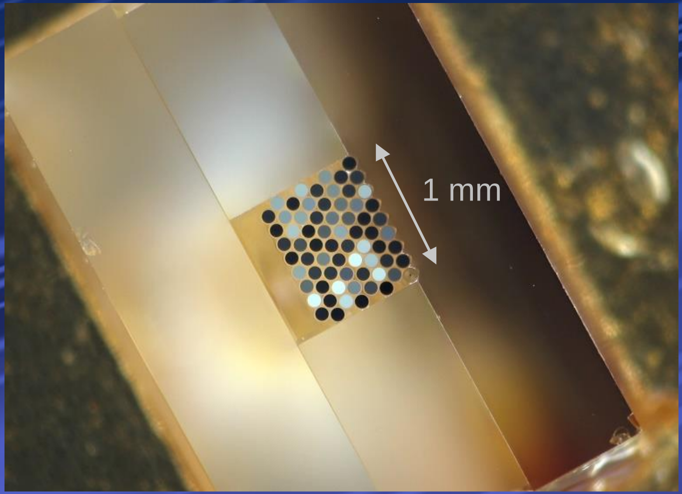
Friedrich-Alexander-Universität
Erlangen-Nürnberg

Fiber-Array-Based Phase Camera for the Einstein Telescope

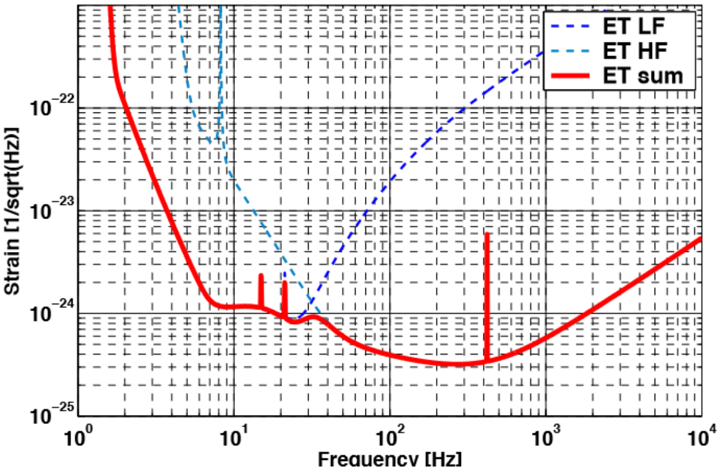
Benjamin Schwab
With Stefan Funk, Adrian Zink
Chicago, 28. August 2024



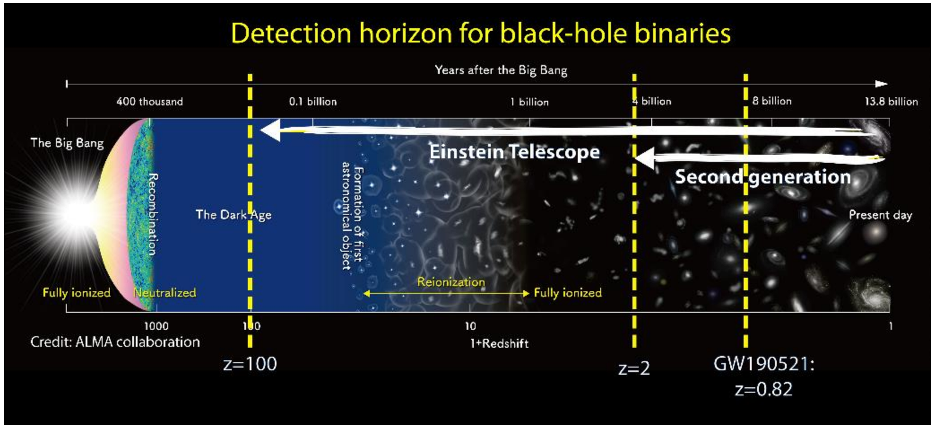
Einstein Telescope

Detector and Science

- Next generational gravitational wave observatory
- Two L-shape detectors or one Δ-shaped detector in discussion
- To increase sensitivity, two interferometers at different wavelengths will be used:
  - 1064nm for high frequency GWs (30Hz – several kHz)
  - 1550nm for low frequency GWs (several Hz – 30Hz)



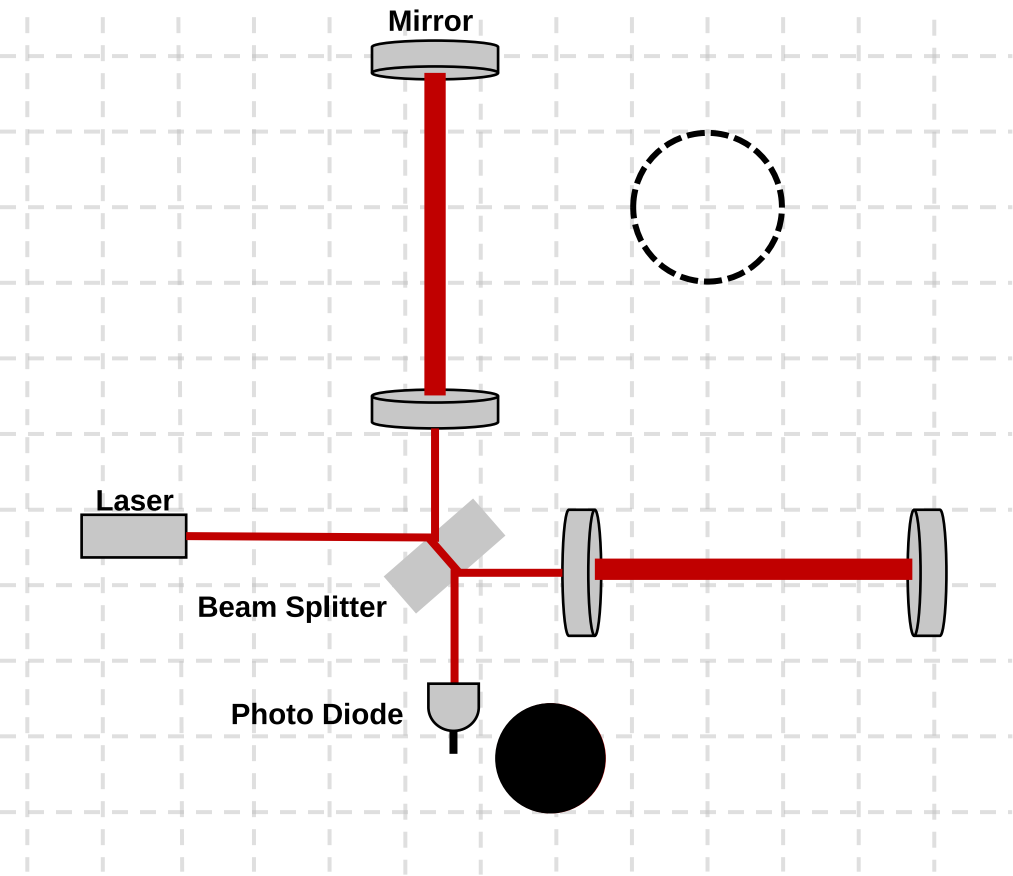
Einstein Telescope Design Report Update 2020



Et-gw.eu

Gravitational Wave Detection

Very Simplified



In its simplest form: Michelson interferometer with Fabry-Pérot-Cavities as arms

→ Phase dependent length measurement sensitive to 10^{-22} m

Gravitational Wave Detection

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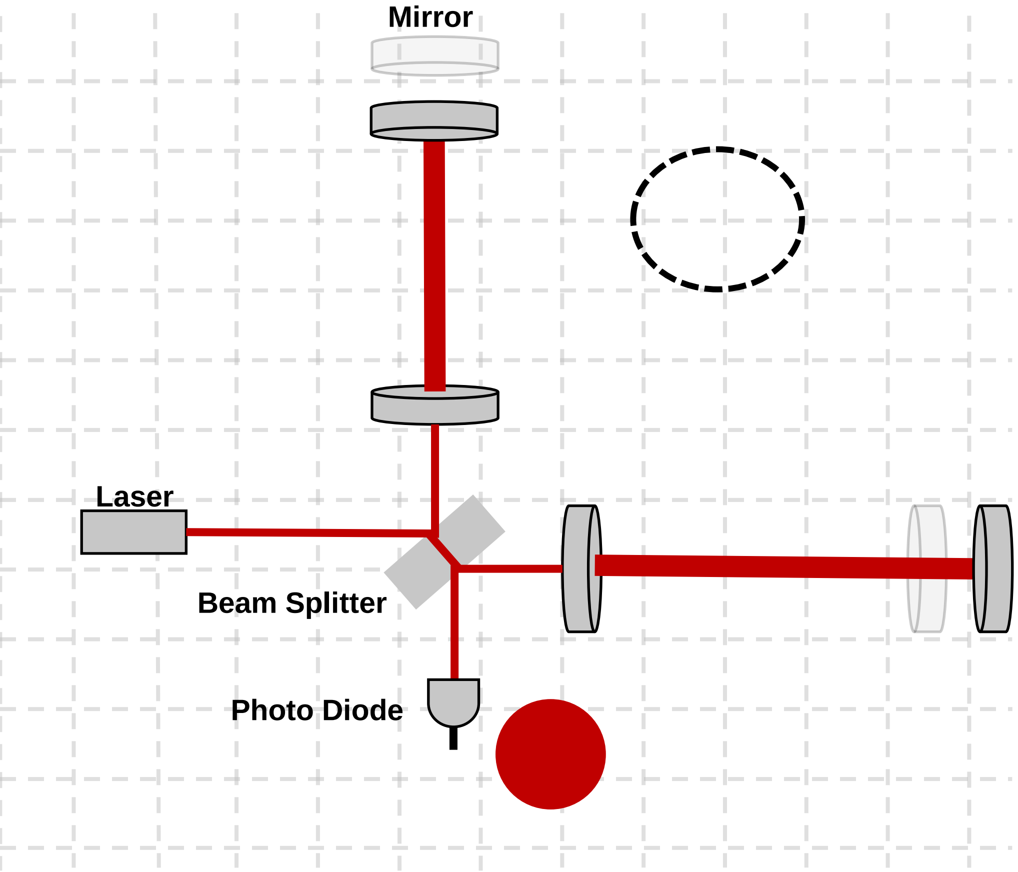

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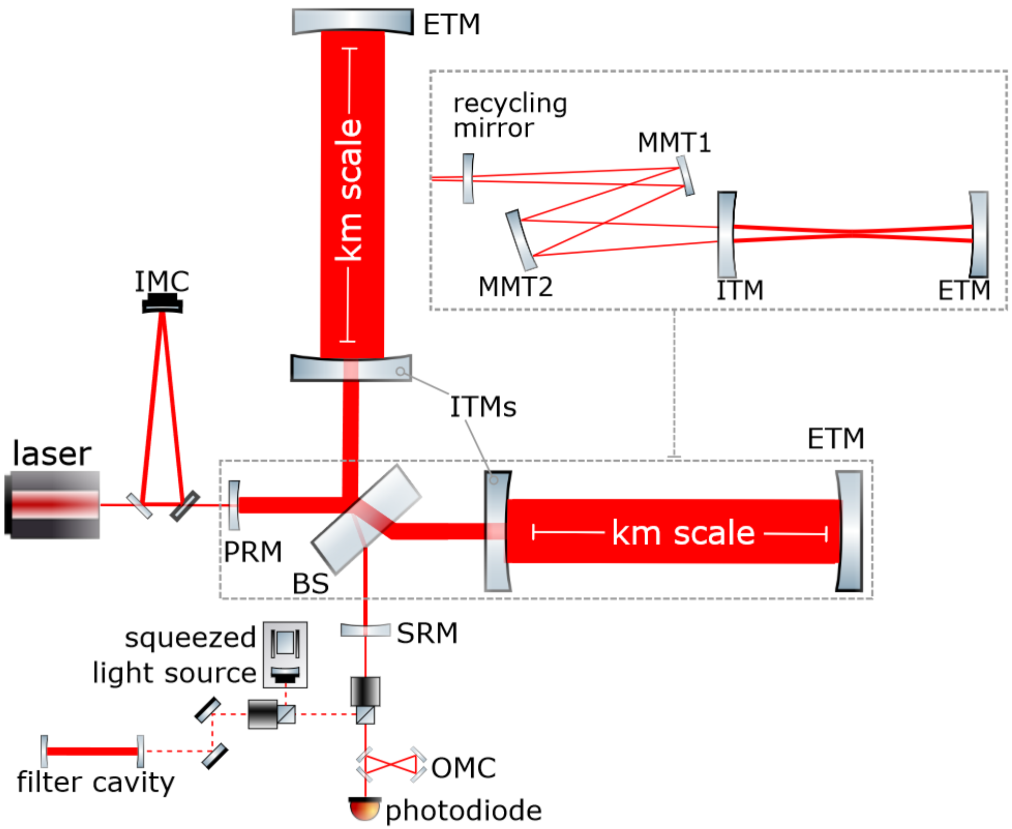
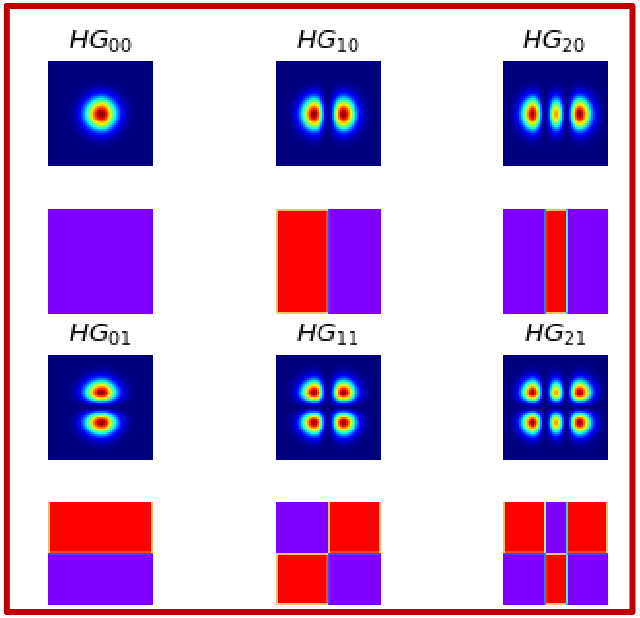
Gravitational Wave Detection

More Realistic View



Transverse Mode Control in Quantum Enhanced Interferometers: A Review and Recommendations for a New Generation

- Mode mismatch, surface figure error, substrate refractive index inhomogeneities, thermal lensing
- All create higher order modes
- Degrades signal!

