

A TABLETOP TESTBED FOR DEVELOPING A HETERODYNE INTERFEROMETER AT MPI

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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:

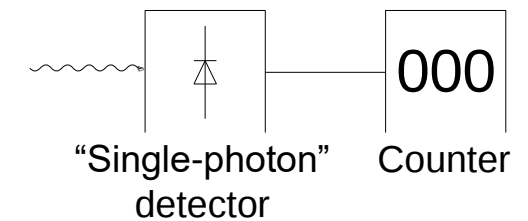
- **Low photon flux** from distant sources
- **Atmospheric turbulence** (i.e. phase disturbance)
- Need for **ultra-high angular resolution**

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

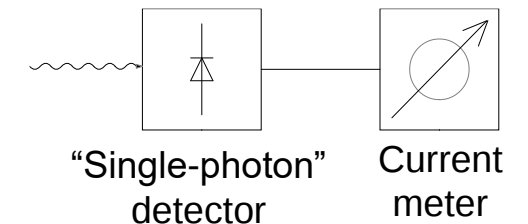
It matters how we detect the incoming light.

Are there additional options to photon counting and flux measurements?

Photon counting:



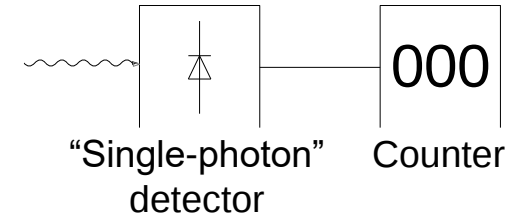
Photon flux measurement



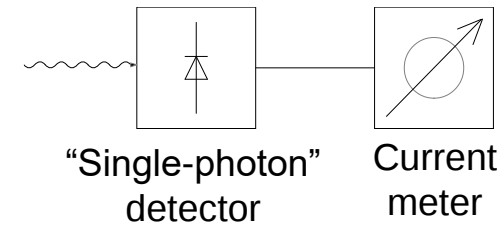
Yes, Heterodyning....



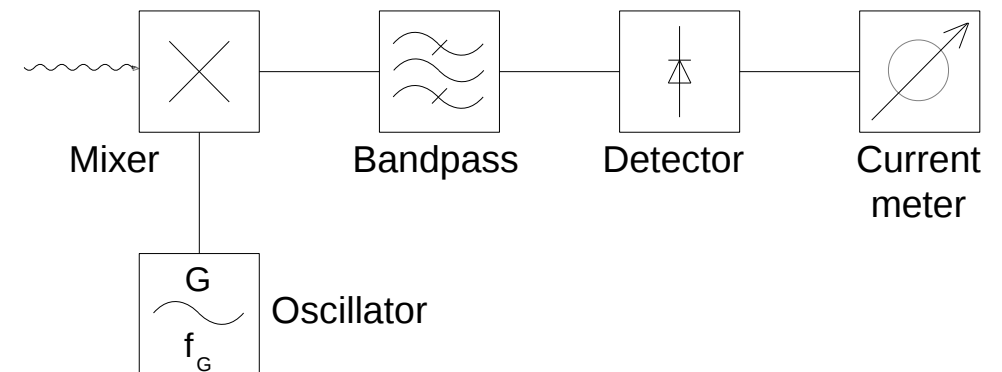
Photon counting:



Photon flux measurement



Heterodyne: Mix 2 different frequencies



HETERODYNE DETECTION: MIXING LIGHT WITH LIGHT

Principle: Mix starlight with a stable local oscillator (laser).

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

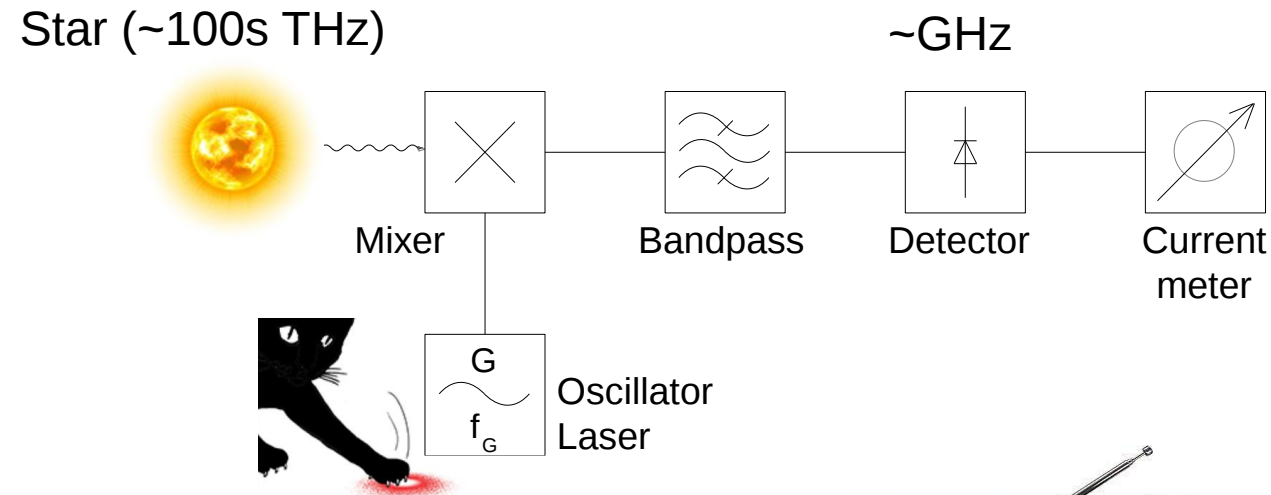
Applications: stellar interferometry, quantum optics, optical data transmission/communications systems.

