"Large Area Multi-Wavelength with Detection Range from FIR to UV - Application for FSO Measurement

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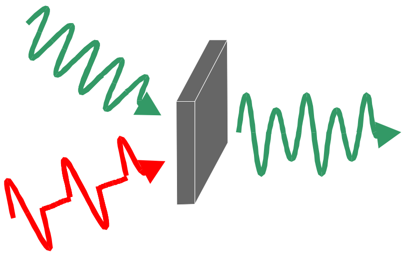
This research was supported by the Office of Naval Research (Award No. N00014-15-1-2393).

Enabling concept

Optical Control / Sensing of quantum devices

allows to bridge spectral regions through

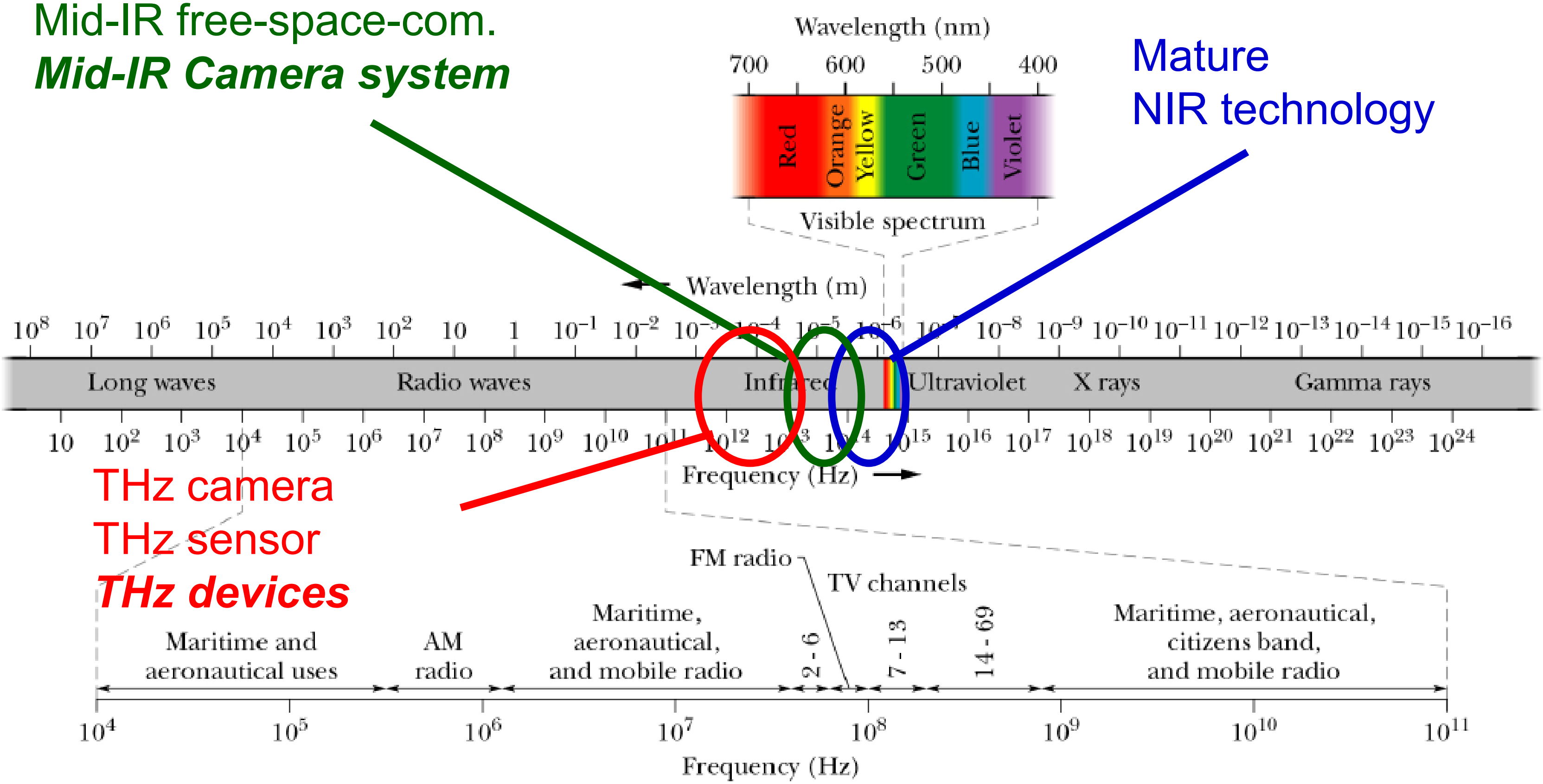
- All-optical modulation
  - ↳ NIR controls MIR emission
- All-optical switching
  - ↳ NIR switches THz (FIR)



- All-optical detector
  - ↳ MIR detected via NIR
- All-optical sensing
  - ↳ NIR detects MIR signature

