $\Delta(\nu_0)\Gamma^2(\nu_0, d) = 1$)

$$n_{\text{eff}} = n \alpha \Sigma = 1.1 \cdot 10^{-3} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1} \cdot 0.2 \cdot 0.2 \approx 4.5 \cdot 10^{-5} \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1}$$

[1] Hanbury Brown, R., *The Intensity Interferometer, its Application to Astronomy*, John Wiley & Sons Inc., New York, Toronto, 1st edition, 1974



SIGNAL-TO-NOISE RATIO: COMPARISON OF DIFFERENT SYSTEMS

- Spectral photon density calculation (sensitivity) for $A_{\text{eff}}=1\text{m}^2$, $\text{SNR}=11$ and $T_A=20\text{min}$:

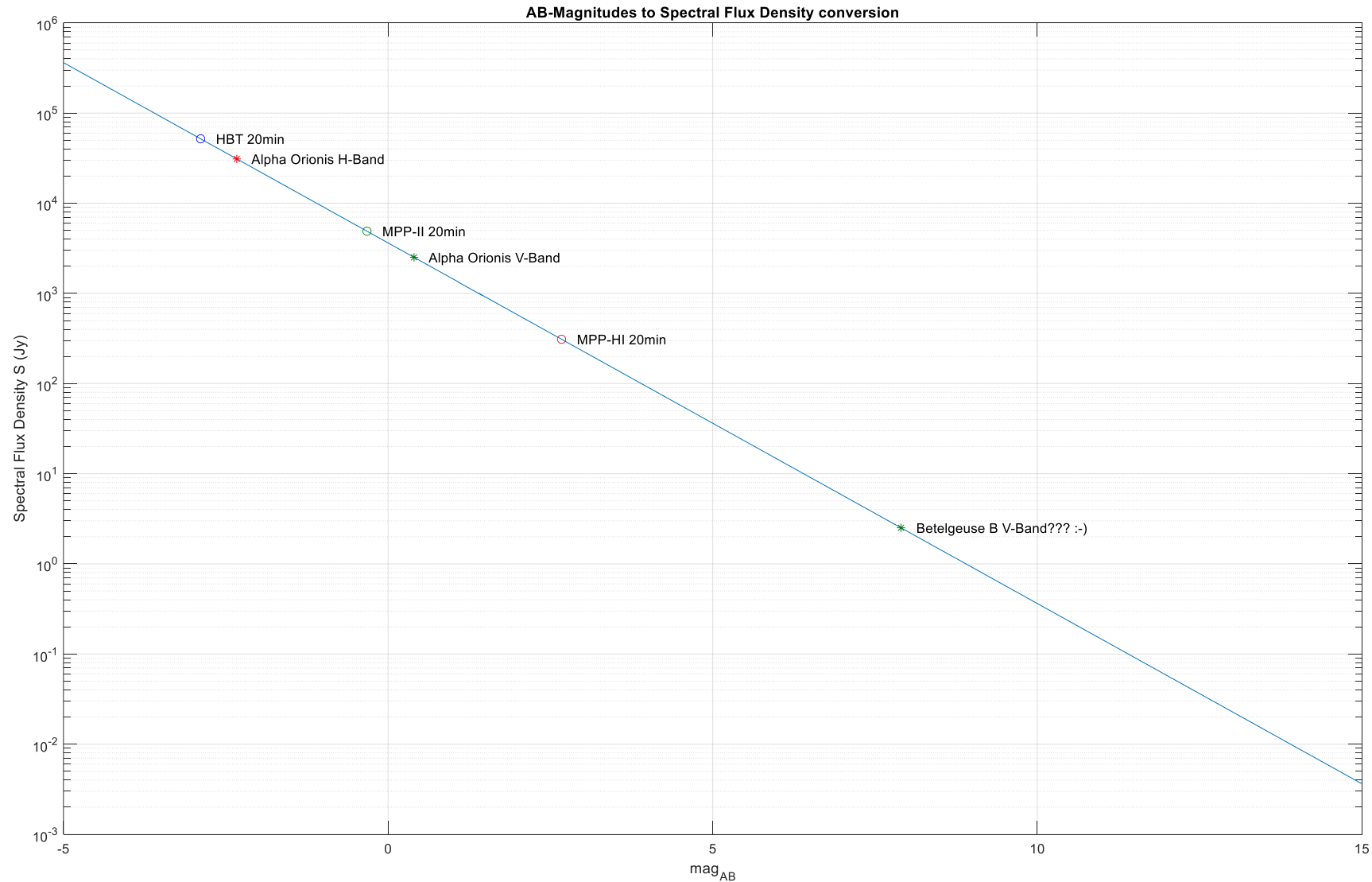
		MPP-II	MPP-HI	HBT [1]
Opt. frequency	ν	562 THz (533nm)	193.4 THz (1550nm)	697.2 THz (430 nm)
Opt. bandwidth	$\Delta\nu$	1 THz	5 GHz	
Quantum efficiency	α		$\approx 70 \%$	20 %
Opt. spectral photon density	n	$(1.3 \cdot 10^{-4} \text{ m}^{-2} \text{ s}^{-1} \text{ Hz}^{-1})^*$	$\approx 4.8 \cdot 10^{-5} \text{ m}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$	$1.1 \cdot 10^{-3} \text{ m}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$
Opt. spectral flux density	S	(4900 Jy)*	620 Jy	51865 Jy
Eff. spectral photon density	n_{eff}	$5.3 \cdot 10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$		$4.5 \cdot 10^{-5} \text{ m}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$

*: assuming numbers from HBT[1] ($\alpha=0.2$, $\Sigma=0.2$)