Some 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



Nothing new!
Heterodyning has been
around a long time.



Starlight

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

Local oscillator

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

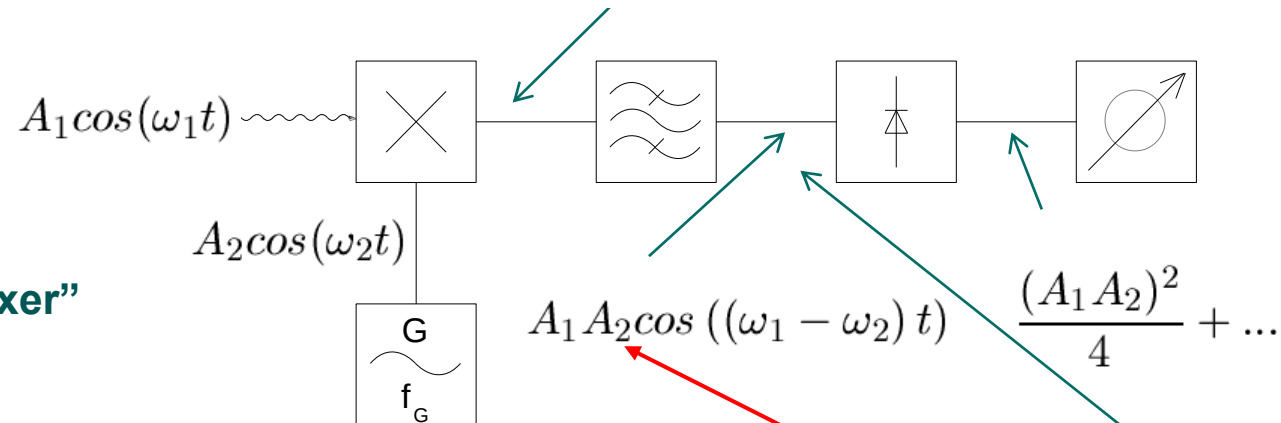
Mixing

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

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

Heterodyning

The Photodetector is the “mixer”



Gain

Amplitude and
phase information
preserved

Key heterodyne advantages:

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

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.

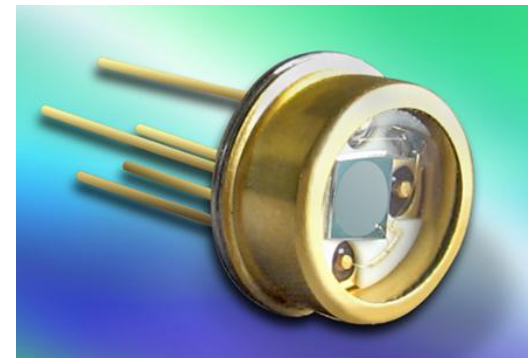
$$\text{Photocurrent: } i(t) \sim P(t) = \frac{|E^2(t)|}{Z_0}$$

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)**



October 13, 1986

Optical synthesis telescopes *

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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.

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.

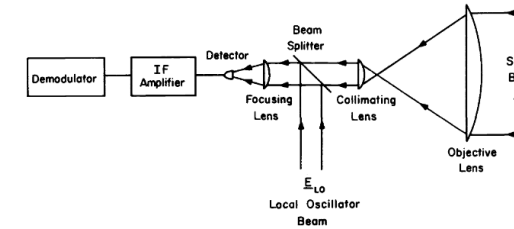


Figure 1. General principle of a heterodyne telescope.