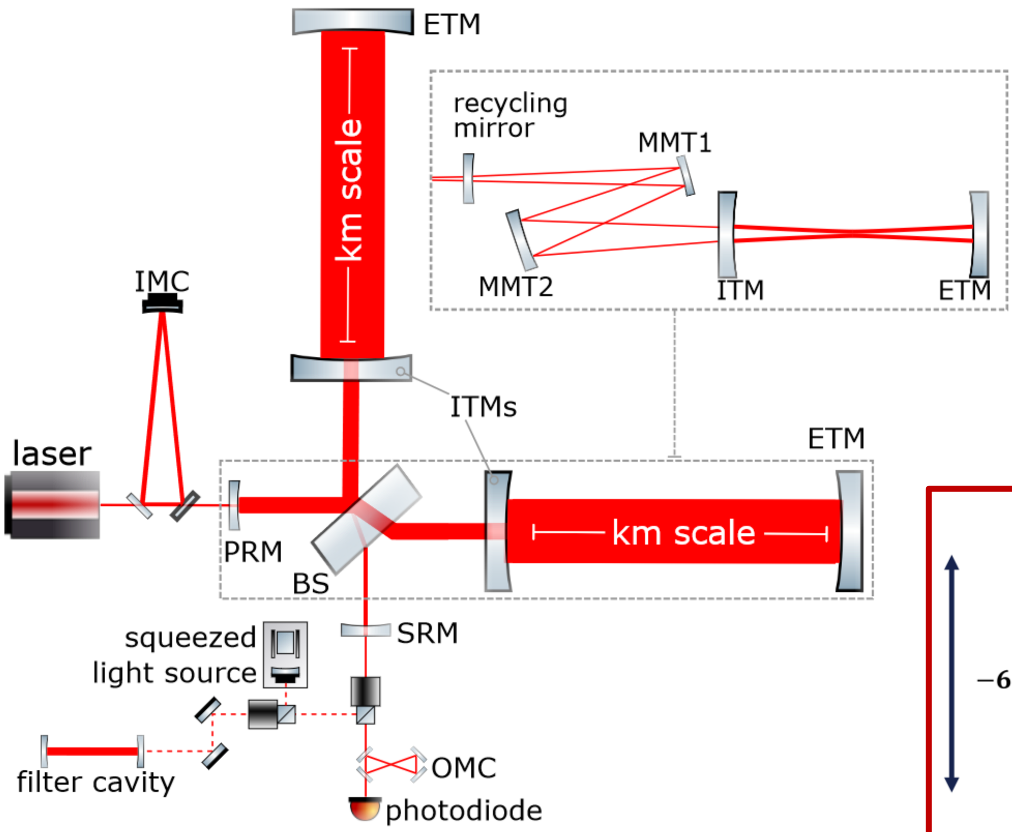


Example higher order modes: Hermite-Gaussian Mode

https://opticspy.github.io/lightpipes/HermiteGaussModes.html

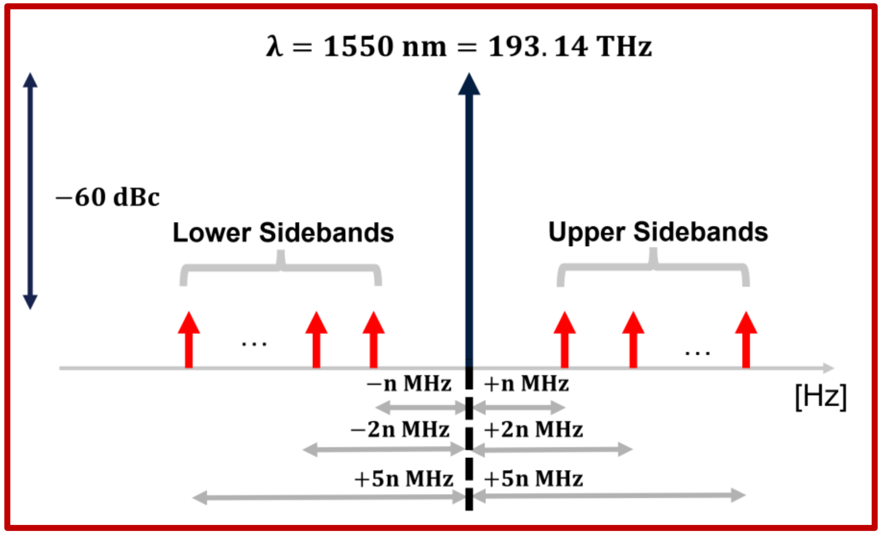
Gravitational Wave Detection

More Realistic View



Transverse Mode Control in Quantum Enhanced Interferometers: A Review and Recommendations for a New Generation

- To stabilize the cavities sidebands are modulated onto the main frequency
- E.g. Virgo has 10 sidebands (Magnitude of $\pm$100 MHz)
- Also need to be monitored



Want to a tool to monitor the wavefront phase and mode content for all bands simultaneously

Phase Camera

How to Measure Phase

Phase measurement of IR light difficult, most detectors only measure intensity

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→ Transfer phase information to intensity information

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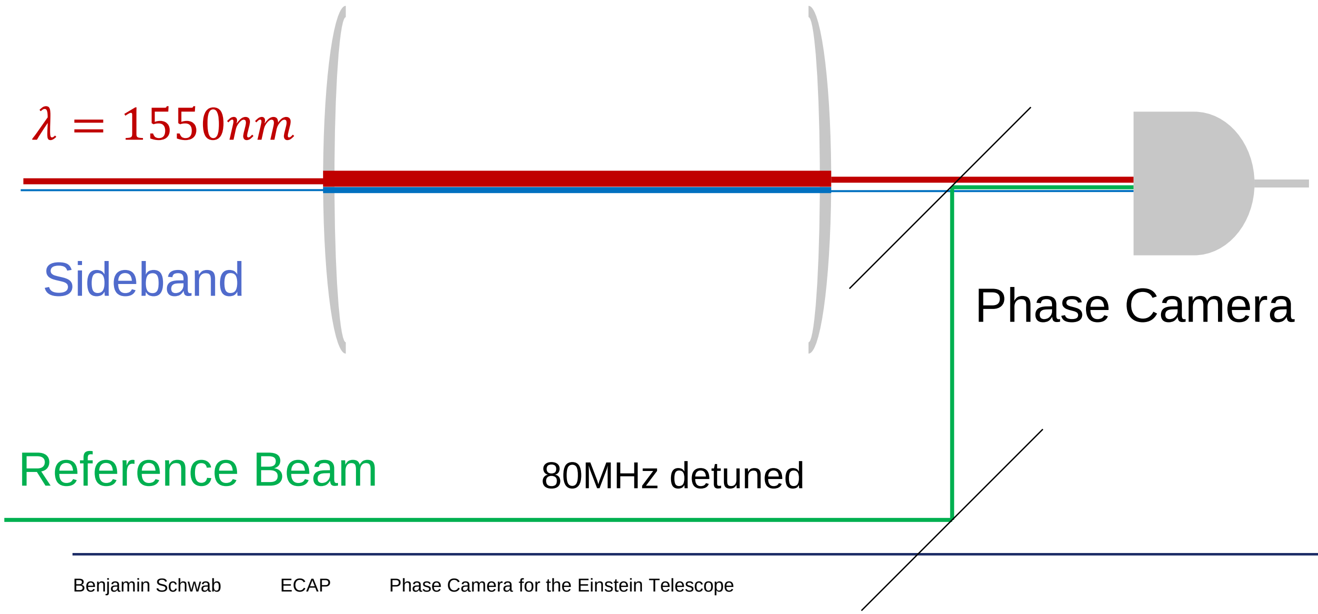
→ Let beam interfere with reference beam detuned several MHz



Phase Camera

How to Measure Phase

Phase measurement of IR light difficult, most detectors only measure intensity

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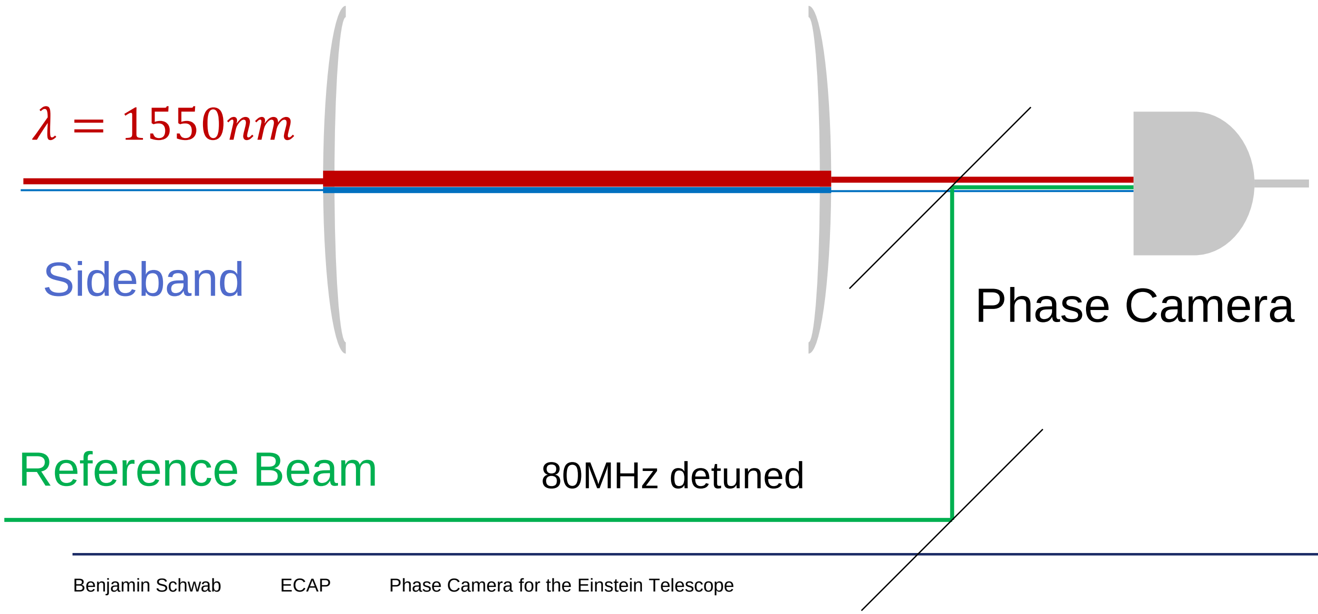
→ Let beam interfere with reference beam detuned several MHz

$$Intensity = \left| E_{1550} \cos(\omega_{1550nm} t + \varphi_{1550nm}) + E_{ref} \cos(\omega_{ref} t + \varphi_{ref}) \right|^2$$