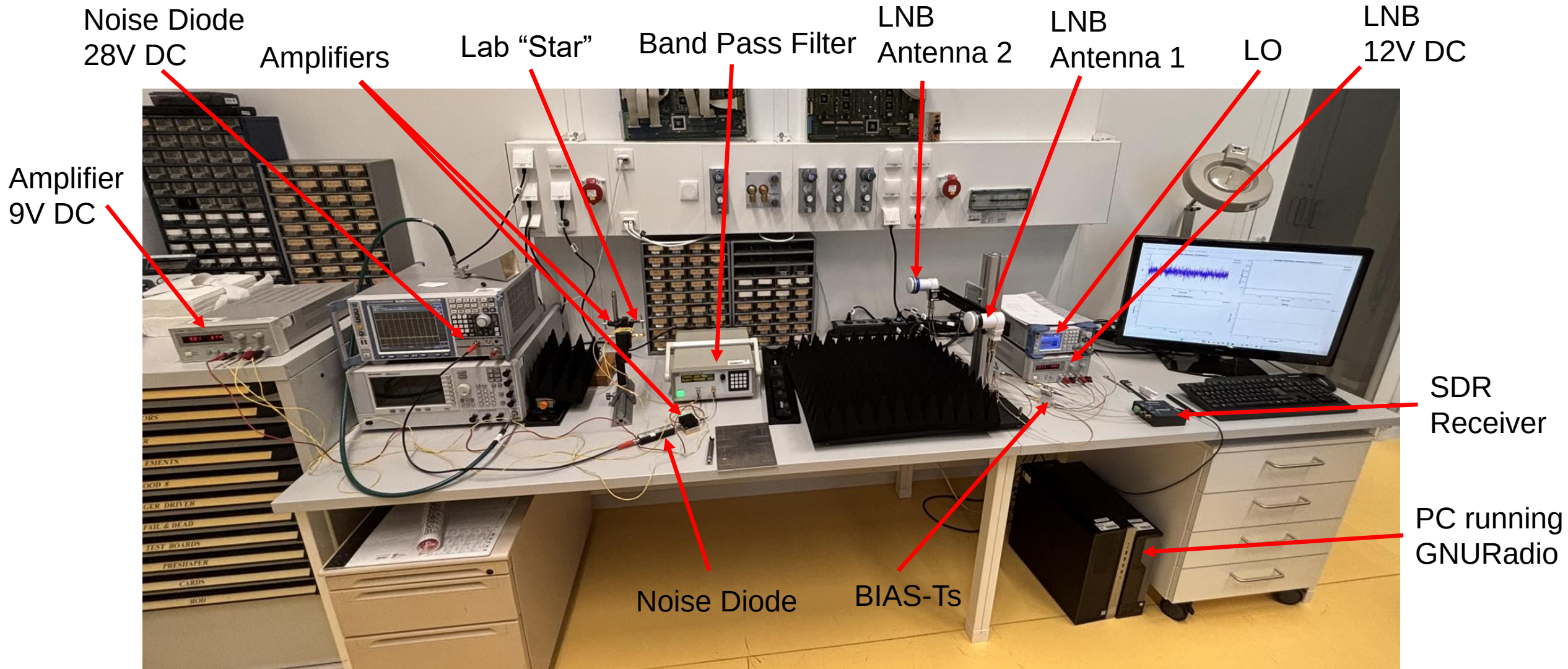
[1] Hanbury Brown, R., *The Intensity Interferometer, its Application to Astronomy*, John Wiley & Sons Inc., New York, Toronto, 1th edition, 1974