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

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)



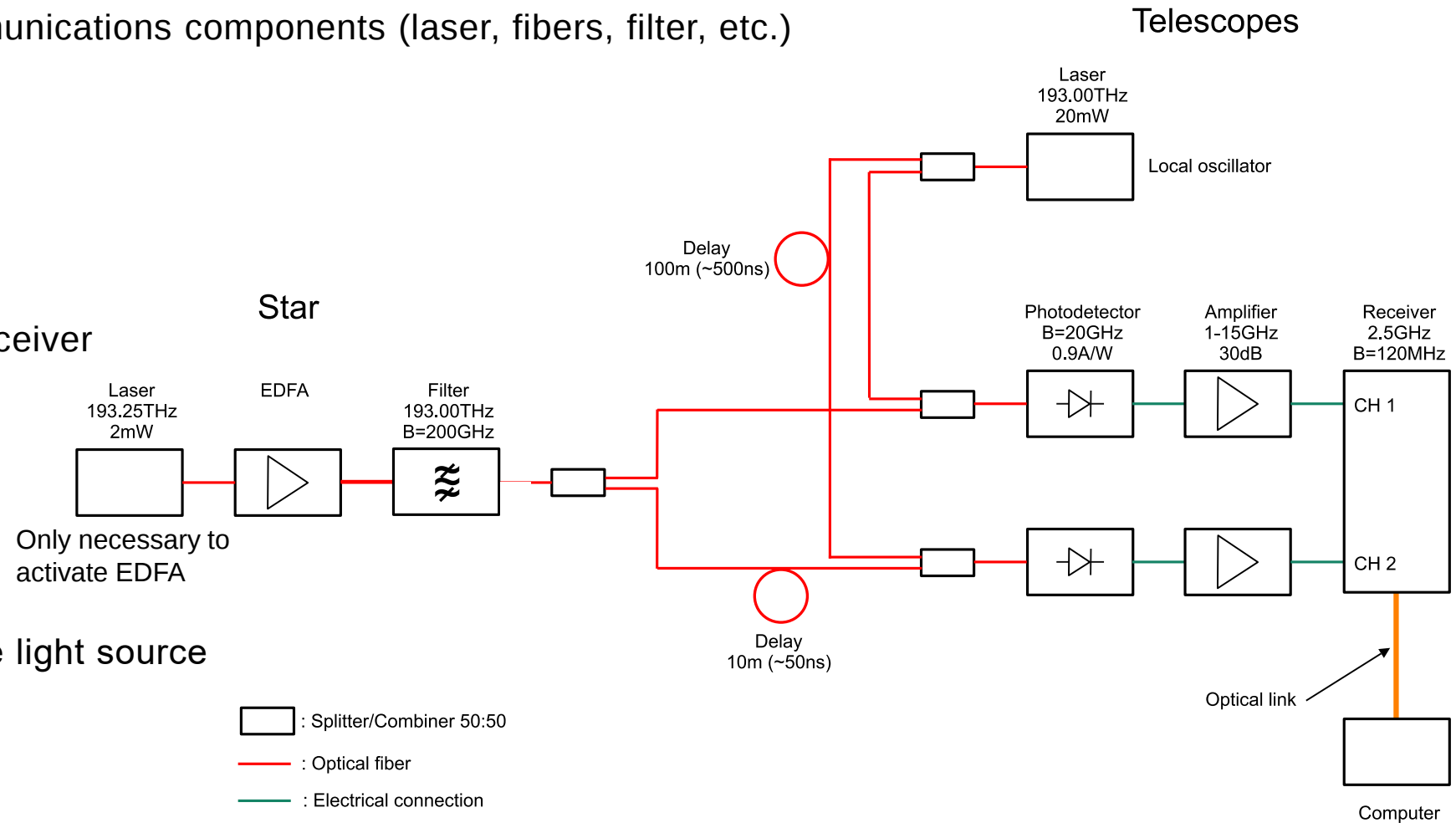
A TABLETOP NIR HETERODYNE INTERFEROMETER

We constructed a NIR heterodyne interferometer using existing lab equipment:

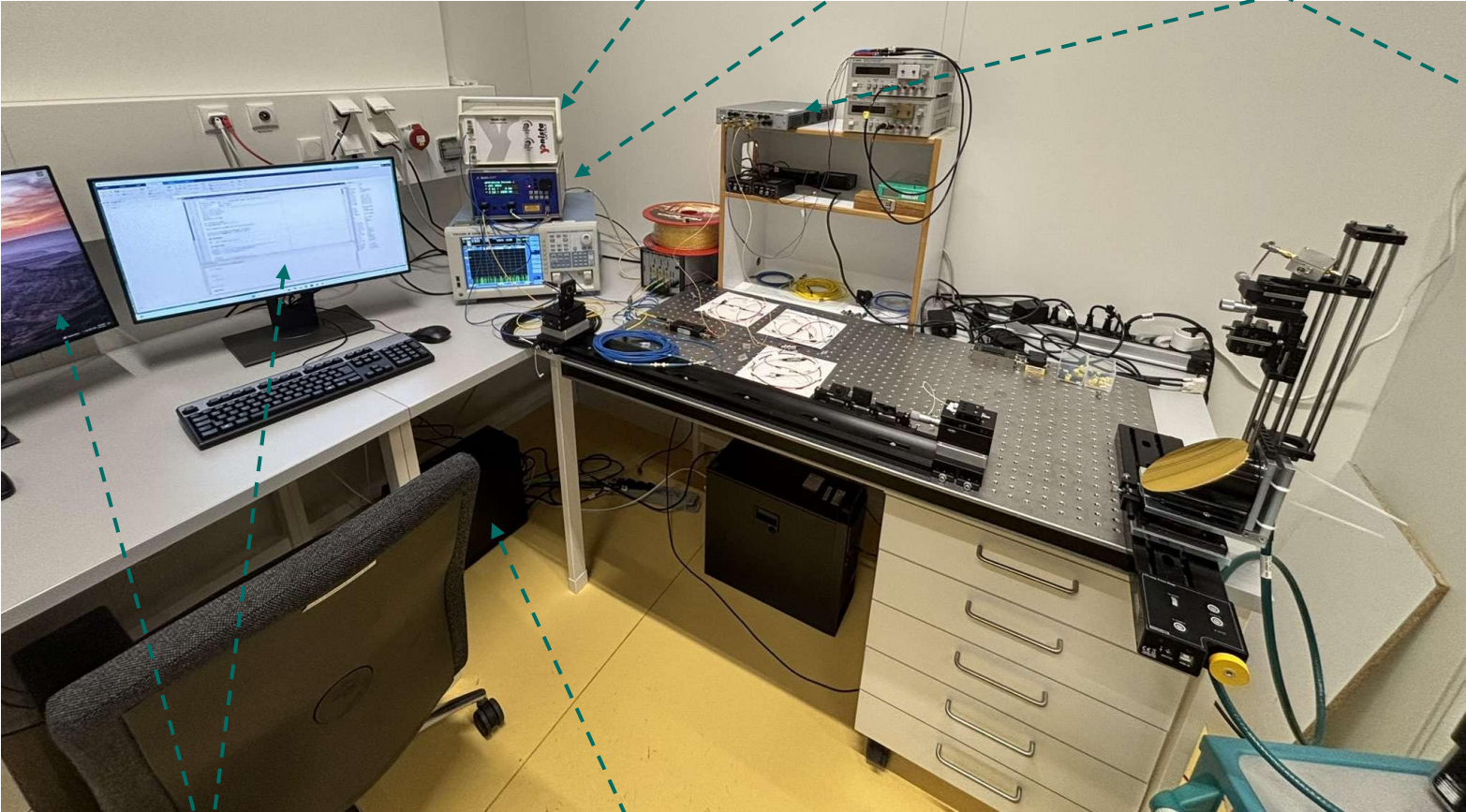
- Commercial 1550 nm telecommunications components (laser, fibers, filter, etc.)
- EDFA as white light source
- 20 GHz InGaAs photodetectors
- Low-noise RF amplifiers
- Ettus Software Define Radio receiver

Concept:

- Construct a “star” out of a white light source
- Down-convert to 2.1 GHz
- Correlate RF signals



THE LAB SETUP



Optical filter

EDFA "star"