Phase measurement of IR light difficult, most detectors only measure intensity

→ Transfer phase information to intensity information

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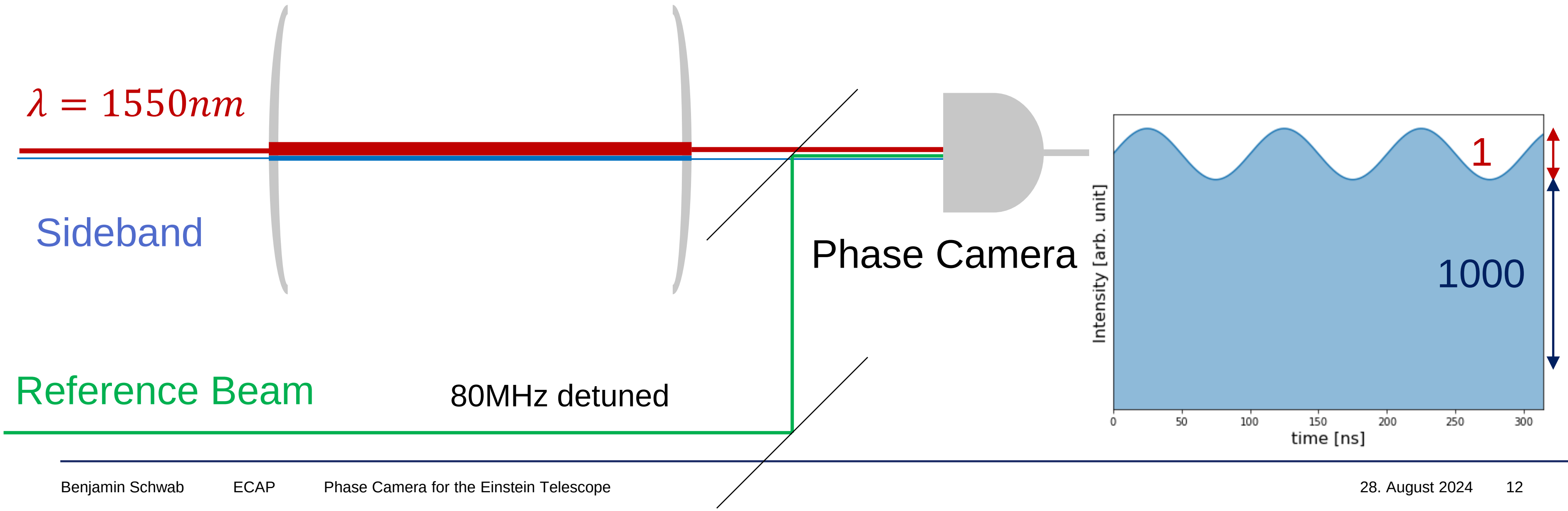
$$Intensity\ = DC + 2E_{1550}E_{ref}\cos(\omega_{80MHz}t + \Delta\varphi)$$



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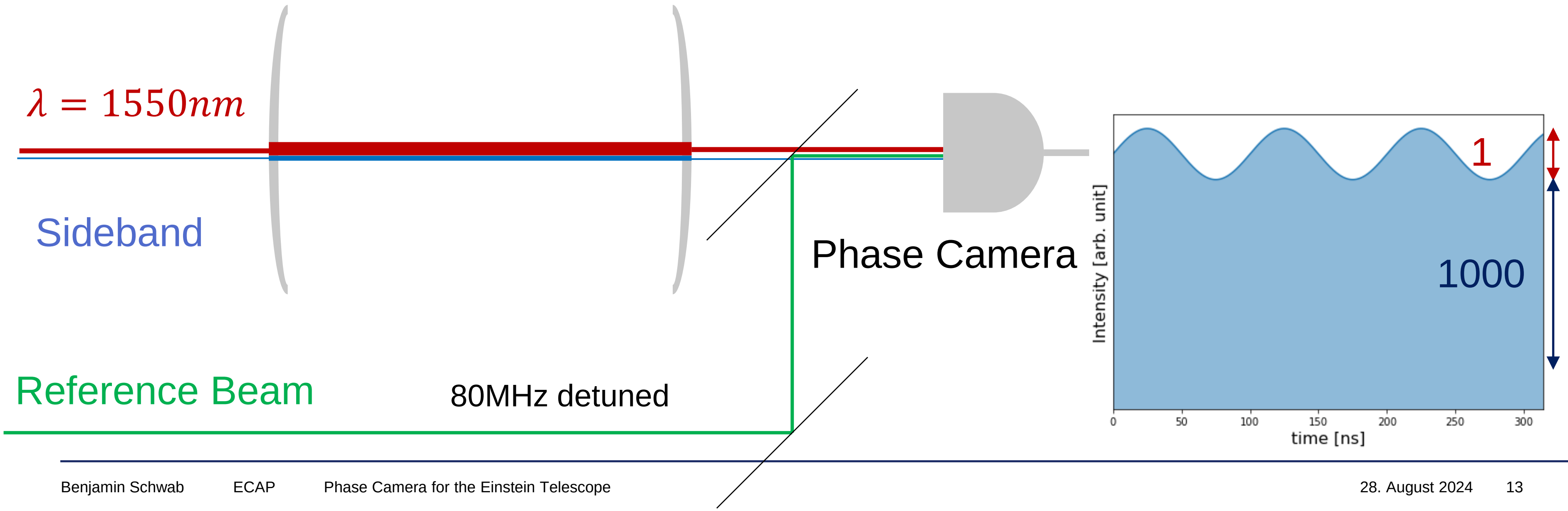
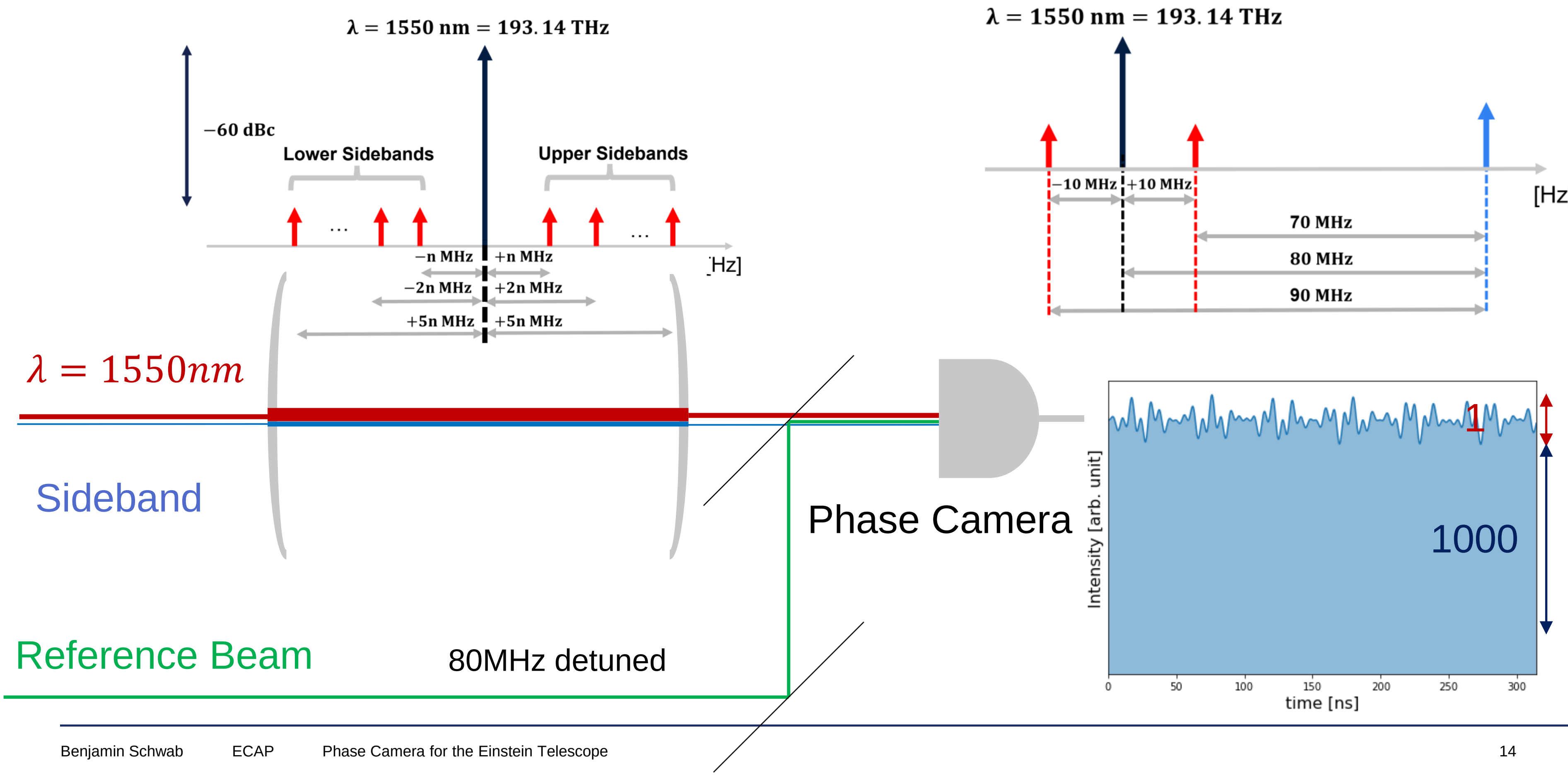


Phase Camera

How to Measure Phase

- Phase Camera measure all sidebands in parallel
- Reference beam also ensures separability of the sidebands



Phase Camera

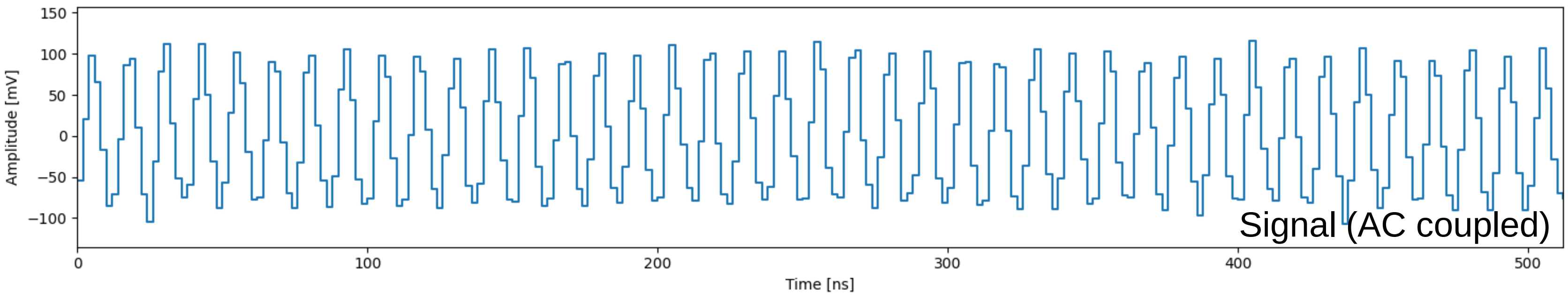
How to Demodulate Measurement

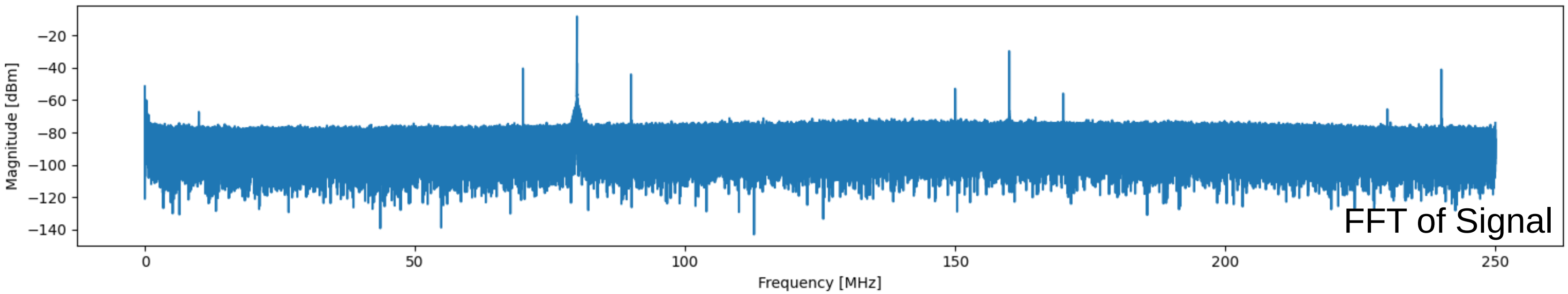
Determine Phase by I,Q demodulation:

$$I = Signal \cdot \cos(\omega t), \qquad Q = Signal \cdot \sin(\omega t)$$

The phase and amplitude of given band is then:

$$\varphi = arctan\left(\frac{\sum Q}{\sum I}\right), \qquad A = \sqrt{\sum Q^2 + \sum I^2}$$