SIGNAL-TO-NOISE RATIO: COMPARISON OF DIFFERENT SYSTEMS



OUTREACH: 2-ELEMENT HETERODYNE RADIO INTERFEROMETER



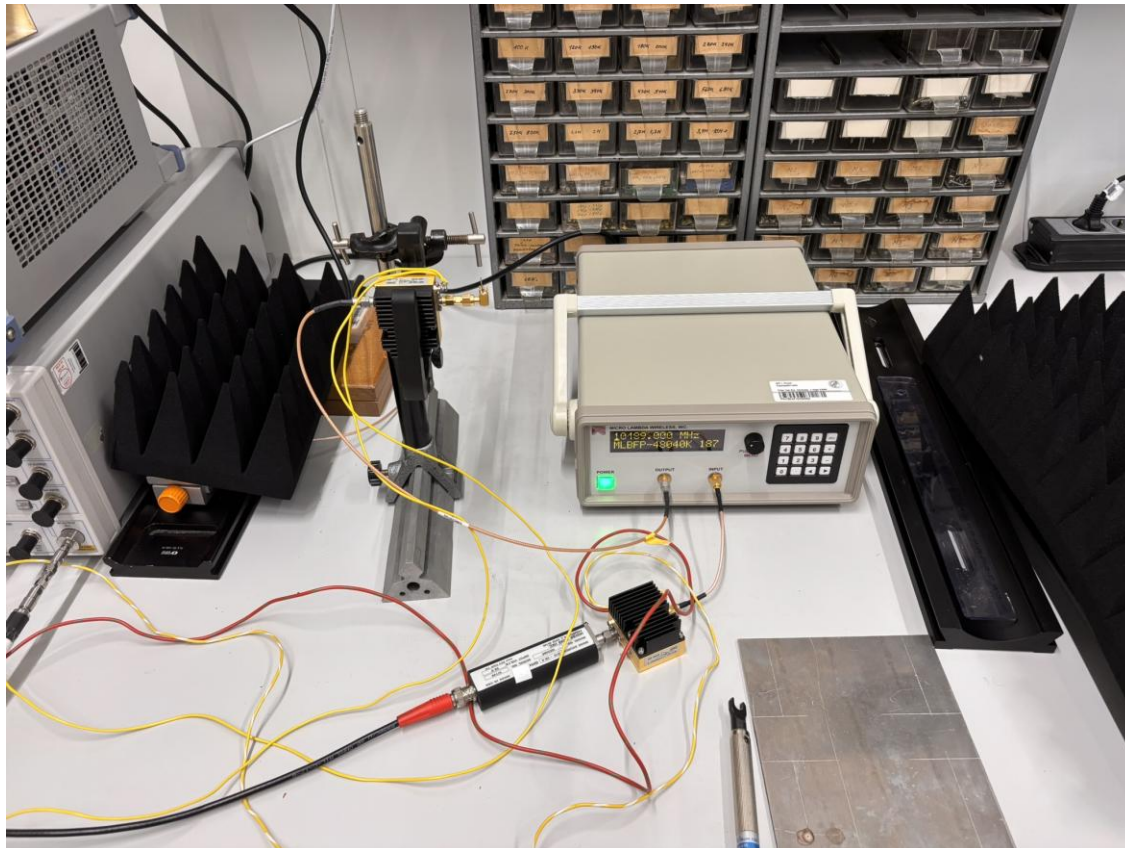
2-ELEMENT HETERODYNE RADIO INTERFEROMETER



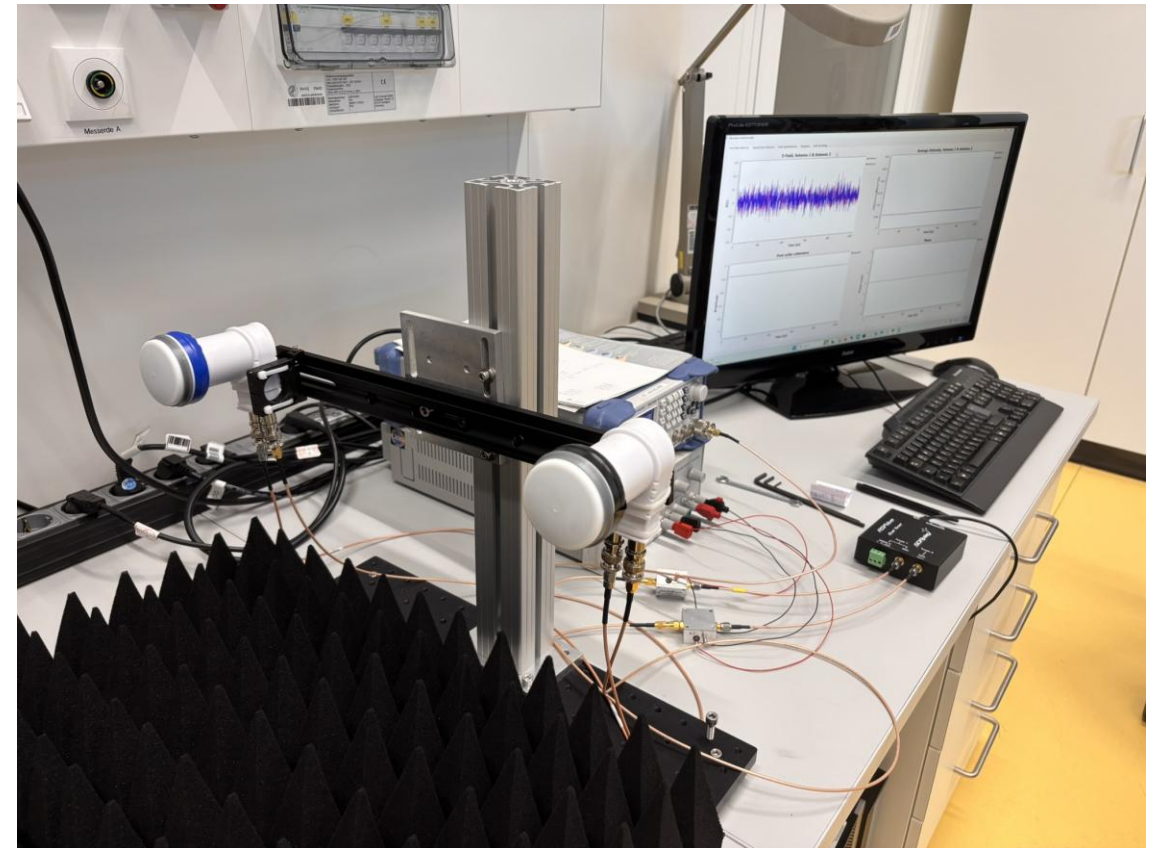
- 10.5 GHz Noise Diode as Source
- Amplifier
- Filter
- Wire antenna Tx

- 2 Low Noise Block Downconverters: 10.5 GHz to 739 MHz
- 9.75 GHz local oscillator (coherent)
- Coherent dual-channel sampling SDR (1kHz to 2 GHz, 2 Msps)