QC-laser modulation
Mid-IR free-space-com.
Mid-IR Camera system

Mature
NIR technology



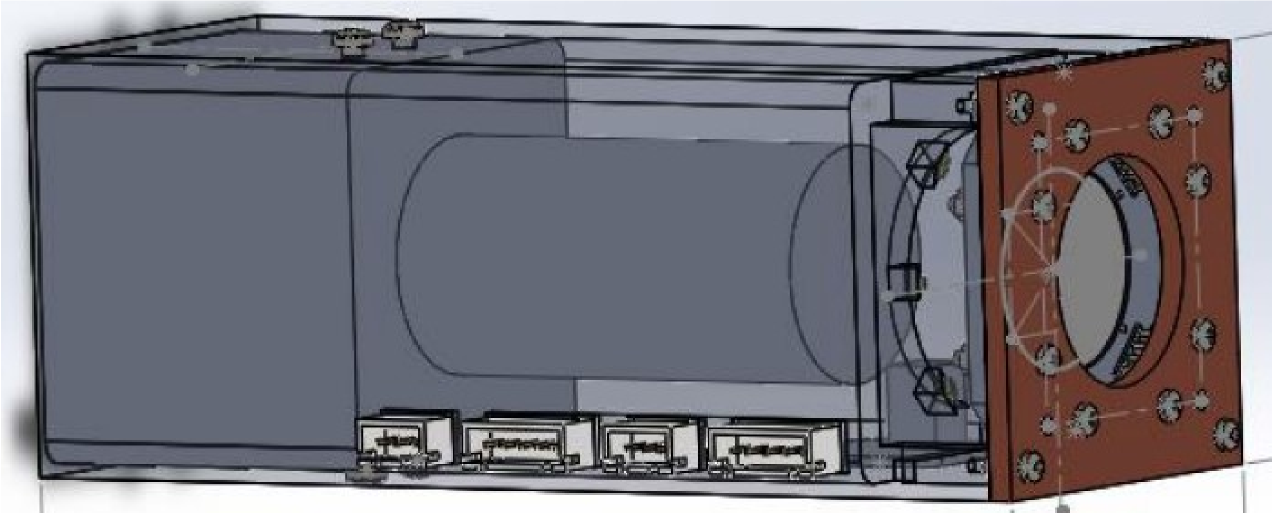
THz camera
THz sensor
THz devices

Overview

- An optical readout approach for sensors:
  - example UV-IR-THz-GHz camera
  - Large Area detection enabling multi-wavelength correlation measurement

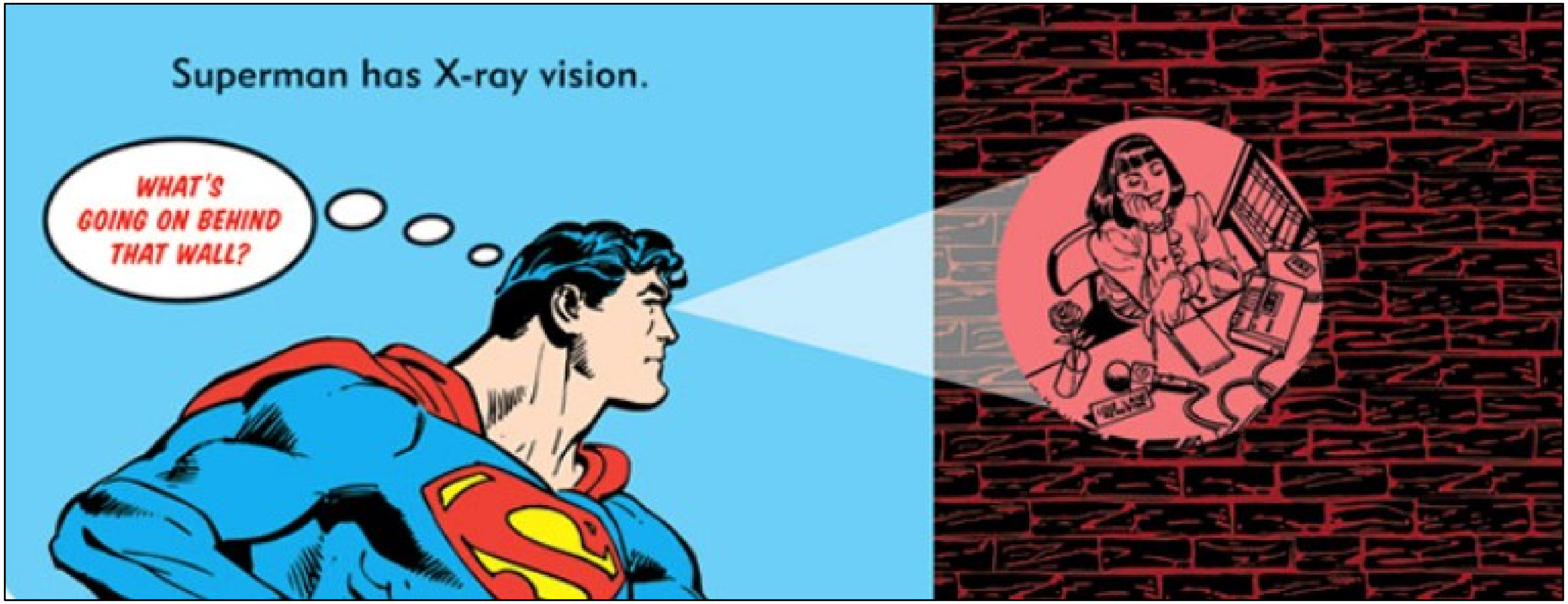
- Advantages of mid-infrared (or longer) wavelength propagation through challenging environments

Multi-spectral Large Area Broadband imaging system



X-ray Vision

- Superman's X-ray vision is amazing. Now imagine, if you had that super power?
- Just like visible light, Microwave is part of electromagnetic spectrum which can pass through the walls. If we had microwave sensitive eyes or a camera, we could see through walls.