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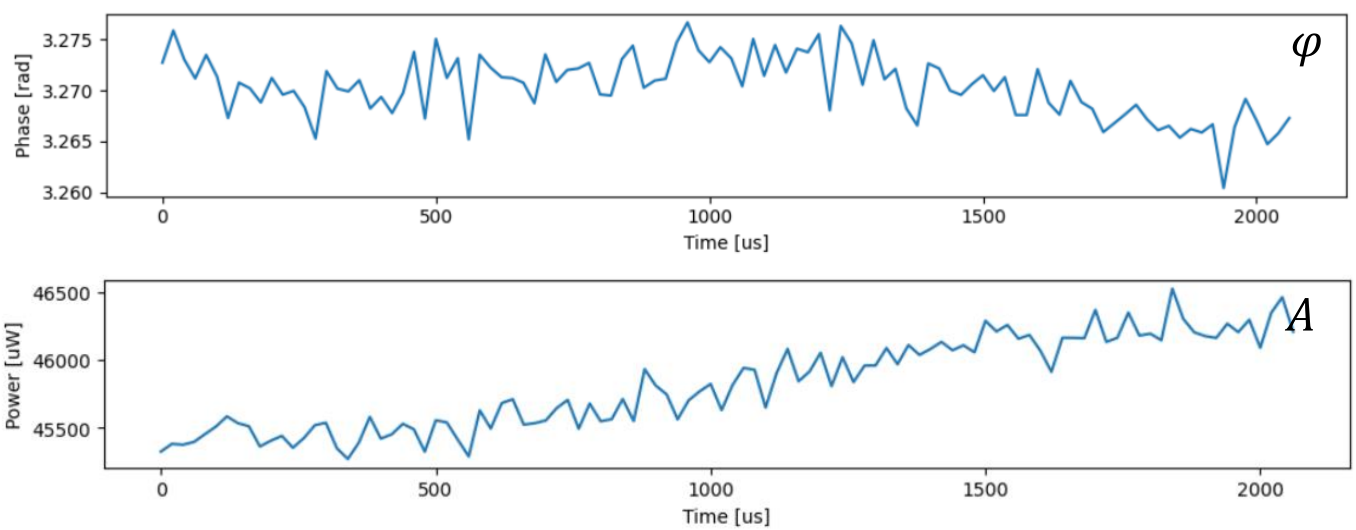
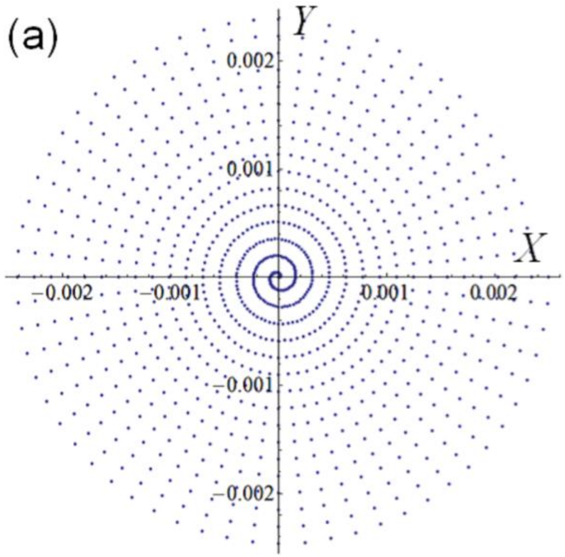


NIKHEF Phase Camera

1D Scanning Camera

- Works and operates succesfully at Advanced Virgo
- Build for 1064 nm
- Single pixel photodiode is scanned across the beam with a Piezo mirror
- Generates a ‘100 x 100‘ pixel image each second



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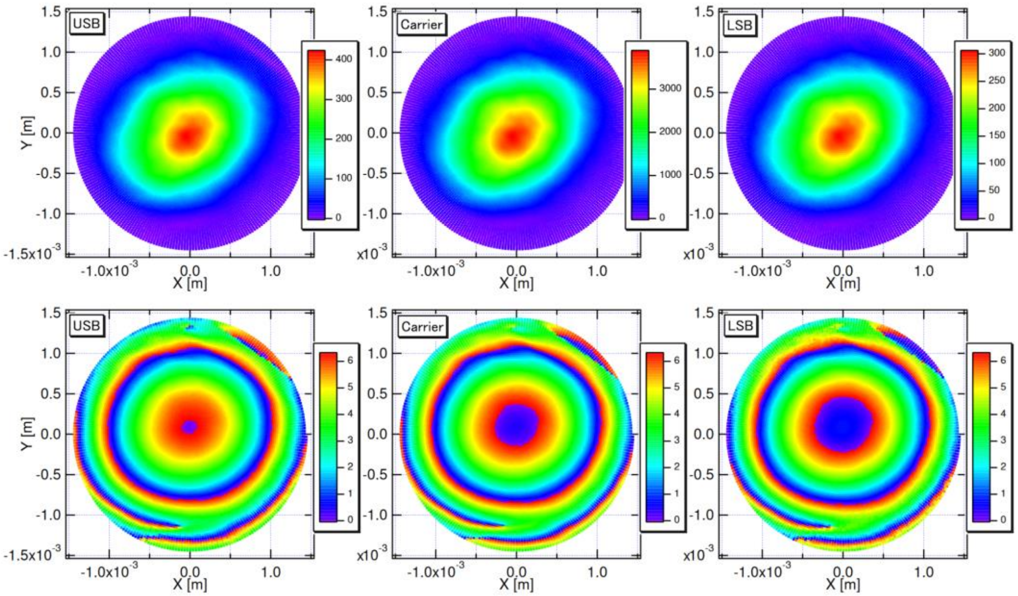


"High-performance phase camera as a frequency selective laser wavefront sensor for gravitational wave detectors„ Opt. Express 27, 18533-18548 (2019)

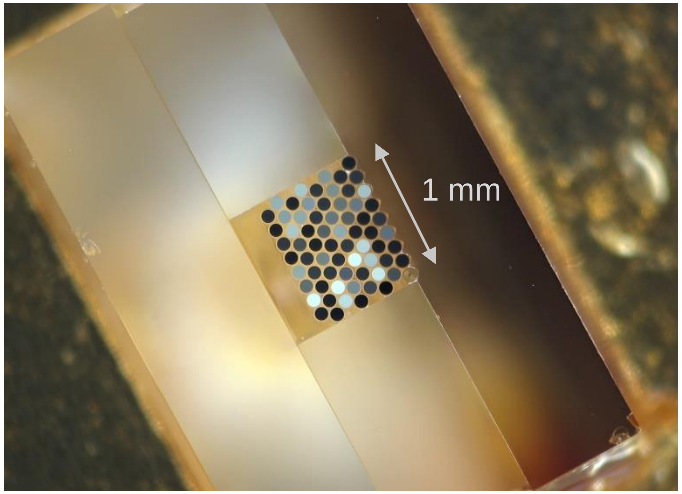
Fiber Array Phase Camera

A 2D Variant

- Develop phase camera for 1550nm
- Formed working group with NIKHEF and Université Catholique de Louvain to work on different approaches

Novel Idea:

- Use 2D optical fiber (MM) array as camera
- Individual photodiode read-out prevents most electrical cross-talk
- Easy to scale up



Advantages of 2D sensor:

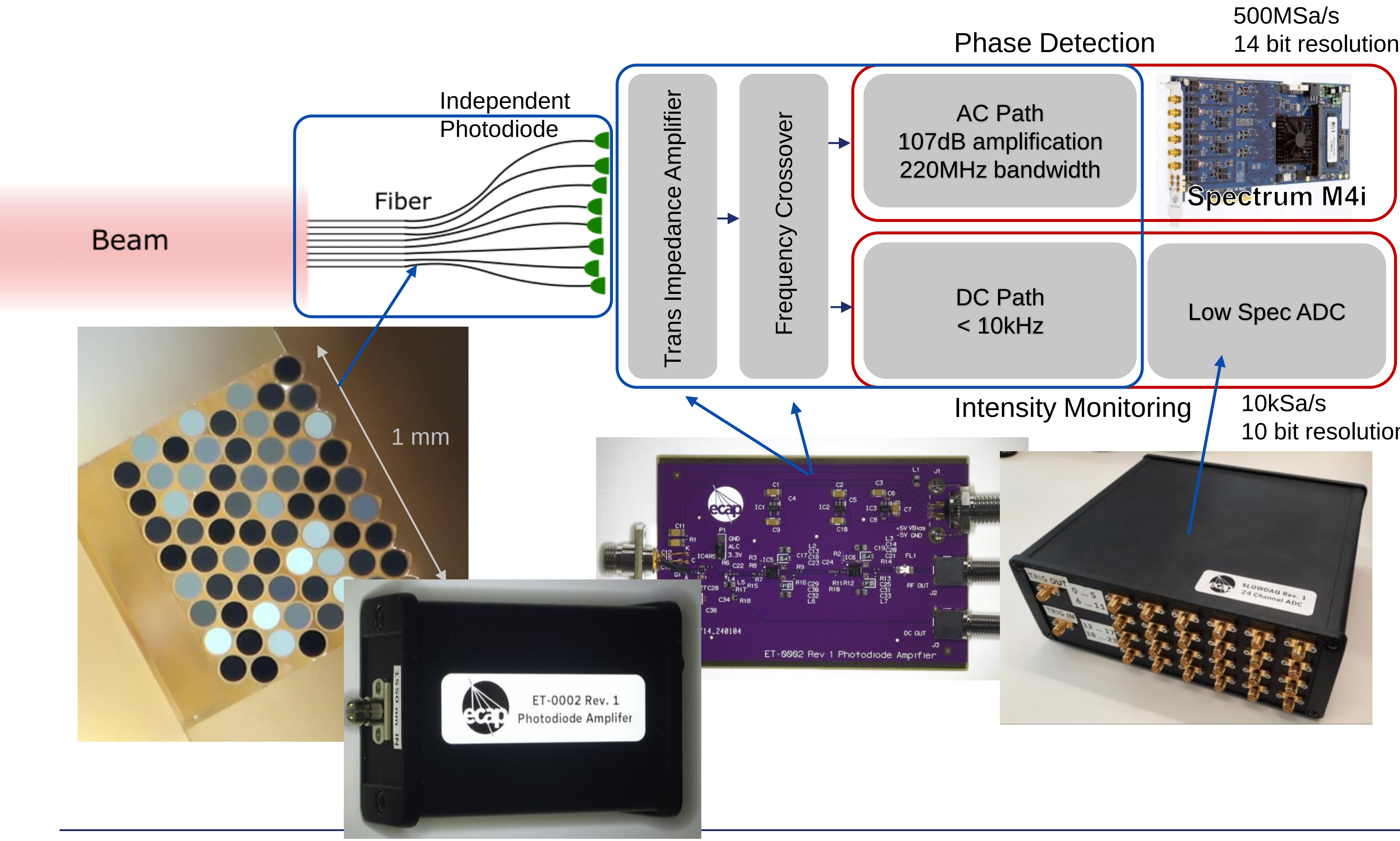
- No dynamical back scattering
- Higher frame rates possible

Disadvantages of 2D sensor:

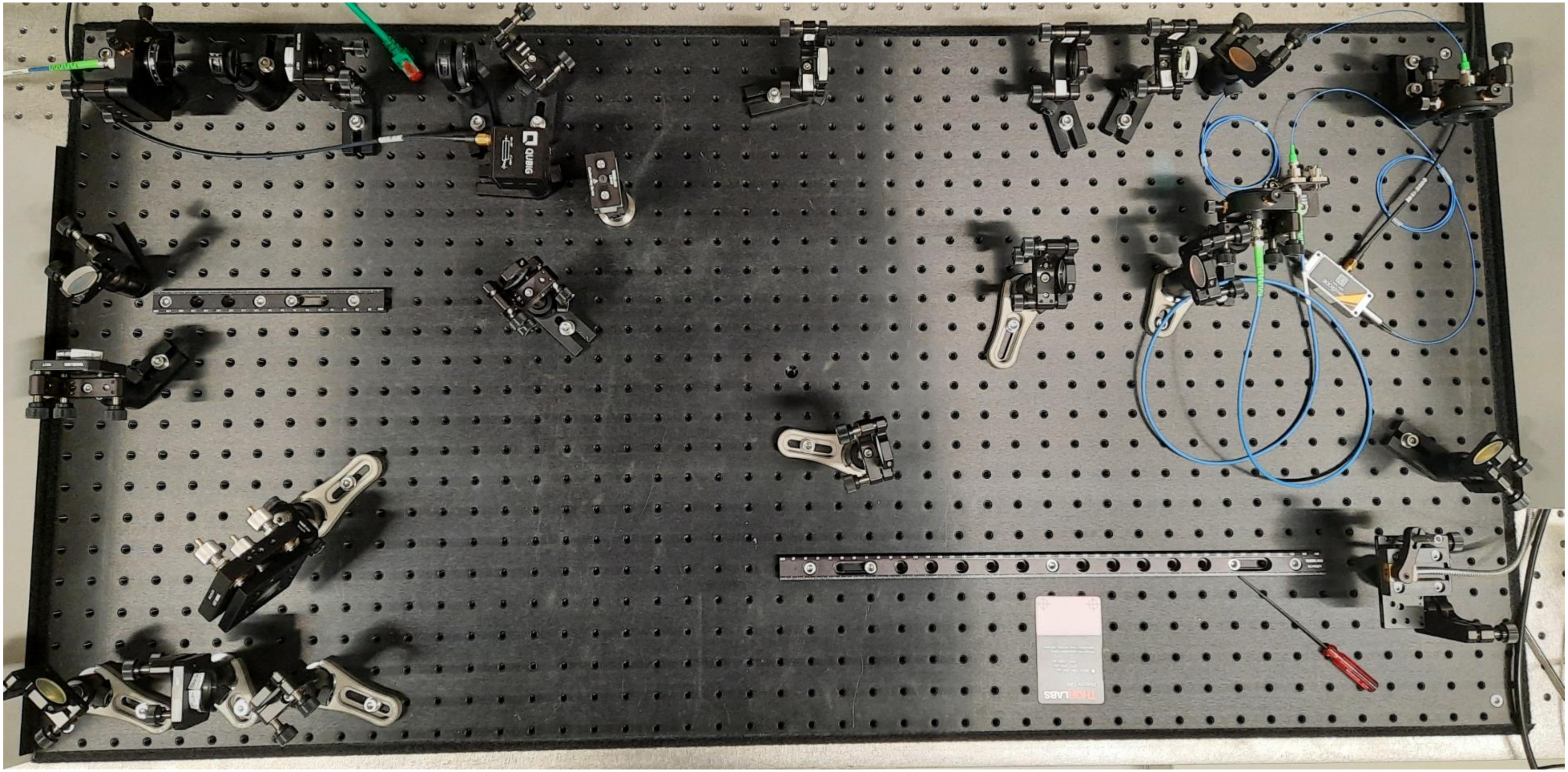
- Parallel digitisation at 500 MSa/s is expensive
- Power loss due to coupling into fiber