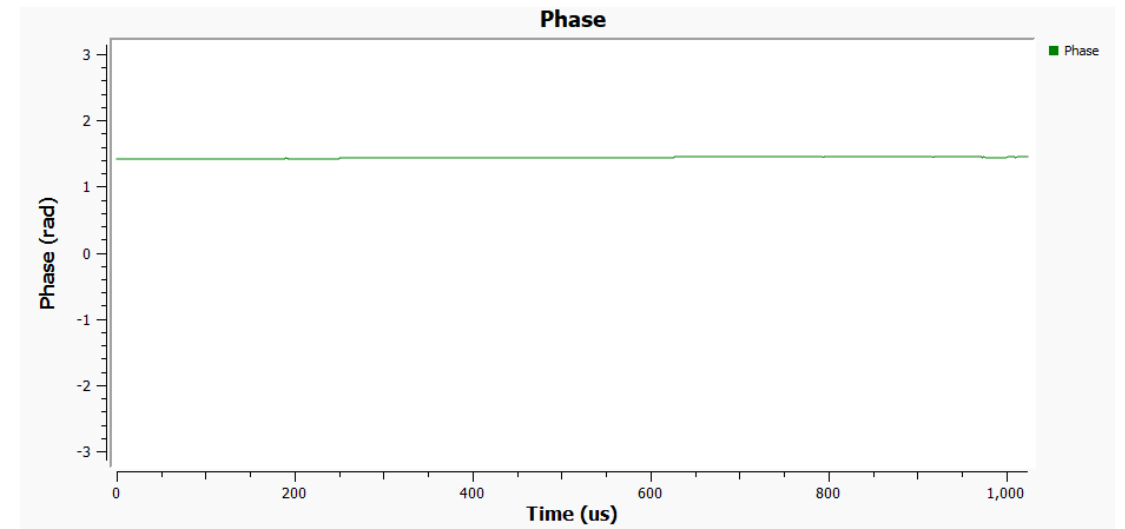
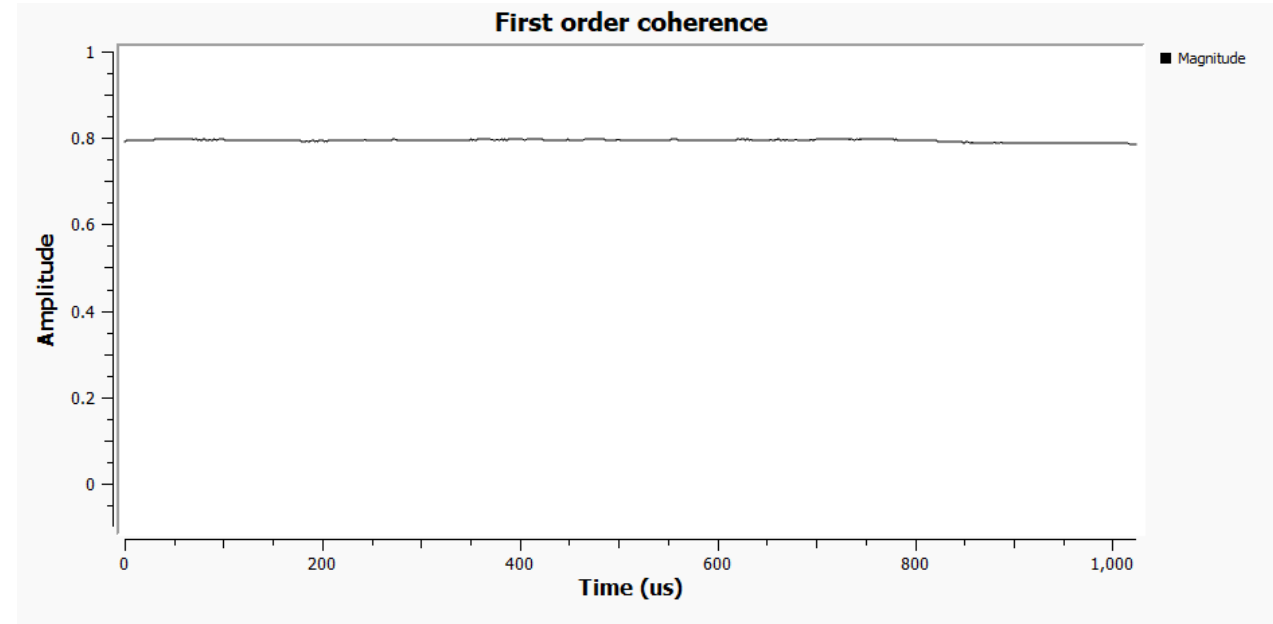
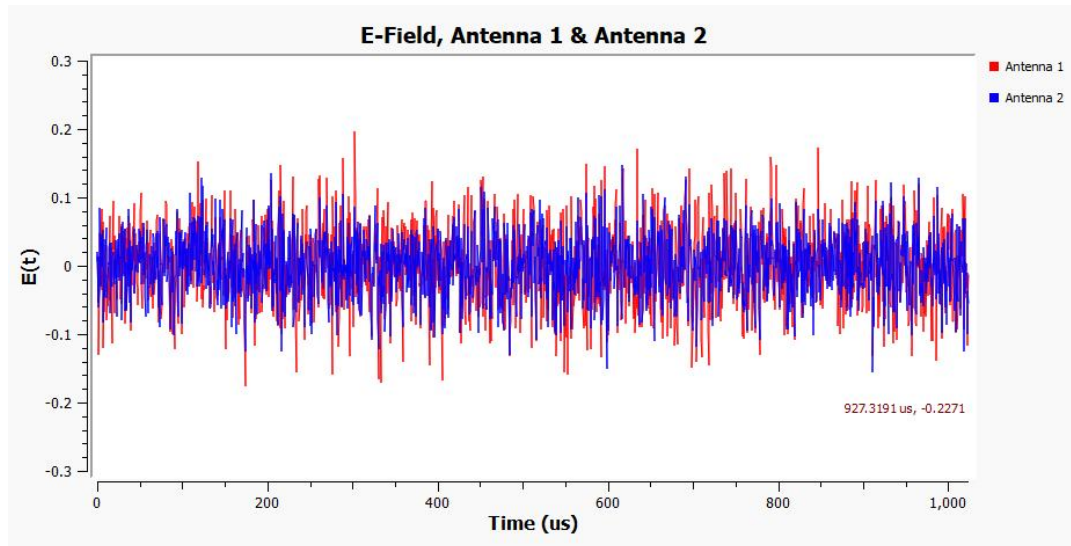
“Star”