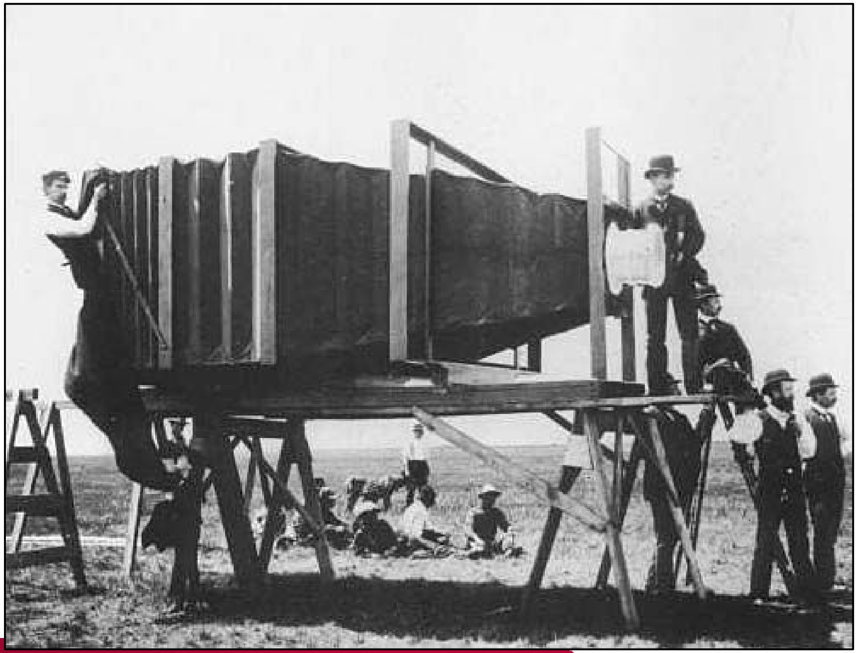


Why it doesn't exist?

- Diffraction limited blur size is directly proportional to wavelength

$$B_{diff} = 2.44\lambda\left(f/\#\right).$$

- For 50Ghz microwave with wavelength of 6mm, diffraction limited blur size is 3cm for f/2.0 aperture. We would need detector size of 2ft x 2ft to get 20x20 px resolution. Traditional silicon detector cannot be made in this size.

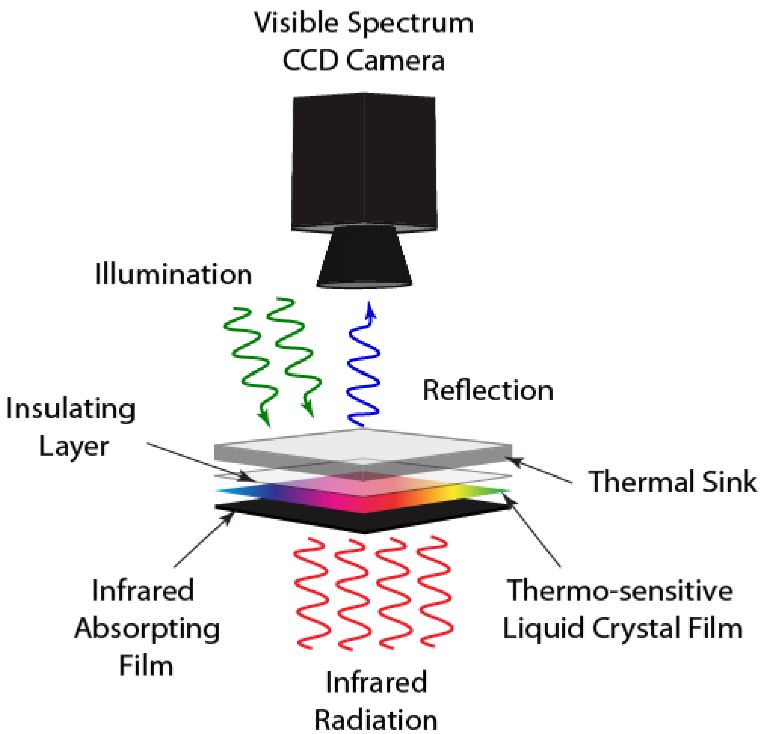


Now imagine the situation with 10Ghz wavelength!!

Example of an optical readout sensor: IR camera

- Basic concept idea for ***O***ptically-***R***eadout:
  1. ***Convert*** signal (incident MIR radiation) into NIR / VIS image in a specified structure,
  2. ***Probe*** the NIR / VIS image with a NIR /VIS beam (which can be actively controlled),
  3. Detect NIR / VIS image with ***commercial high-resolution camera***.

How does Wavelength Transformation Work?



Process of Wavelength Transformation

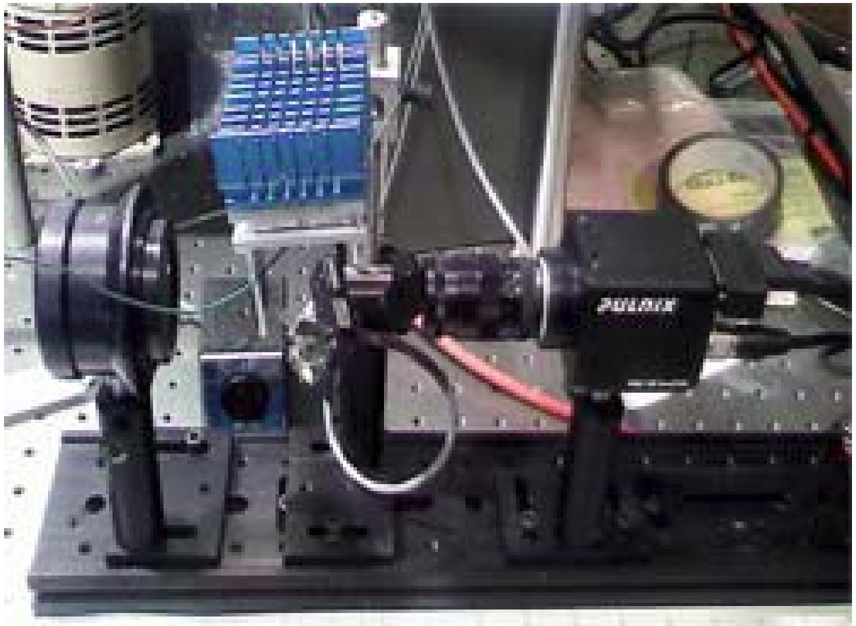
1. Photons incident on an absorbing film (radiative detection)
2. Film converts the energy of the photons into heat
3. Thermo-Sensitive Polymer Reacts to Heat through an change in optical properties
4. Probe the optical changes with a camera.