Receiver

Amplifiers

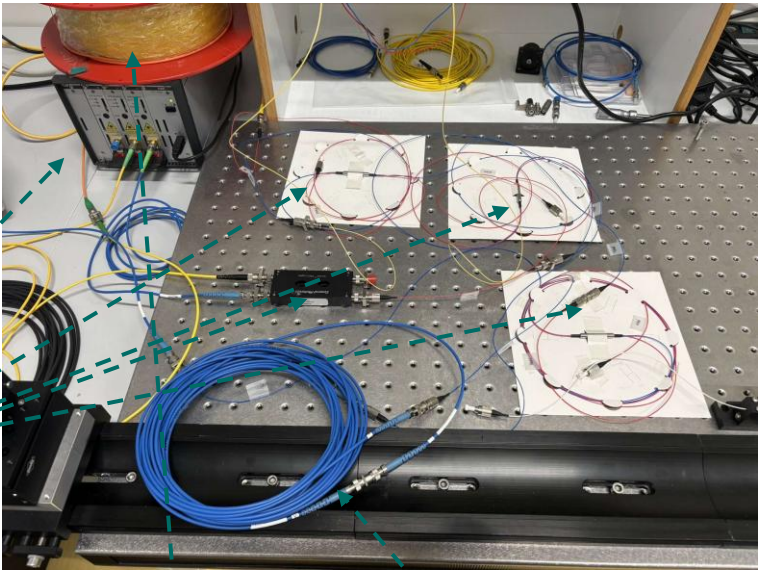
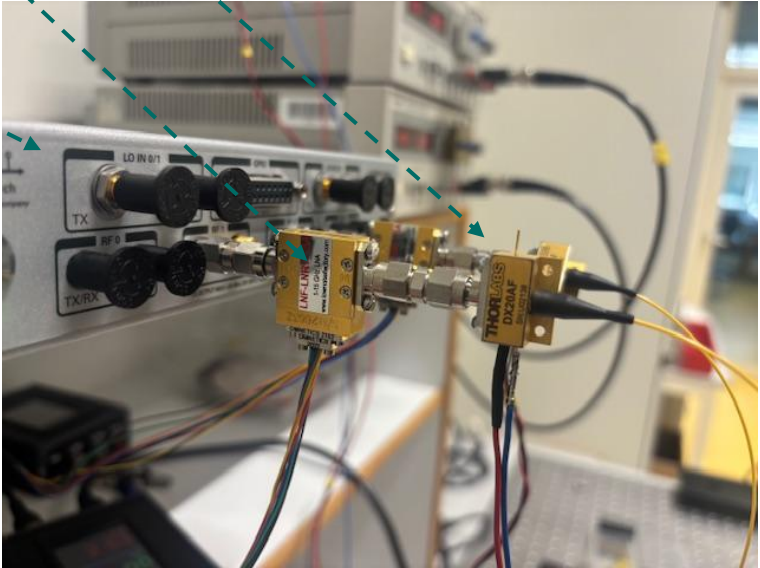
Photodetectors