Telescope

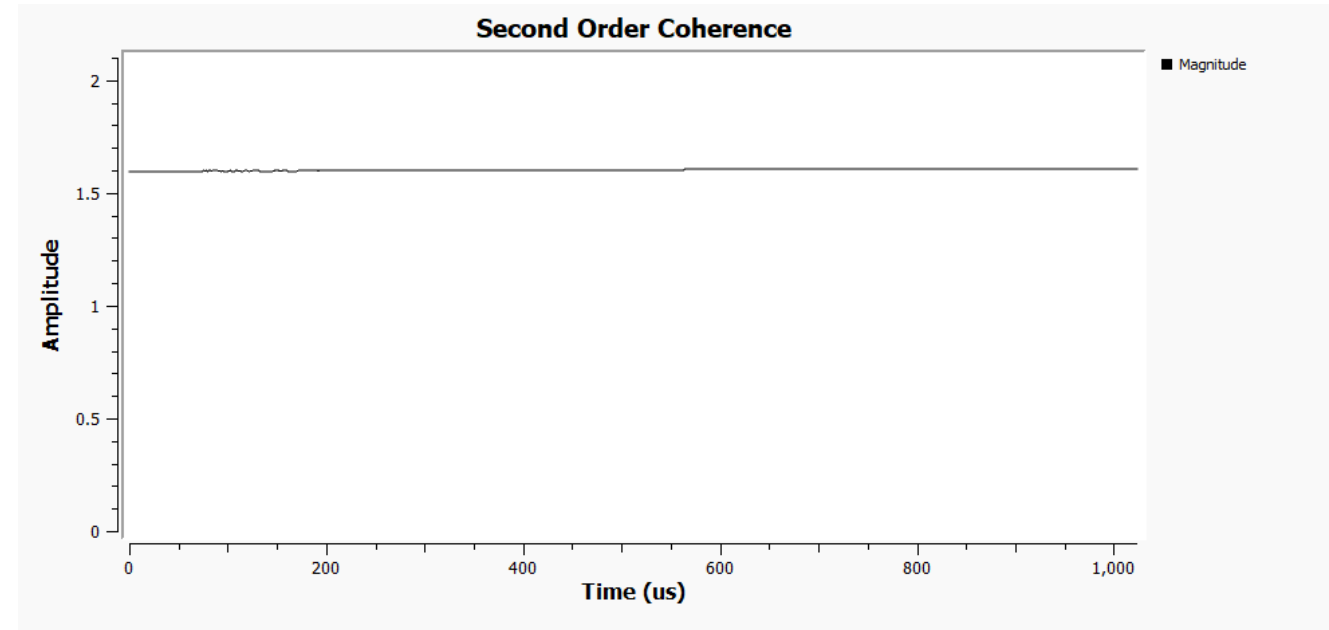
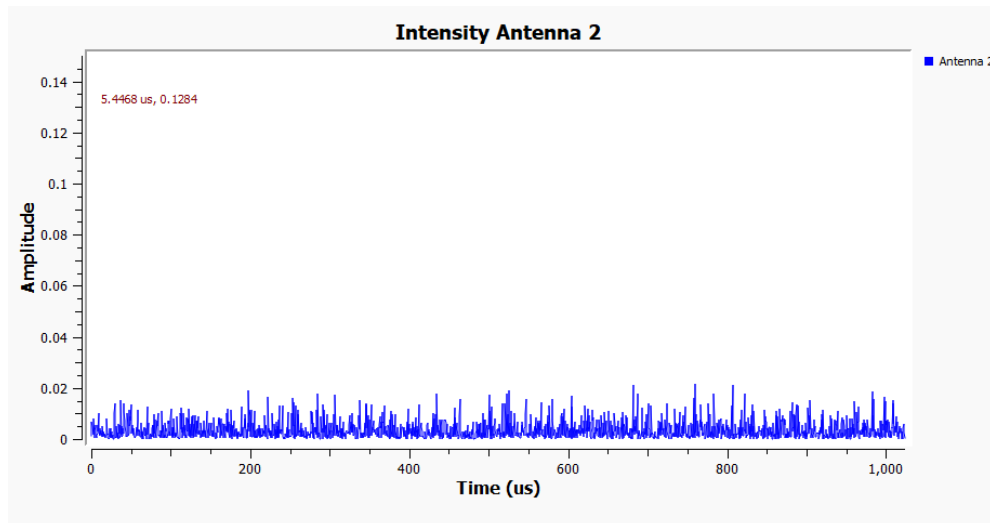
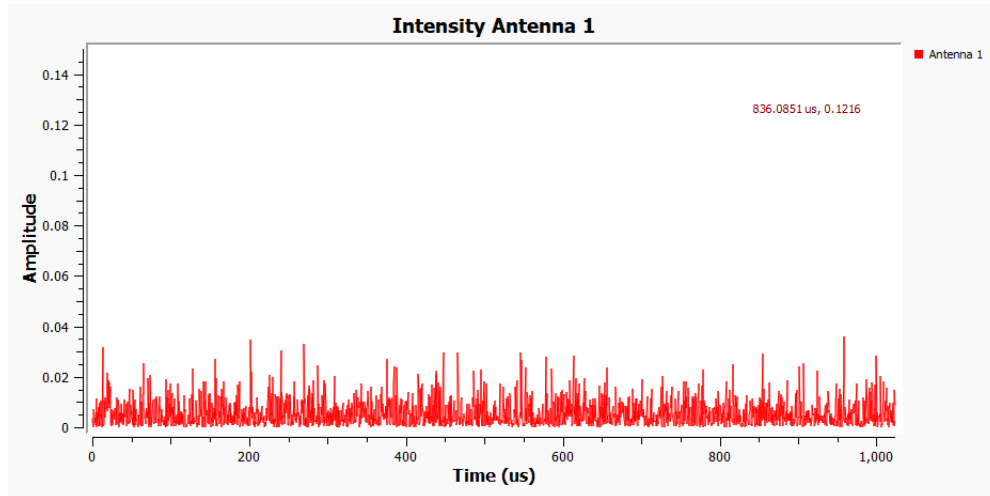