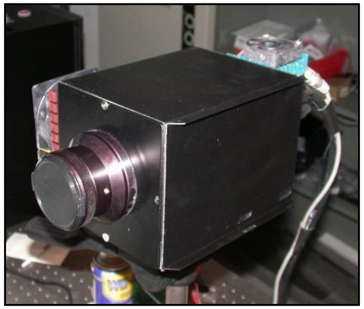
Advantages

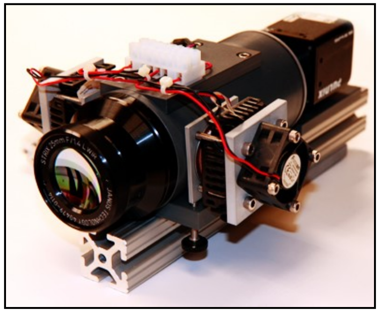
- Simple construction, no structuring necessary
  - Cheap, **scalable**, no contacts, electrically immune
- Pixelation only in VIS/NIR camera
  - High resolution possible
- Separation of absorption and sensing
  - Separately optimized / exchanged
- Only temperature stabilization needed
  - No major cooling needed / room-temperature possible

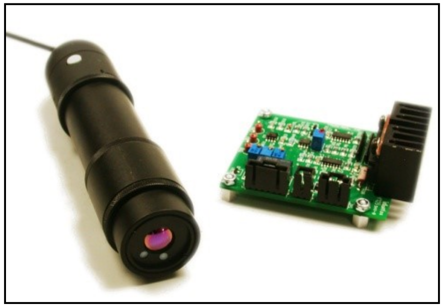
- Many levels of enhancement possible….

Prototypes….