Control and DAQ monitors

Correlator PC

Lasers

50:50 Splitters/Couplers

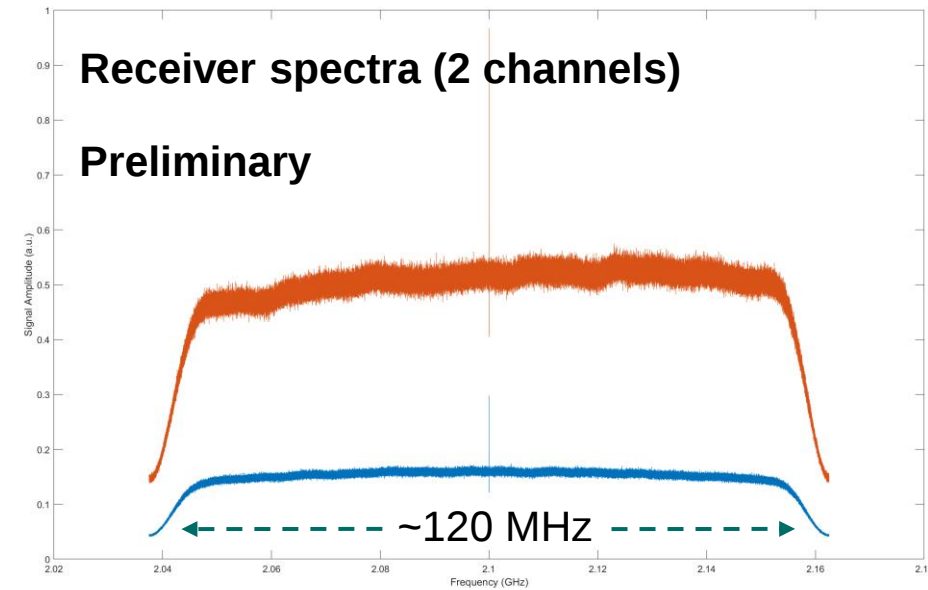


100 m Delay

10 m Delay

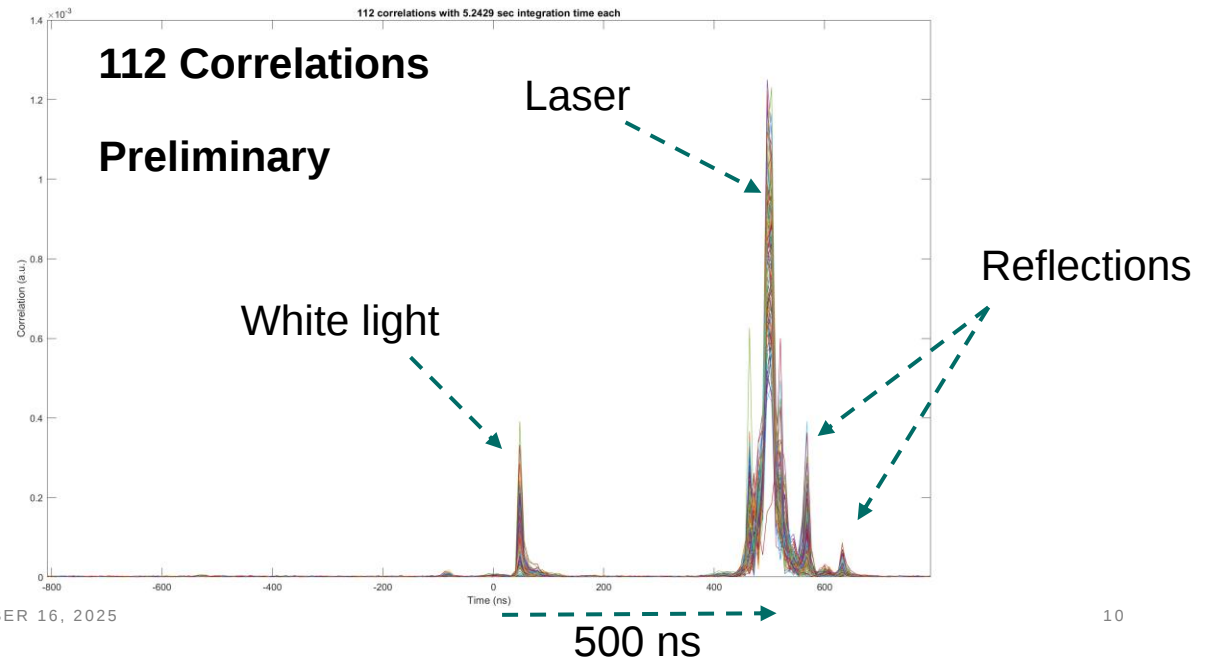
Spectra at 2 receiver inputs

- ~120 MHz bandwidth
- Central line is the zero bias peak
- Flat noise spectrum
- Blue spectra scaled for visibility



Correlator output

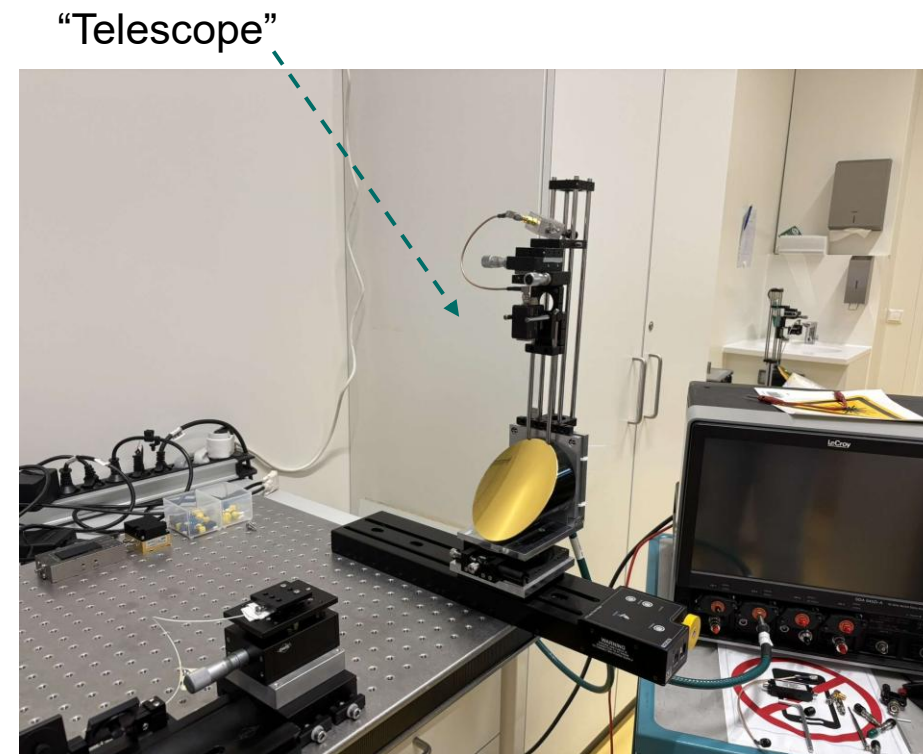
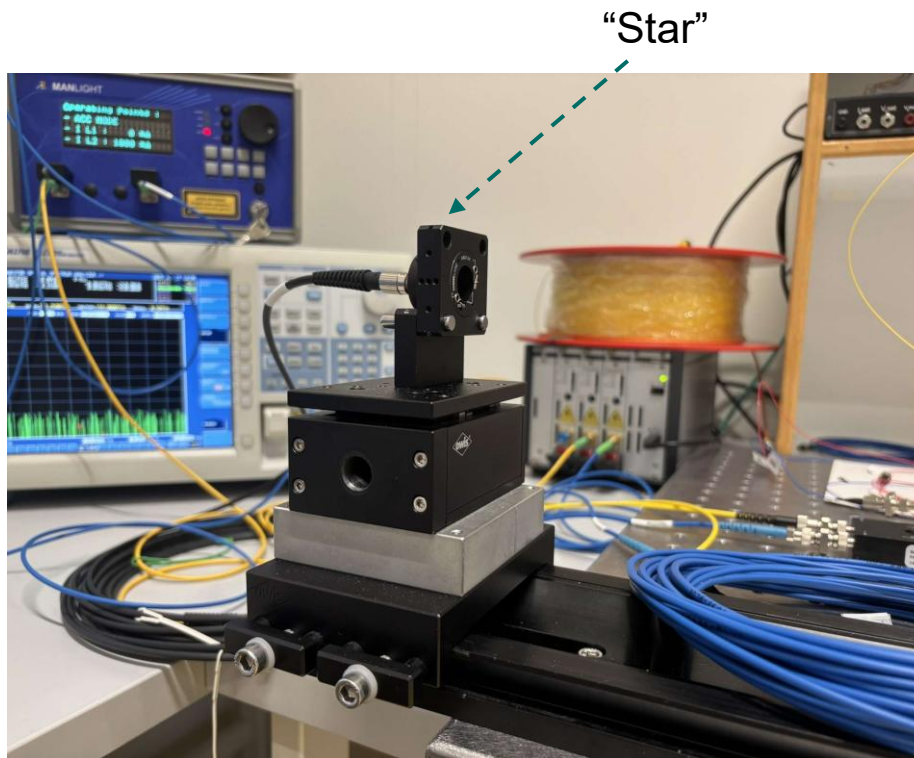
- Real-time correlations (GNU Radio)
- 112 correlations with ~5s averaging
- White light correlation peak at 48ns (10m delay)
- Laser correlation at 500ns (100m delay)
- Poor laser linewidth (3 MHz)