FIRST-ORDER COHERENCE FUNCTION





SECOND-ORDER COHERENCE FUNCTION



SUMMARY



Light is the fundamental carrier of astronomical information and how photons are detected matters.

Heterodyning is an attractive light detection method.

- Higher sensitivity due to parametric amplification
- Benefits from well-established methods in radio astronomy
- Scalable to km-long baselines

We presented a description of an improved tabletop testbed interferometer constructed at the MPP lab to further explore the advantages and limitations of the heterodyne approach.

A direct comparison of the sensitivity of 3 different systems were made.

- Heterodyning is shown to be more sensitive than II systems (at least in the NIR)
- More studies are needed

Plans are to move to a free space interferometer (and VIS) and further improvements to the setup.

- Preliminary steps made to go to green light, but not all equipment already available in house



THANK YOU



BACKUP



BRIEF HISTORICAL PERSPECTIVE

October 13, 1986

Optical synthesis telescopes *

G. W. Swenson, Jr., C. S. Gardner

Electrical and Computer Engineering Department, University of Illinois
Urbana, Illinois 61801

and

R. H. T. Bates

Electrical and Electronic Engineering Department, University of Canterbury
Christchurch, New Zealand

Abstract

A new type of optical/infra-red telescope is suggested, based on a combination of the principles of radio astronomical interferometric image synthesis and computational phase retrieval. Physical configurations, design principles, necessary technical developments, possible modes of operation and important possible uses of the telescope are discussed. The design philosophy is that it should not be necessary to maintain tighter mechanical tolerances than those required conventionally for radio telescopes. Because it is intended to realize milli-arc-second resolution, implying a telescope aperture of the order of 100 m, it is recognized that it is impractical to achieve optical tolerances, so that the adopted design principles should not rely on them. The design goals can be attained by relying on heterodyne detection followed by purely digital processing, thereby permitting useful signal-to-noise ratios to be conveniently obtained by multiplexing parallel channels with the aid of large-scale-integration techniques. Besides offering highly resolved images of many of the more important astrophysical objects, the telescope could be used for imaging certain types of space vehicles. The kind of telescope proposed herein could be usefully constructed either on the surface of the earth or outside the Earth's atmosphere.

1988

UC Berkeley Infrared Spatial Interferometer (ISI)

Charles Townes and Co. build world's first mid-IR interferometer
(2.25 micron and 11 micron).

The Berkeley Infrared Spatial Interferometer:

A Heterodyne Stellar Interferometer for the Infrared,

D.D.S. Hale et. al., The Astrophysical Journal, 537:998-1012 (2000)

Heterodyne principles

Photographic film and electronic photodetectors respond to intensity rather than amplitude. Phase information is not preserved in the detected signals. However, phase can be measured if heterodyne detection or holographic techniques are used. In heterodyne detection, the optical signal is combined with a local oscillator beam and both signals are focused onto the same detector. Heterodyne detection receivers respond to signal amplitude and were originally developed for use in the far infrared region of the spectrum to overcome limitations imposed by poor detector sensitivity. Heterodyne systems have been developed for remote sensing, imaging and communications applications⁶.

A simple heterodyne detection receiver is diagrammed in Figure 1. The local oscillator (LO) beam is combined with the optical signal and both are focused onto the detector. Because the objective and collimating lenses demagnify the signal beam, the receiving telescope illustrated in Figure 1 is optically equivalent to combining the signal and LO in front of the objective lens. Optical mixing of the signal and LO beams produces an intermediate frequency (IF) signal in the detector output which is proportional to the signal amplitude. The IF is the difference between the signal and LO frequencies.

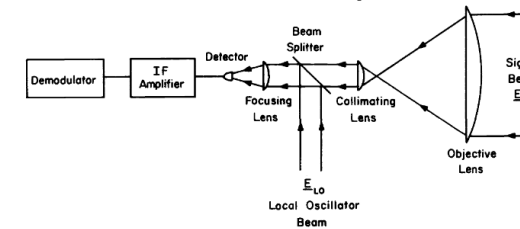


Figure 1. General principle of a heterodyne telescope.