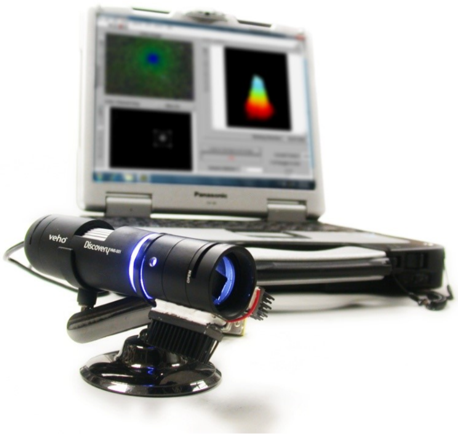


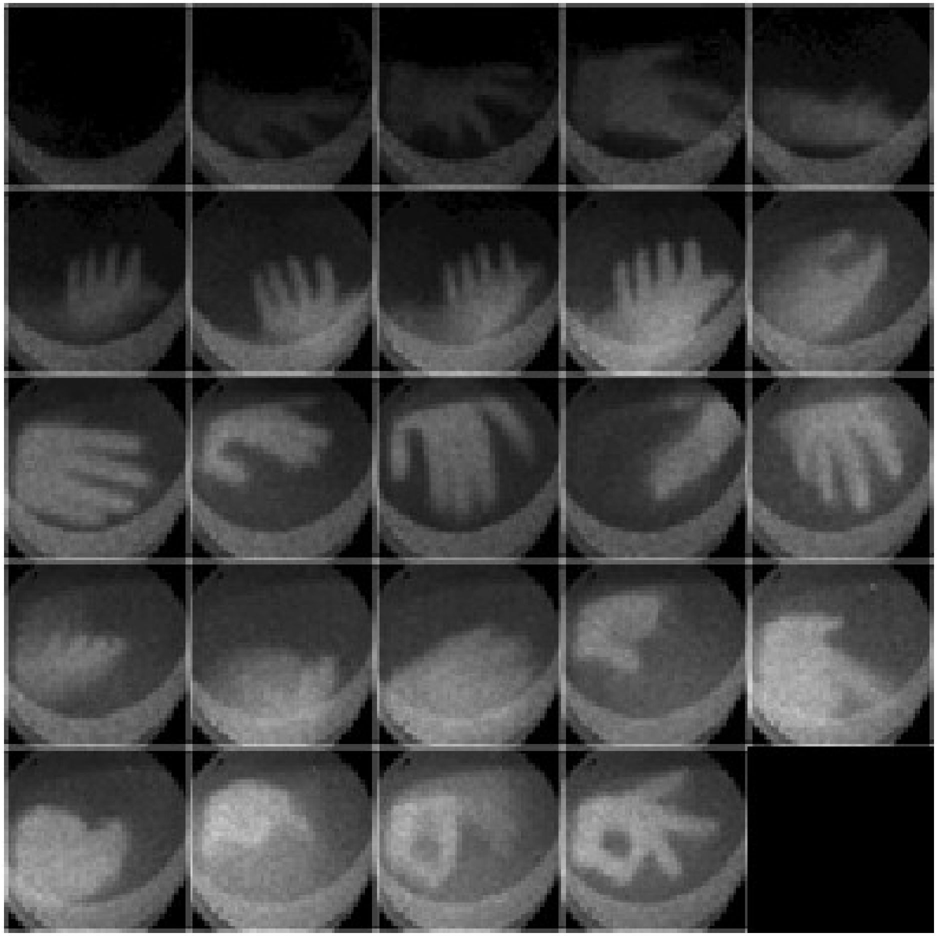




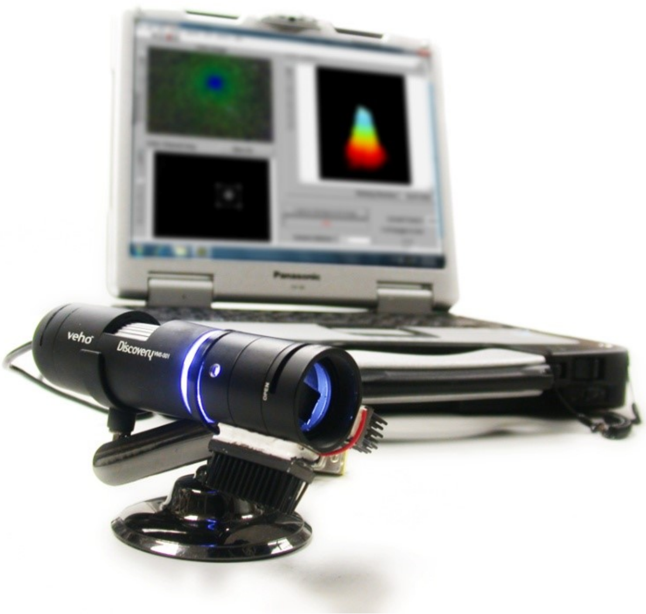


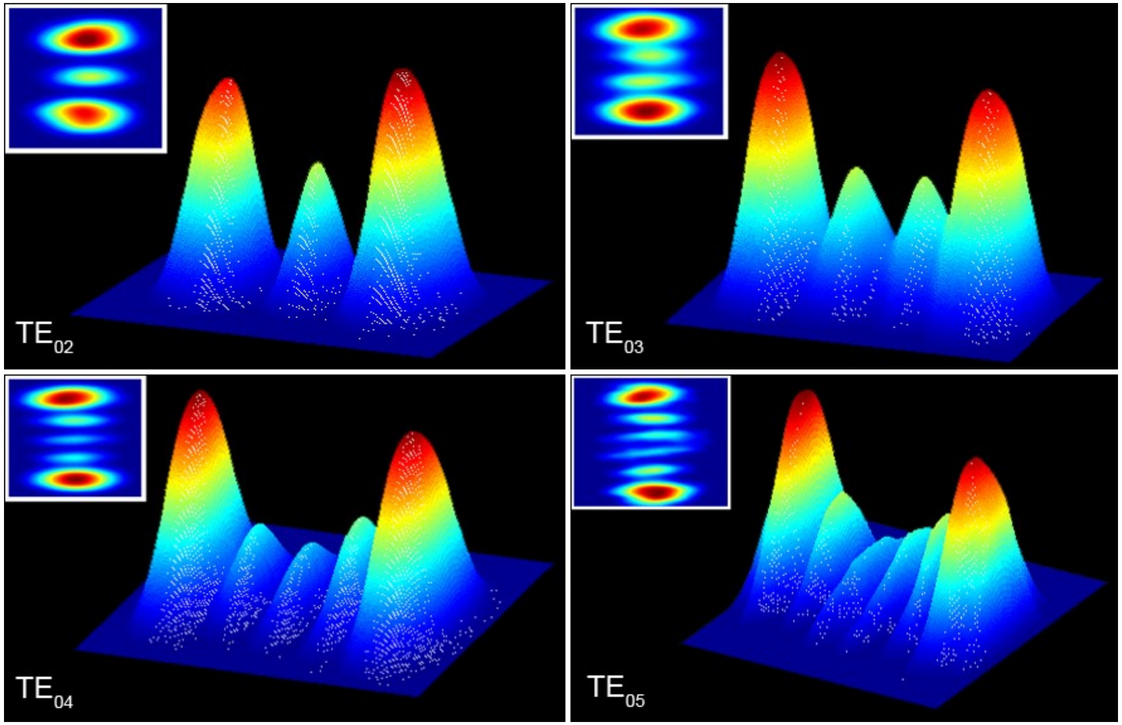
First tests with hand…..