TOWARDS A FREE SPACE SETUP

Building a free space setup with two telescopes

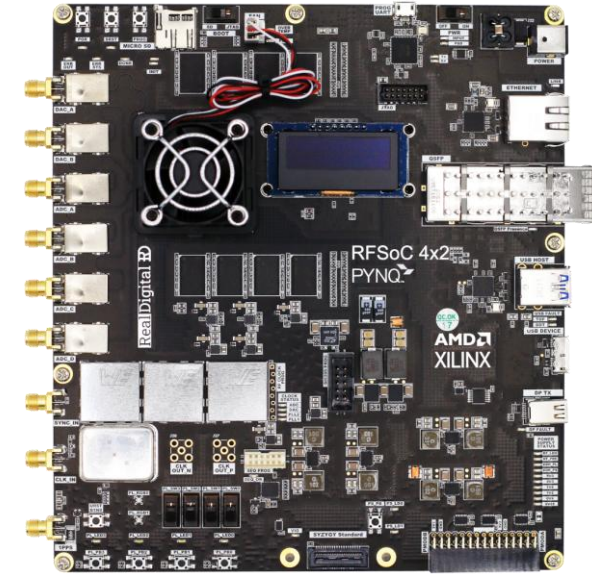
- Infrared “star” with 3 micron fiber aperture
- Two 10cm diameter telescopes (gold mirrors), 8 GHz free-space photodetectors
- Some preliminary tests performed, but system needs to be mechanically improved before further measurements



Next steps:

- **Improve tabletop setup**

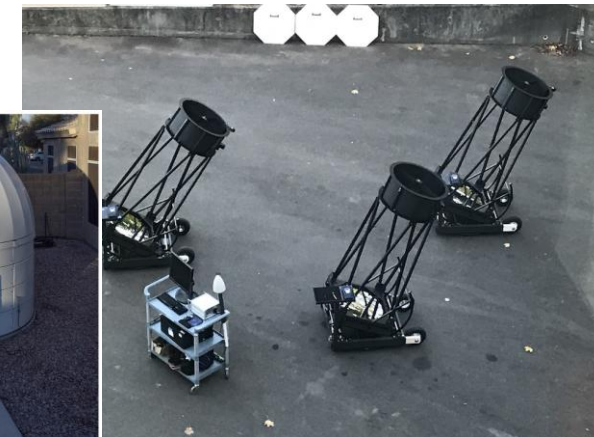
- Incorporating atmospheric “turbulence” (phase disturbance)
- Better receiver system (RFSoc), already in lab
- Go to 10cm free space star system with two telescopes
- Adapt system to larger telescopes with multiple baselines and aim to measure real stars (e.g. from the backyard)



Inspired by backyard interferometers:
e.g. JayZ & Southern Connecticut Stellar Interferometer

- **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



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 a tabletop testbed interferometer constructed at the MPI lab to further explore the advantages and limitations of the heterodyne approach.