Electrical Setup

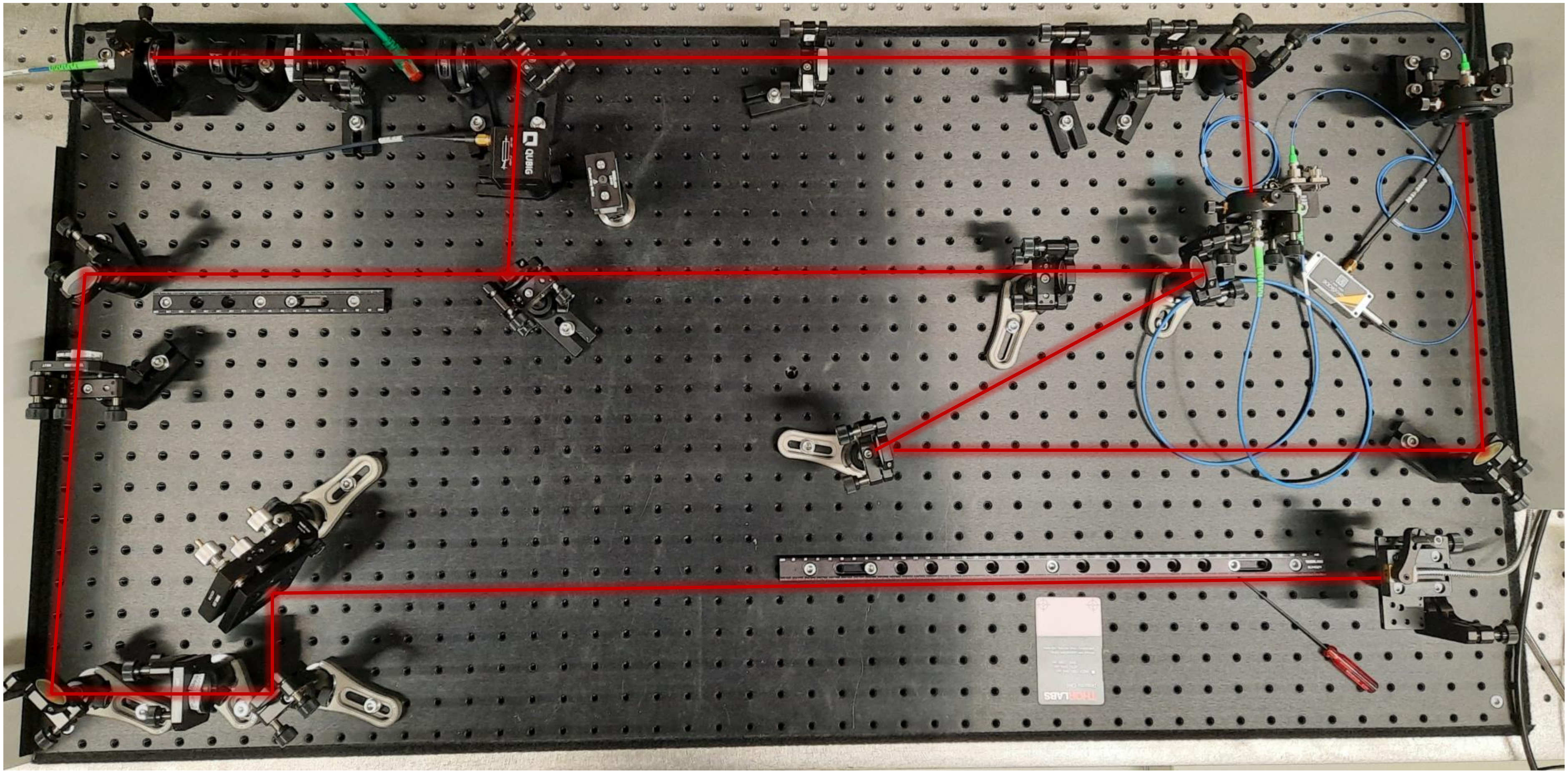
Schematic



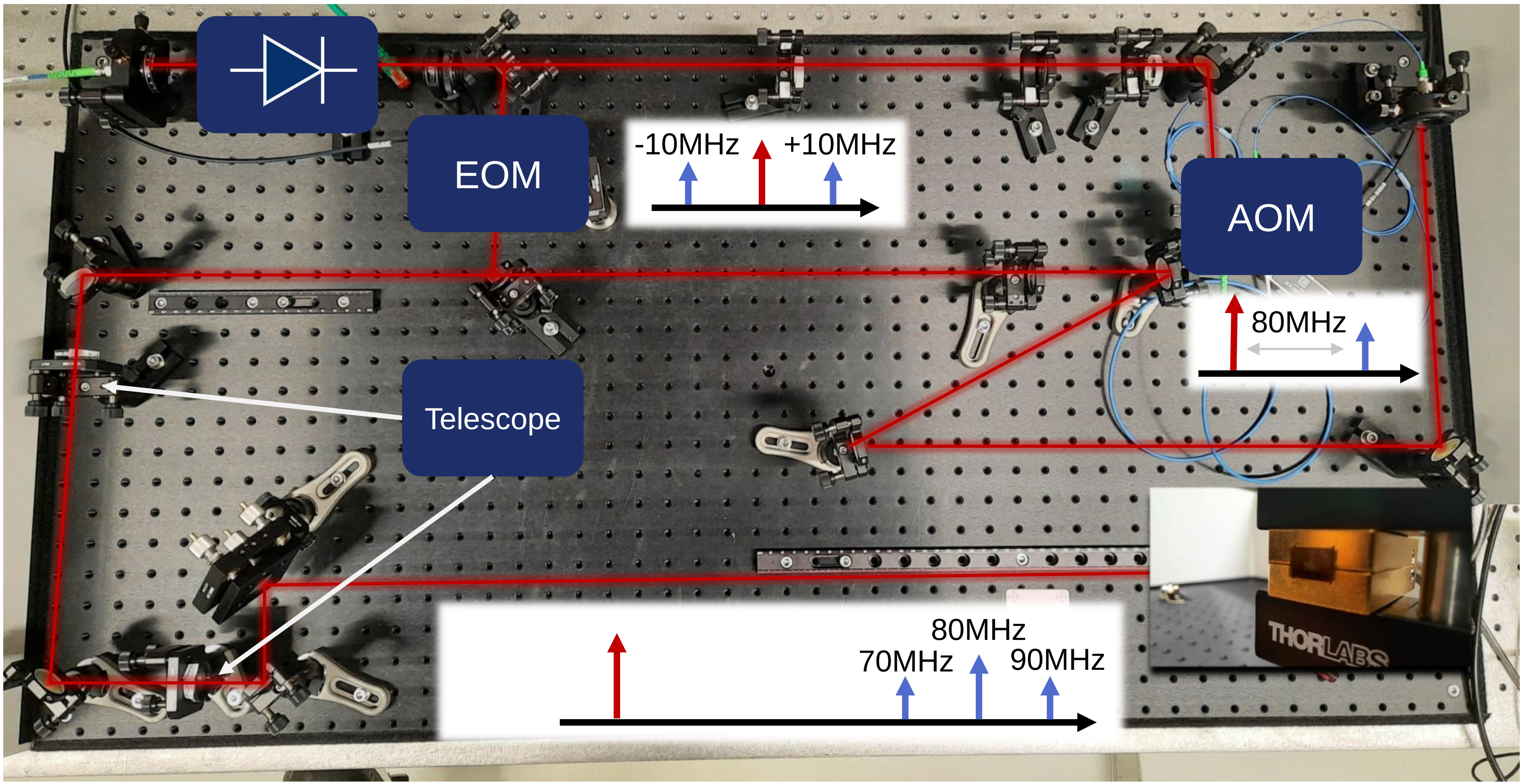
Optical Setup



Optical Setup

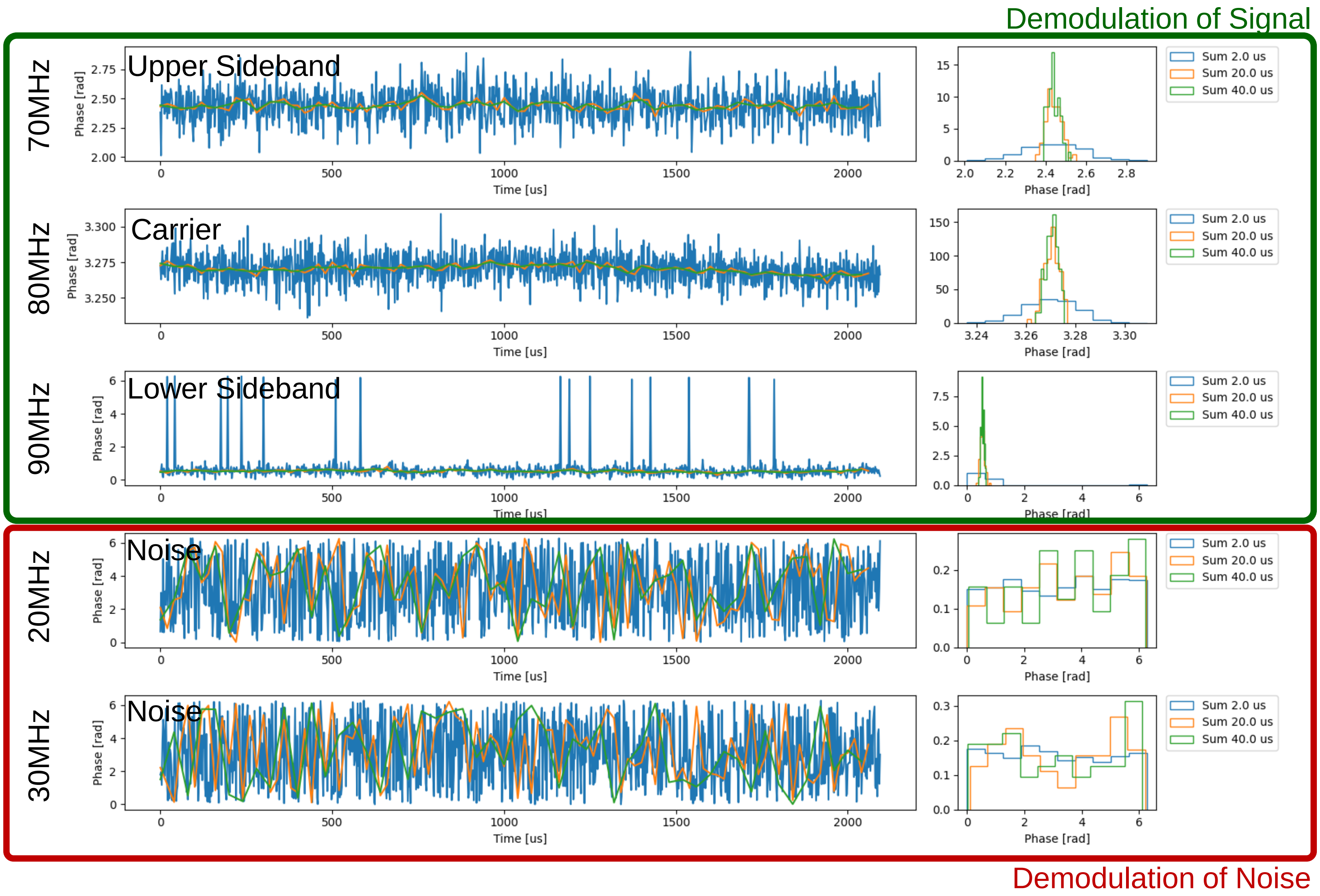


Optical Setup



Fiber Array Phase Camera

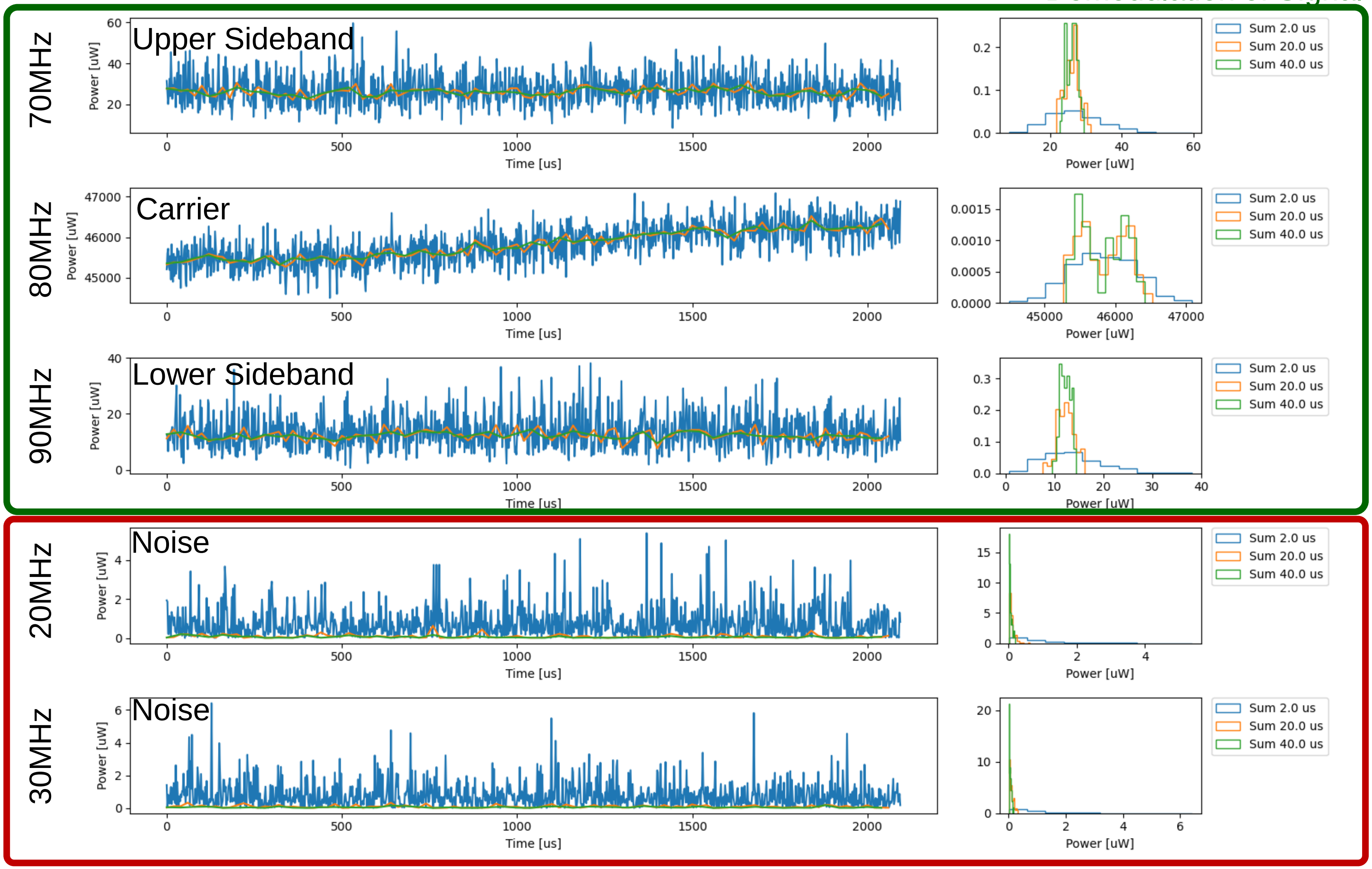
Example Measurements: Time Series of One Pixel



Fiber Array Phase Camera

Example Measurements: Time Series of One Pixel

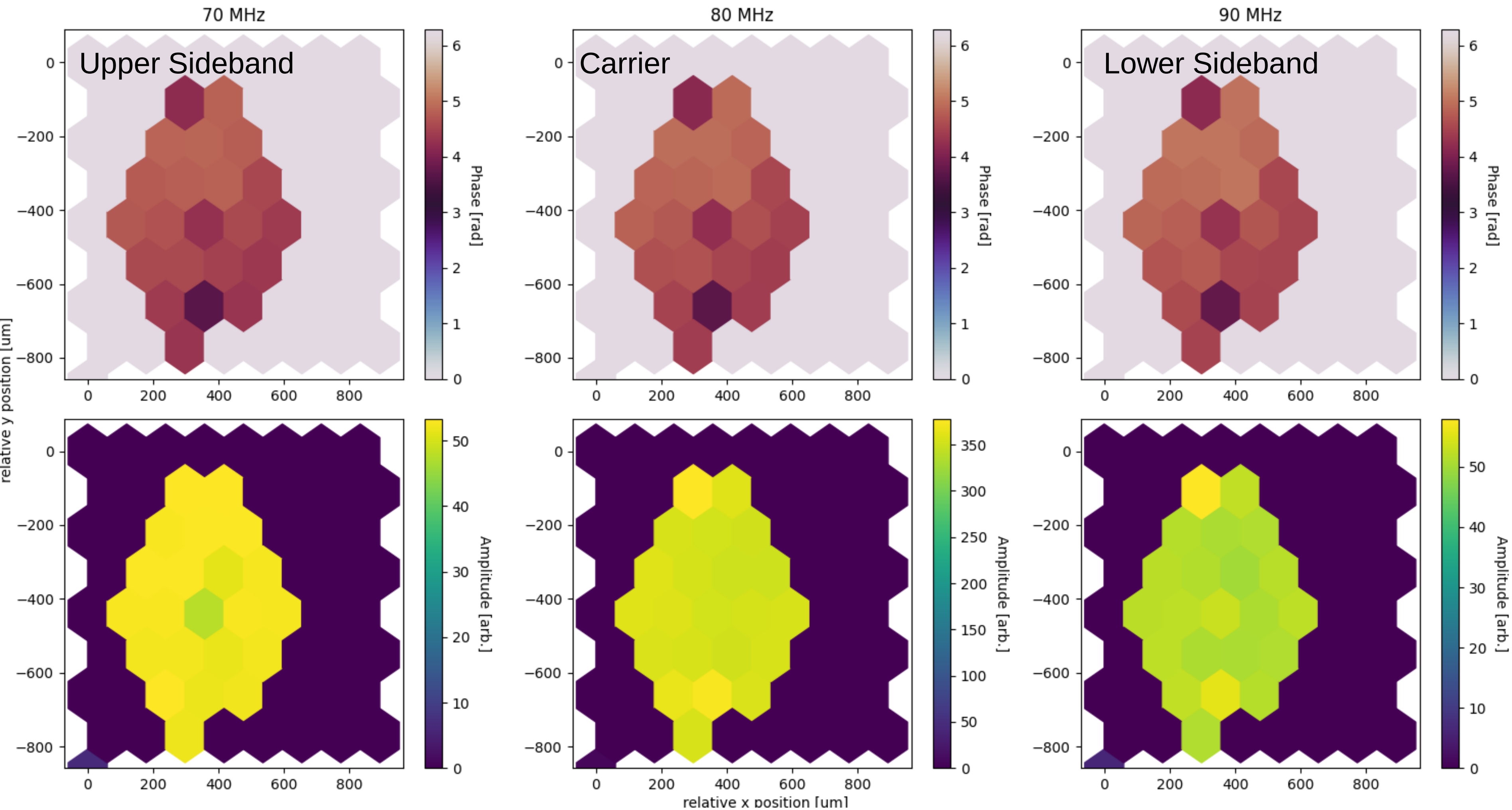
Demodulation of Signal