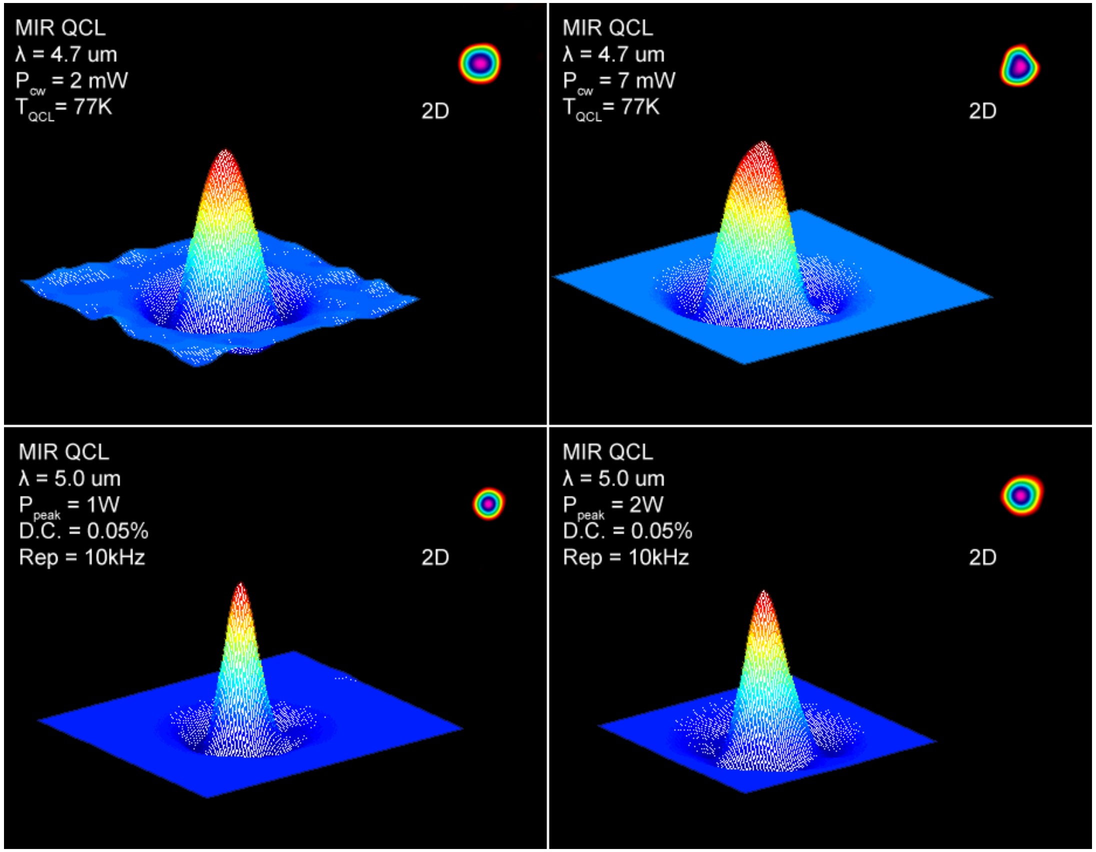


NIR Laser mode imaging



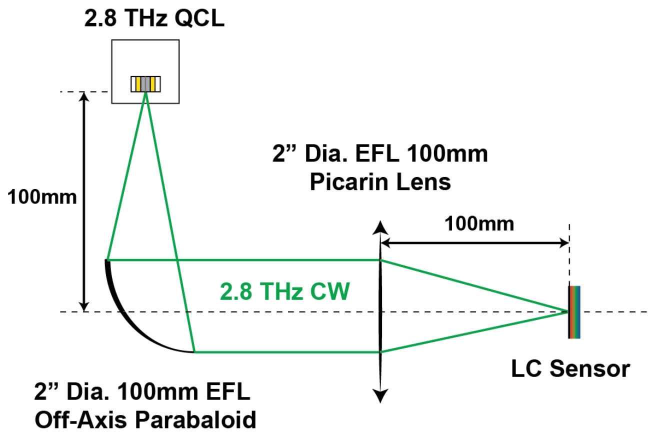


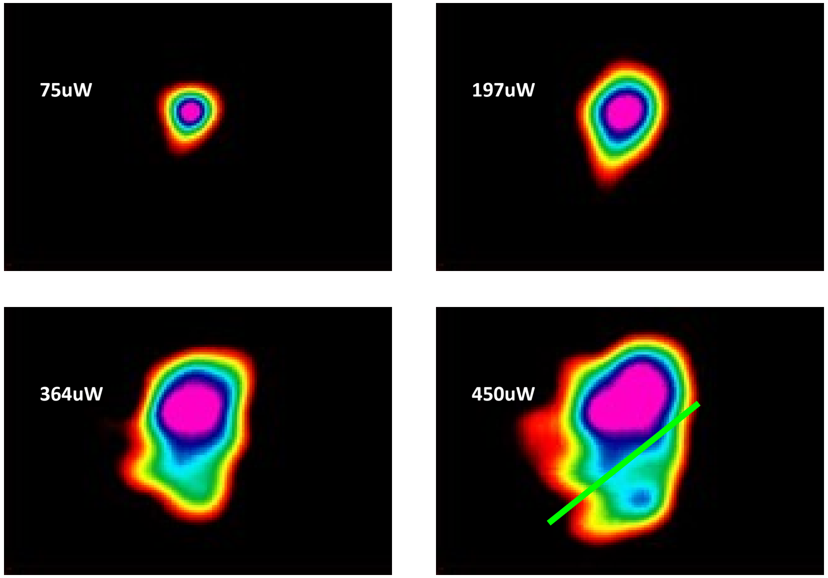
Laser modes MIR QCL

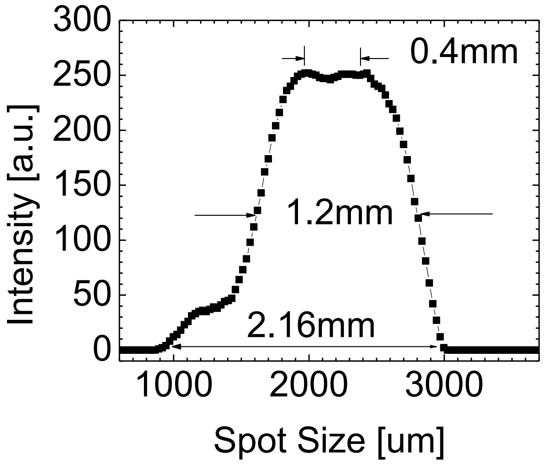


We would like to thank Claire Gmachl from Princeton University for her assistance in these measurements