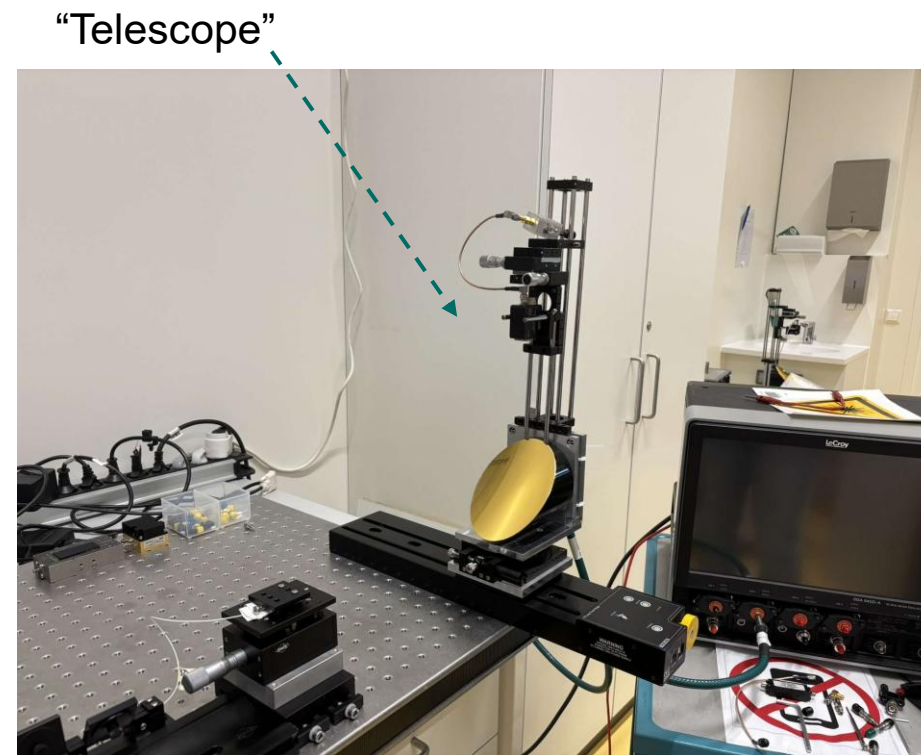
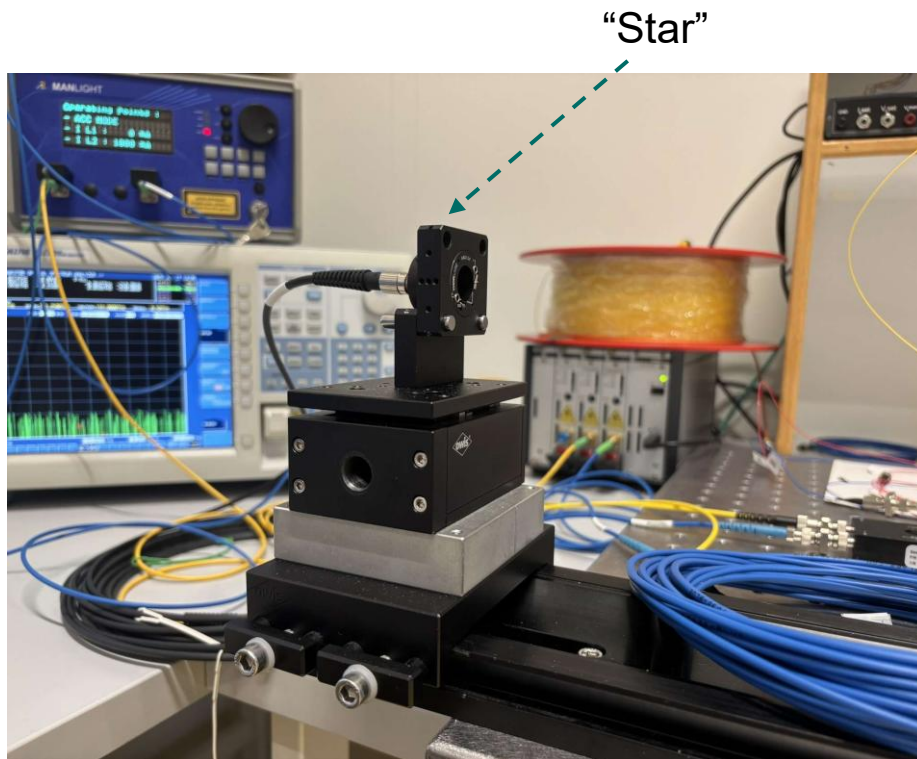
130 / SPIE Vol. 643 Infrared, Adaptive, and Synthetic Aperture Optical Systems (1986)