Demodulation of Noise

Fiber Array Phase Camera

Status



- 22 working pixel for 64 pixel proof-of-concept camera
- At the moment limited by the amount of available spectrum digitiser cards

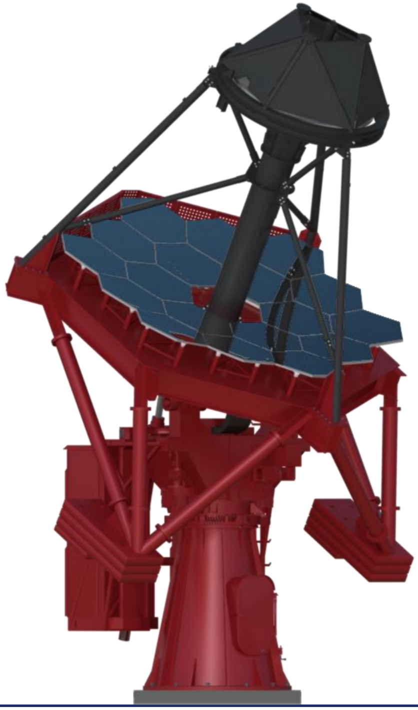
Main disadavantage is the cost of 500MSa/s digitiser

Possible solution: TARGET

- Custom built ASIC for the Small Sized Telescope of CTA
- Specialised for single photon detection

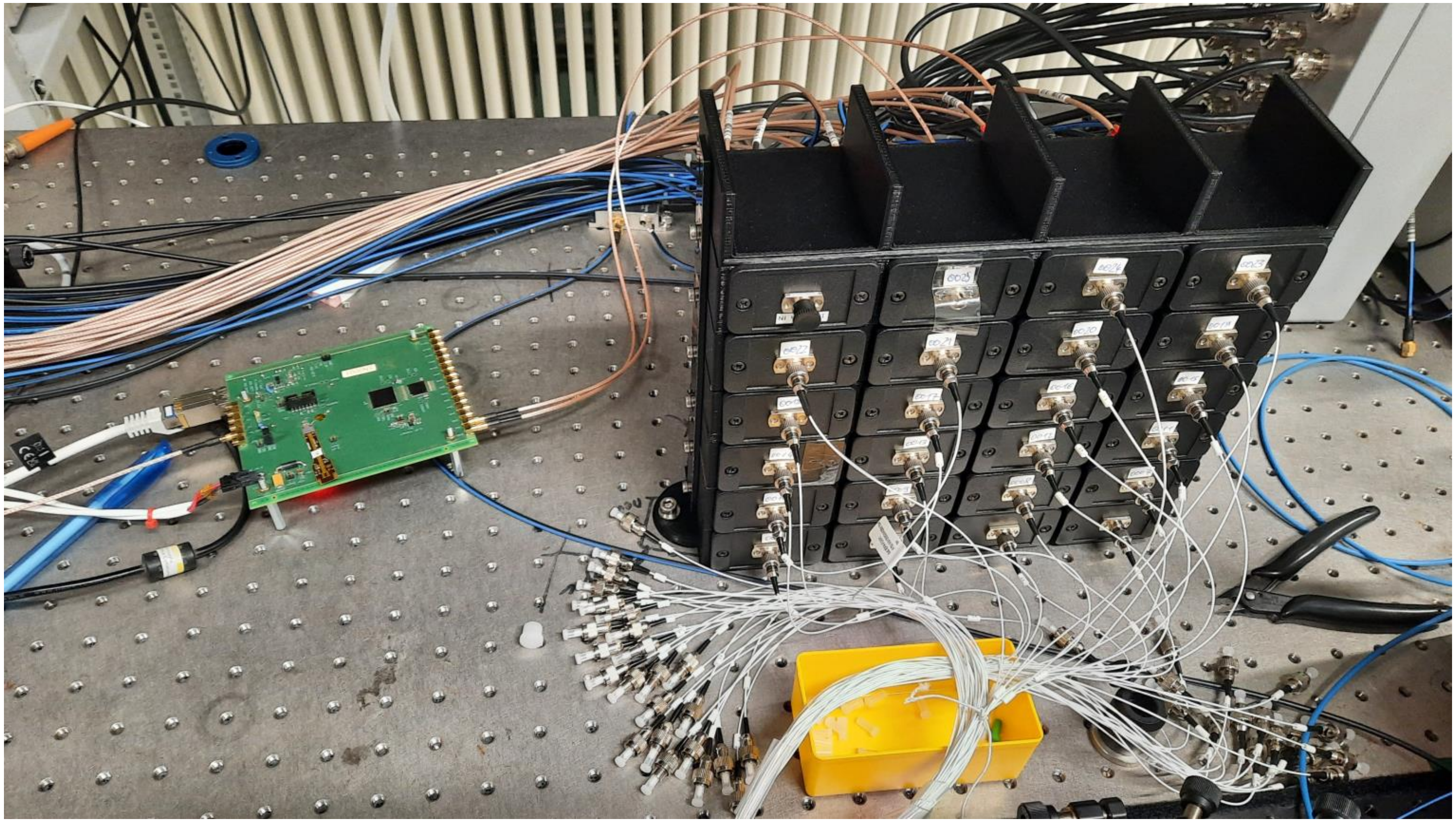
Specifications:

- 16 channel
- 0.5 - 1GSa/s continuous sampling
- 12 bit Analog to Digital Converter
- 16k deep storage buffer
- Random access full waveform readout
- Cost efficient



TARGET Based Phase Camera

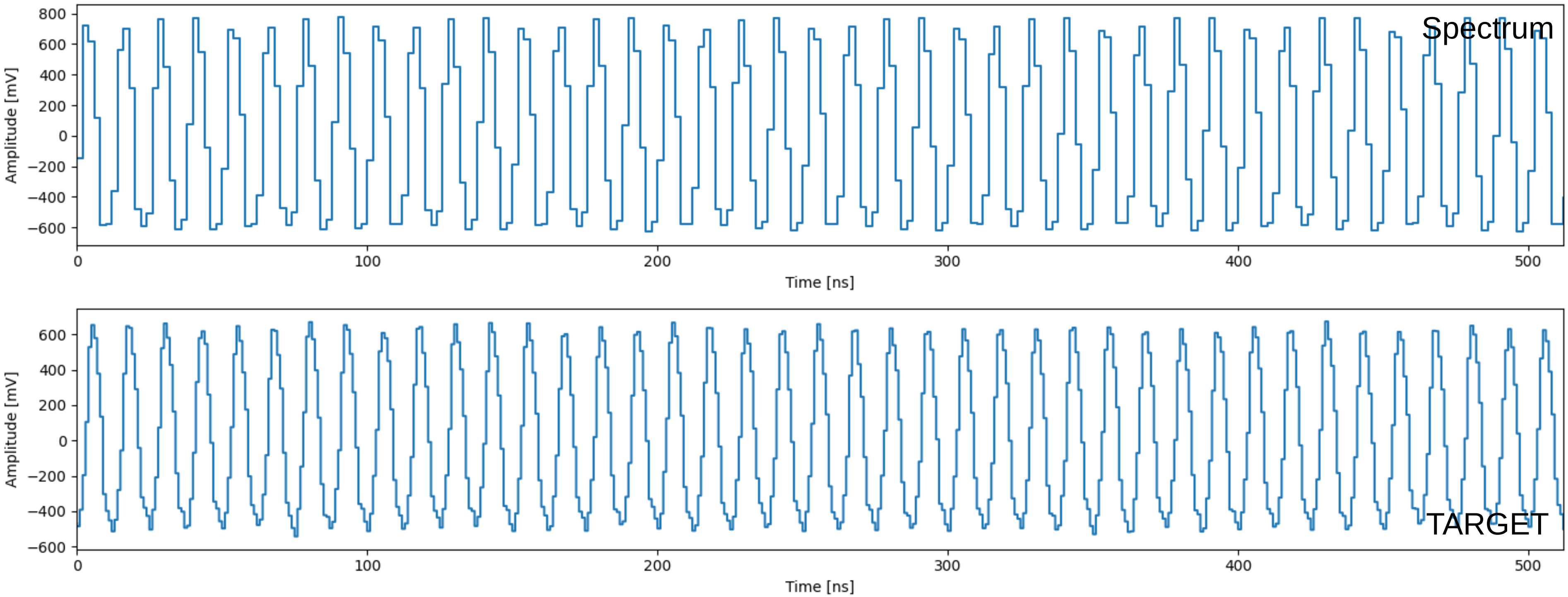
Setup



Use the evaluation boards from the commissioning of the TARGET ASICs for the SST Camera

TARGET Based Phase Camera

Is it suitable? Yes



Spectrum:

- 500MSa/s
- 14 bit ADC
- Arbitrary long waveforms

TARGET:

- 1GSa/s (atm)
- 12 bit ADC
- Max 4k sample waveforms (atm)

TARGET Based Phase Camera

Is it suitable? Yes

Measure four adjacent pixel:

- Pixel 43 digitised with TARGET, rest with Spectrum
- Take 4096 samples at 100 Hz → One phase measurement at 100 Hz

TARGET Based Phase Camera

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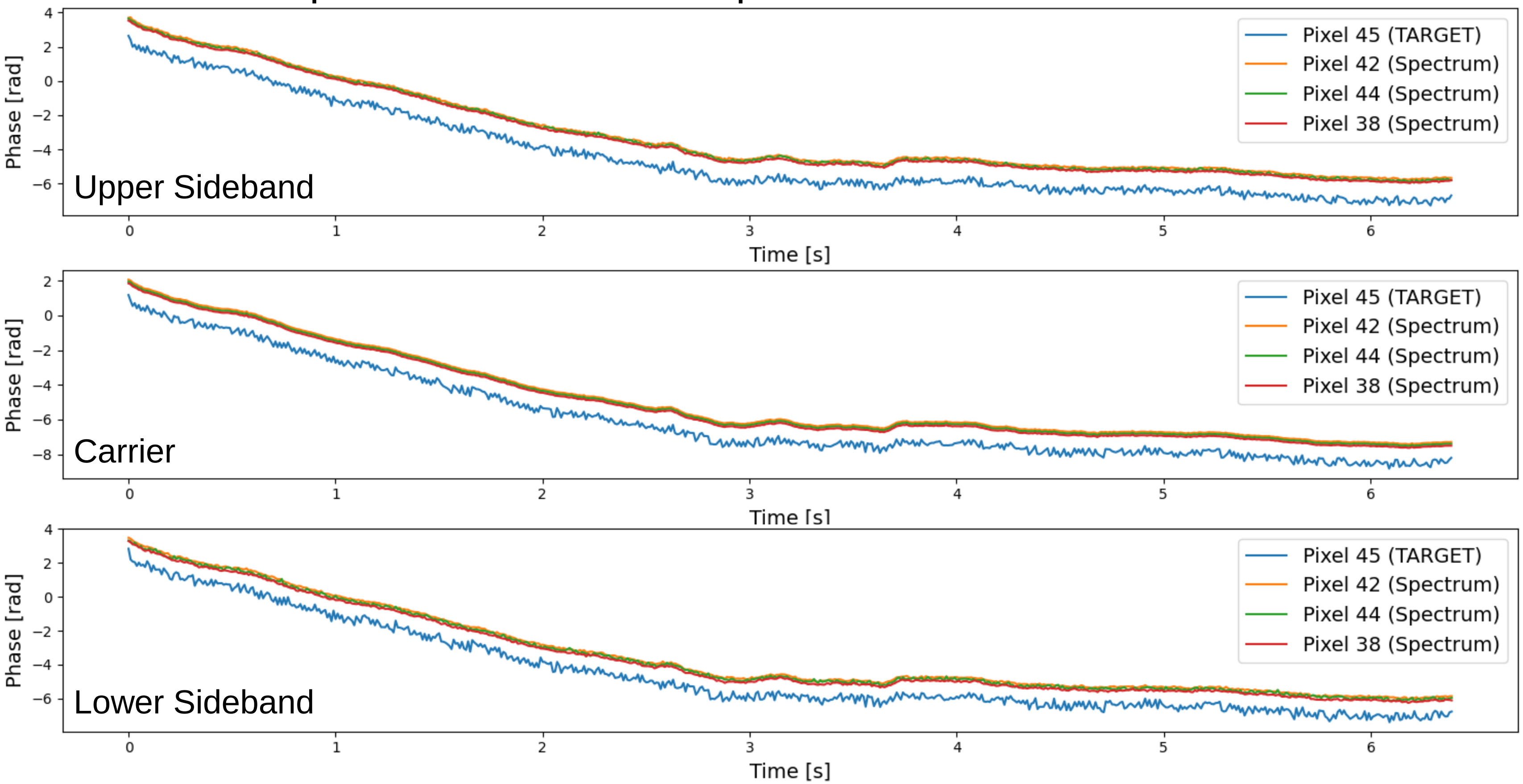

TARGET Based Phase Camera

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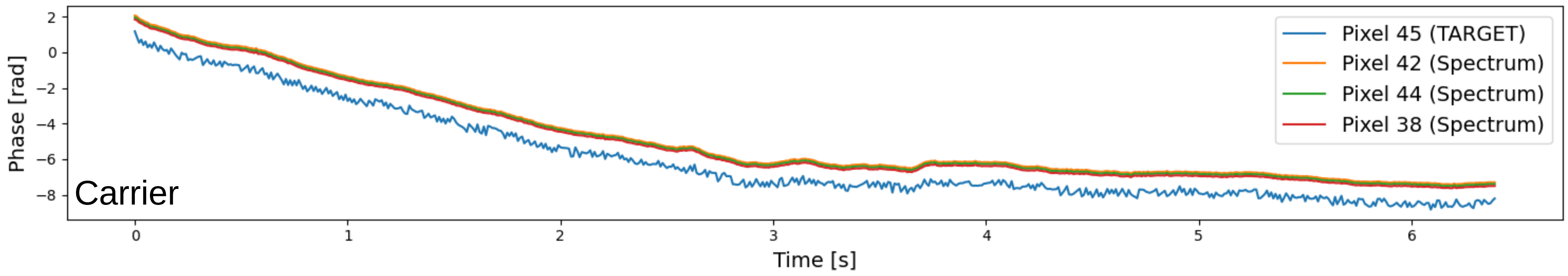


- Worse SNR for TARGET (Integration time halved, 12 bit vs 14 bit ADC)
- Large Offset:
  - Different cable length to digitizer lead to phase
  - 1.25rad = 2.5ns delay at 80 MHz
  - Corresponds to 50cm cable difference as used
  - Offset gets smaller with higher demodulation frequency (as expected)

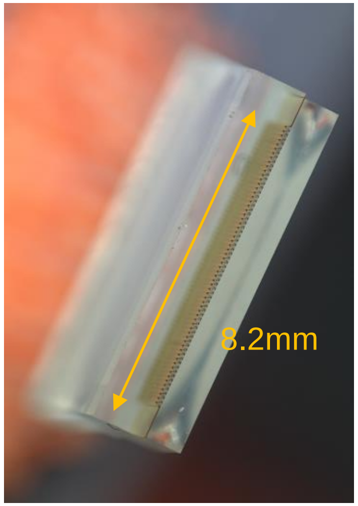
Summary + Outlook

Summary:

- A multimode fiber array is suited for a phase camera
- The TARGET ASIC is suited as digitiser for a phase camera
  - Can take 4us burst data at technical maximum of 280Hz
  - 64 x 64 camera possible and affordable

Outlook:

- Full calibration of the signal chain
- Explore the limitations of the approach
  - Noise level
  - Sensitivity
- Measure wavefront curvatures
- Measurement campaign at ET Pathfinder



Thank You for Your Attention!

Back Up

ECAP Phase Camera Characteristics

Fibers:

- Multi-Mode fibers, 105µm core, 125µm cladding
- Number of fibers: 2D 8x8 or 1D 64

  (future plans: can be extended, 64x64 possible i.e.)
- Pitch: 2D 127µm, 1D 127µm

Photodiodes:

- InGaAs PIN Diodes, 120µm size, FC connector

Amplifiers:

- ~220MHz bandwidth, two stages, 107 dB gain, low noise (-110dBm/Hz)

Digitisation:

- 24 channel at 500MSa/s (Spectrum M4i Series), 32 channel at 1GSa/S (TARGET ASIC) and 24 10kSa/s continuous (Arduino duo)

Data analysis:

- Python based, on CPU/GPU (future plans: real-time analysis, FPGA based analysis)