2.8 THz Quantum Cascade Laser





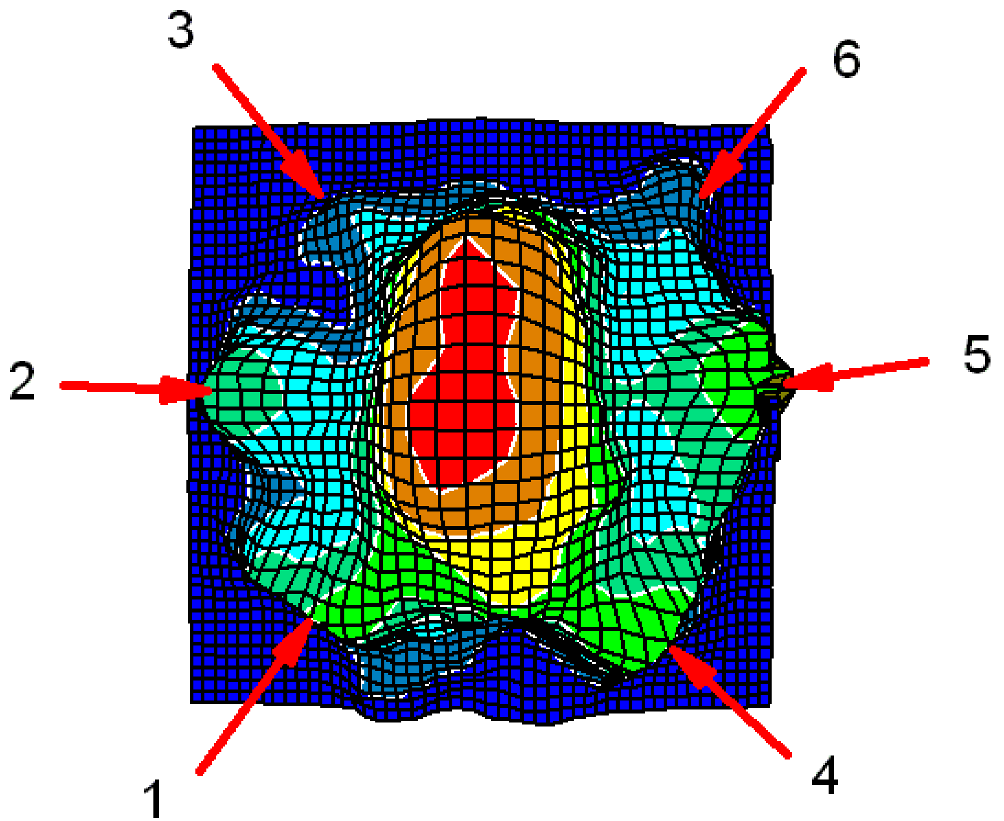


Measurements performed at Sandia National Laboratory, Albuquerque, NM

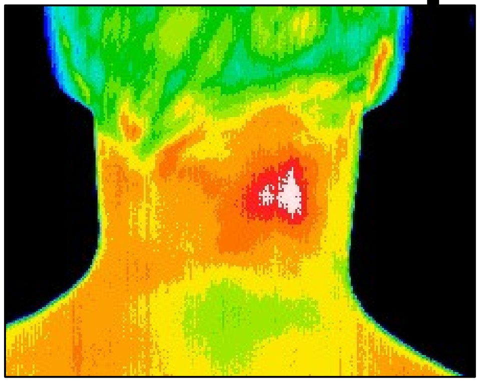
We would like to thank Mike Wanke and Albert Grines for their assistance.

And last but not least: 110GHz

- Source:
  Antenna driven
  by 7mW, 110GHz
- Increased absorption through water layer
- To my knowledge first 100GHz camera

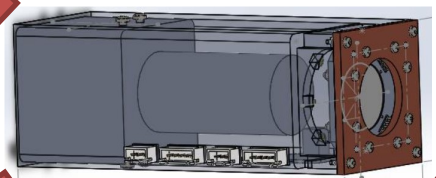


Potential application



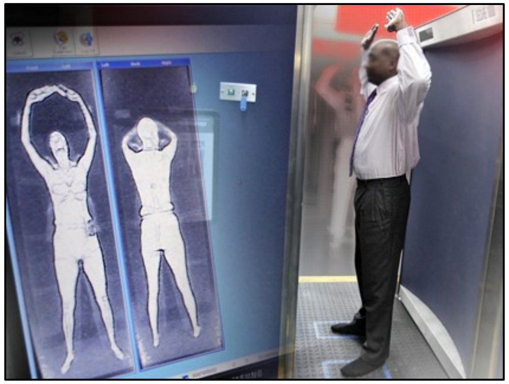
Medical imaging

5G high band(24Ghz-71Ghz)