TOWARDS A FREE SPACE SETUP

Building a free space setup with two telescopes

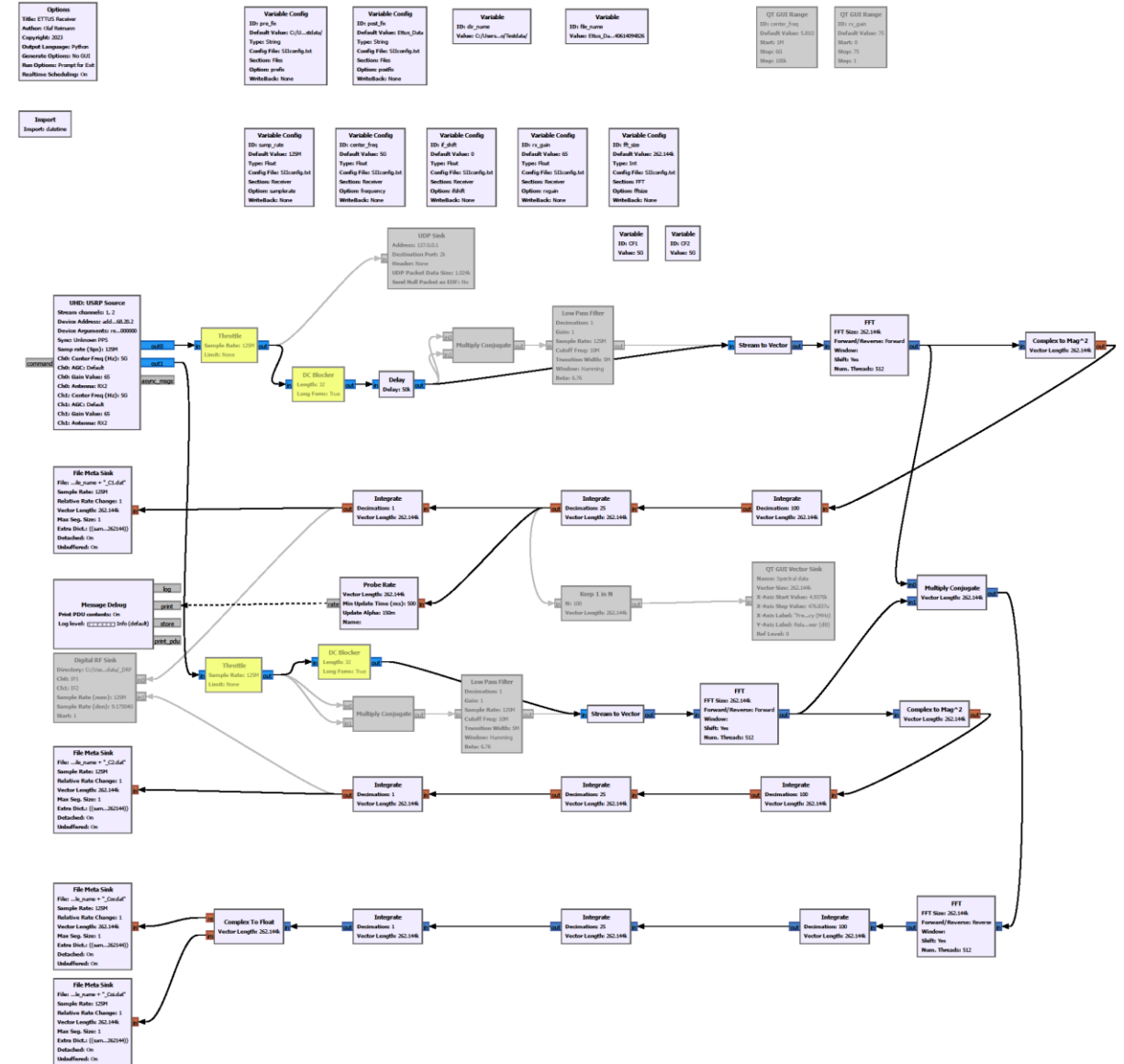
- Infrared “star” with 3 micron fiber aperture
- Two 10cm diameter telescopes (gold mirrors), 8 GHz free-space photodetectors
- Some preliminary tests performed, but system needs to be mechanically improved before further measurements



CORRELATOR

Real-time correlator:

- Using GNU Radio (FOSS)
- Using only processing cores
- 125 MS/s IQ sampling rate
- Using FFT/IFFT correlation technique
- 2^{18} (2^{19}) sample FFT
- ~5s averaging
- Output (every ~5s)
 - 2 channel spectral intensities
 - Complex cross correlation of the 2 channels





HETERODYNE INTERFEROMETER

WHAT IS THE DIFFERENCE TO INTENSITY INTERFEROMETRY?

- Correlation signal for monochromatic input signals (without proof)

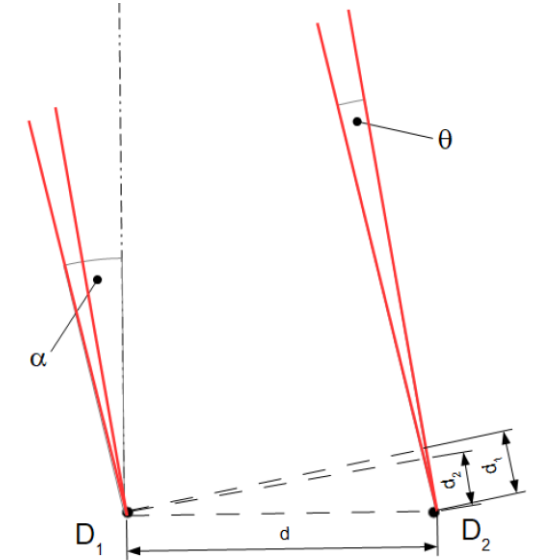
- Intensity interferometry:

$$I_I = \frac{K E_{10}^2 E_{20}^2}{2} \cos(T_D \omega_O - T_2 \omega_D) \quad T_D = T_1 - T_2$$

- Heterodyne (field) interferometry

$$I_H = \frac{K_1 E_{10}^2 E_{LO}^2}{2} \cos(T_1 \omega_O) + \frac{K_2 E_{20}^2 E_{LO}^2}{2} \cos(T_2 \omega_O) + \frac{K_2 E_{20}^2 E_{LO}^2}{2} \cos(T_2 \omega_D) + \frac{K E_{10}^2 E_{20}^2}{2} \cos(T_D \omega_O - T_2 \omega_D)$$

- ω_O : Optical (radian) frequency
- ω_D : Frequency difference between signal 1 and signal 2
- E_{10}, E_{20} : Field amplitude of signal 1 and signal 2
- E_{LO} : Field amplitude of local oscillator signal ($E_{LO} \gg E_{10}, E_{20}$)
- K, K_1, K_2 : Detector constants

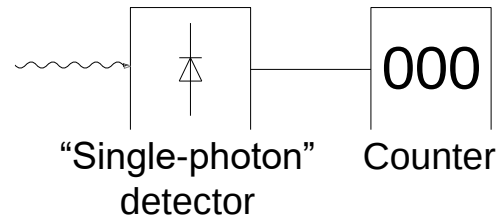




YES, HETERODYNE DETECTION

Heterodyne detection is an alternative technique to photon counting and photon flux measurements.

Photon counting:



Photon flux measurement