Phase Cameras

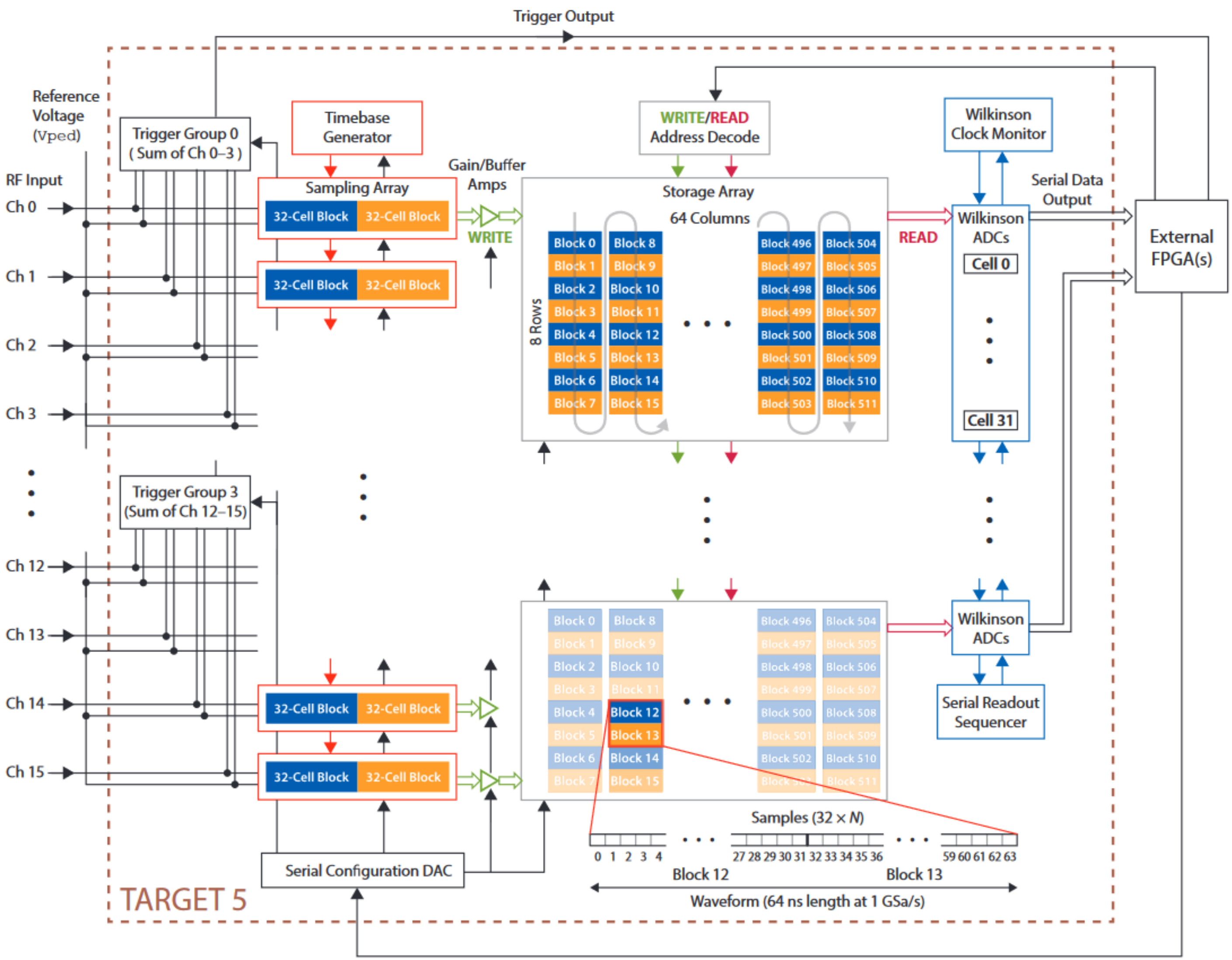
Table 1. Phase Camera Parameter Comparison[a]

	Scanning	Optical Lock-In	Time-of-Flight
Pixels (px)	128 × 128	2048 × 2048	320 × 240
Frame rate (fps)	1 (max. 10)	10 (max. 100)	max. 60
Sensitivity (dBc/px)	−61 (at 1 fps)	−62 (at 0.5 fps)	−62 (at 1 fps)
		−72 (120 × 128 px, 1 fps)	−50 (at 7 fps)
Detectable beam diameter change (%)	2.3	0.15	1.1
Spatial precision (mode weight ppm)	16500	1100	7800
Phase RMSE (nm)	0.7	Not available	0.1
Maximum frequency	250 MHz	100 MHz	100 MHz
Num. demodulations	11	1	1

Transverse Mode Control in Quantum Enhanced Interferometers: A Review and Recommendations for a New Generation

TARGET ASIC

TeV Array Readout electronics with Gsa/s sampling and Event Trigger



Phase Difference between the Sidebands

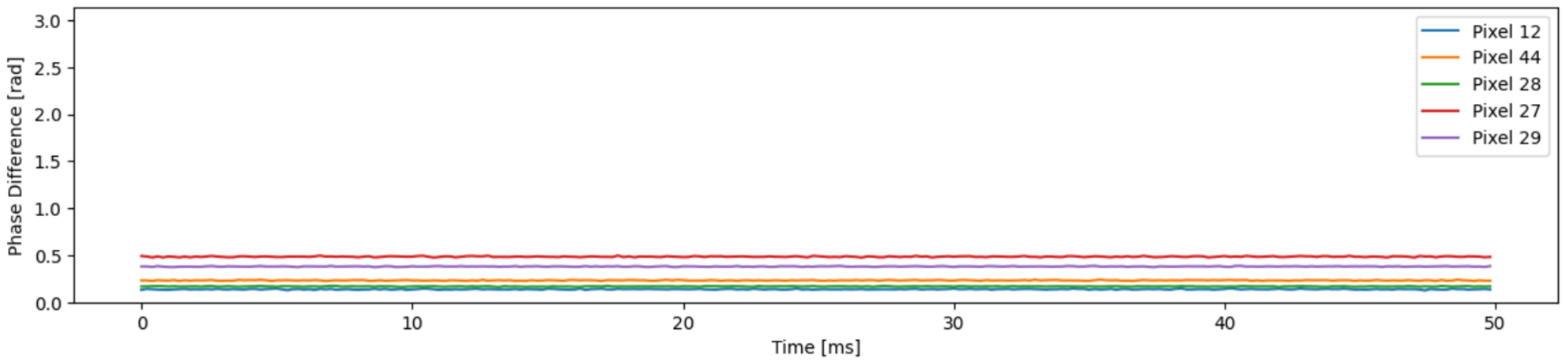
- LSB and USB (Lower and Upper SideBand) have 20MHz difference
- Propagating along an optical/electrical path, the phases of both should drift apart due to the different wavelength

$$\Delta\varphi = 2\pi \frac{d}{\Delta\lambda}$$

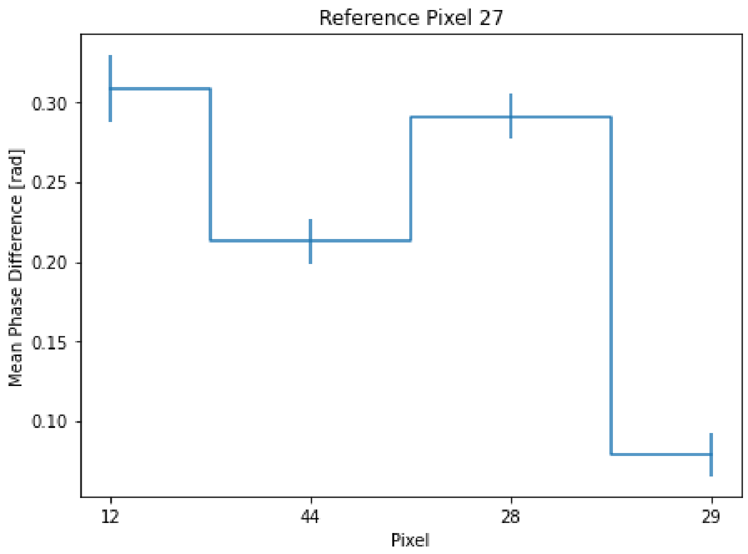
- Can measure the phaseshift between the sidebands at arbitrary distance and compare to the assumption
- If this is correct, we indeed measure phase!

Phase Difference Between Pixel

Time stability of wavefront geometry, all cable 5m

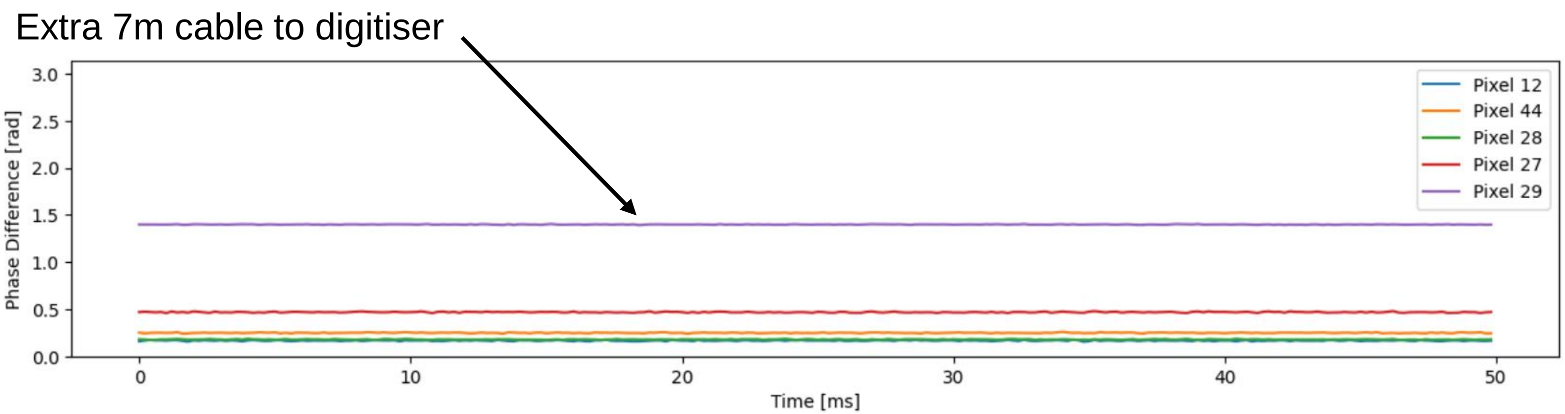


- Phase shift due to geometry stable over 2h of data
- Need to check if these phase shifts match the expected geometry



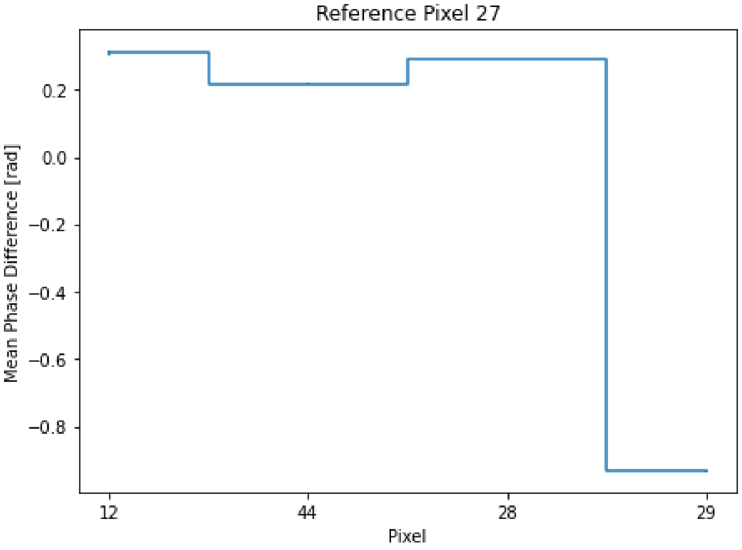
Phase Difference Between Pixel

Try now extra 7m cable on one pixel

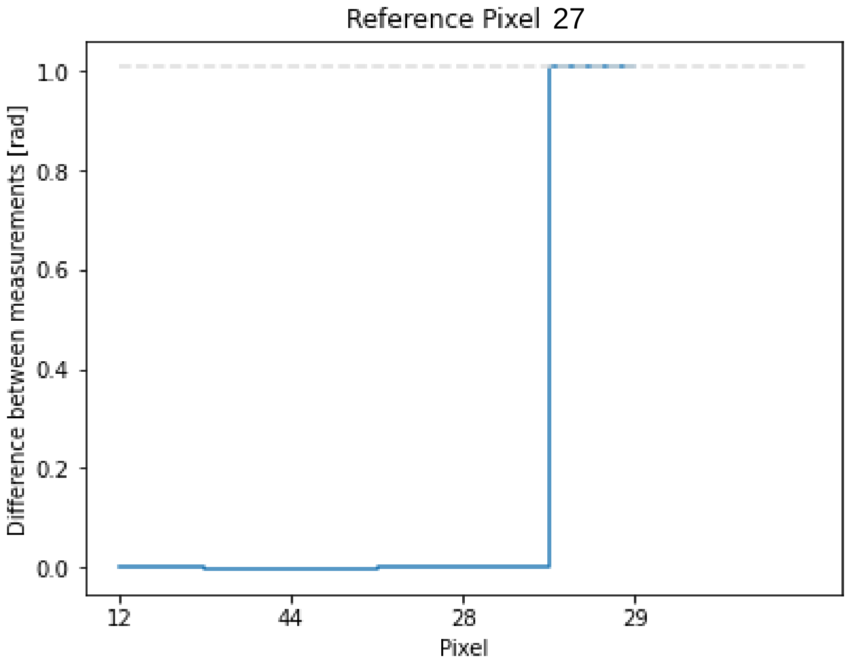


- Pixel 29 has the extra 7m cable
- Check if the phaseshift between pixel is constant between both runs!

→ Subtract the geometrical phase shifts from each other + Compare to assumption



Phase Difference Between Pixel



- Cable length for pixel 12, 27, 28, 44 unchanged between runs, expect no phase shift as the wavefront should be independent of time
- Pixel 29 has additional 7m coax cable → expect additional ≈ 1 rad phase shift

→ Expectations match measurements

→ We measure phase!