Preliminary results for the received spectrum and correlation at NIR were presented.

- Initial setup constructed with equipment already in the lab
- Clear correlations are observed

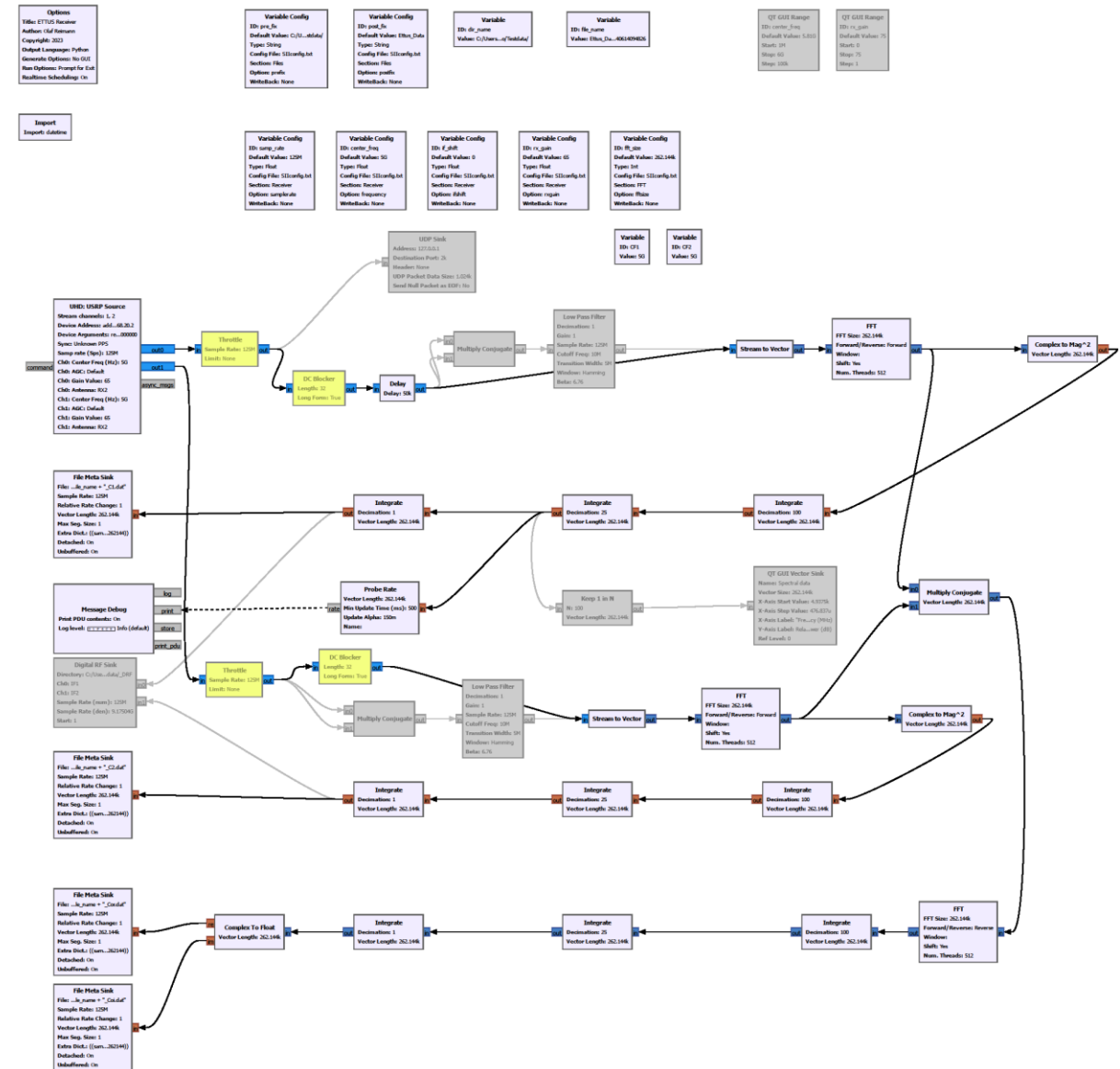
Plans to move to a free space interferometer (maybe VIS) and improvements to the setup were discussed.

- Work needed to improve system stability
- Preliminary steps made to go to green light, but not all equipment already available in house

BACKUP

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



EDFA as a white light source

- 200 GHz bandwidth (filtered)