Military-thru wall imaging

Airport security scanning



Overview

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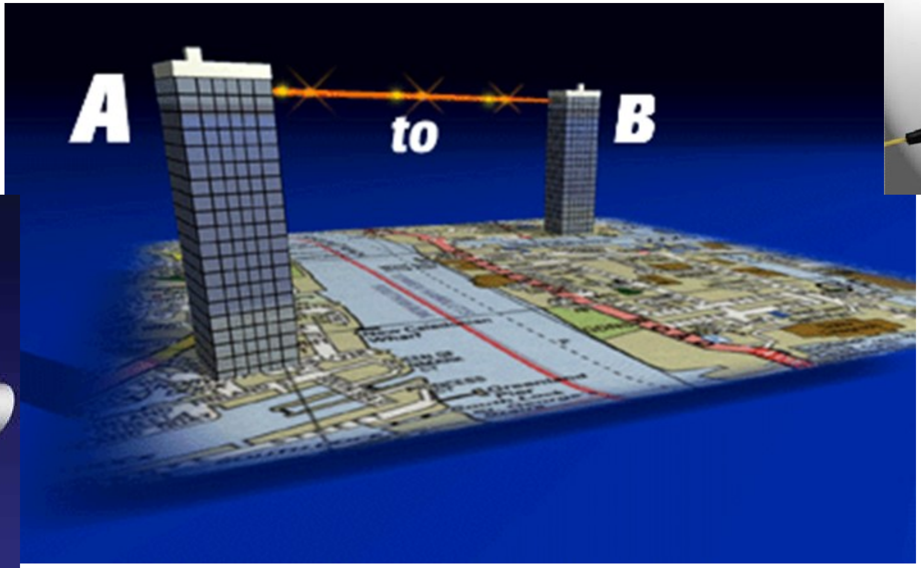
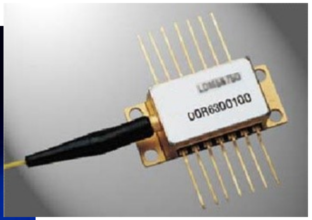
- Advantages of mid-infrared (or longer) wavelength propagation through challenging environments

Background: MIR - FSO?

Hybrid optical-wireless technology

- Inexpensive (~$20k), fast (1 day), efficient (~ Gbps),
- Based on conventional semiconductor lasers in Near-IR region (0.81μm → **1.55μm**)
- Basic advances in mid-infrared spectrum: less scattering

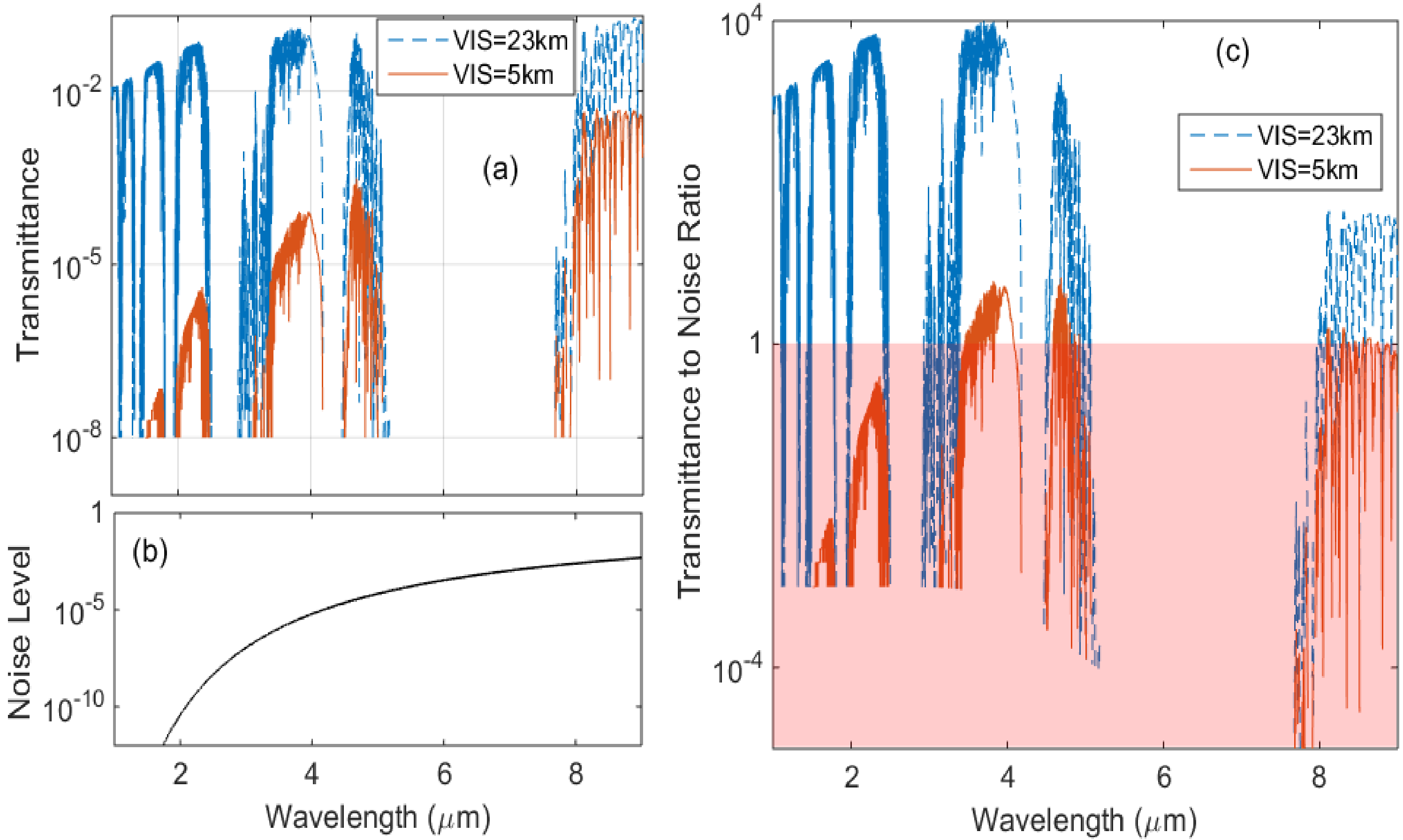




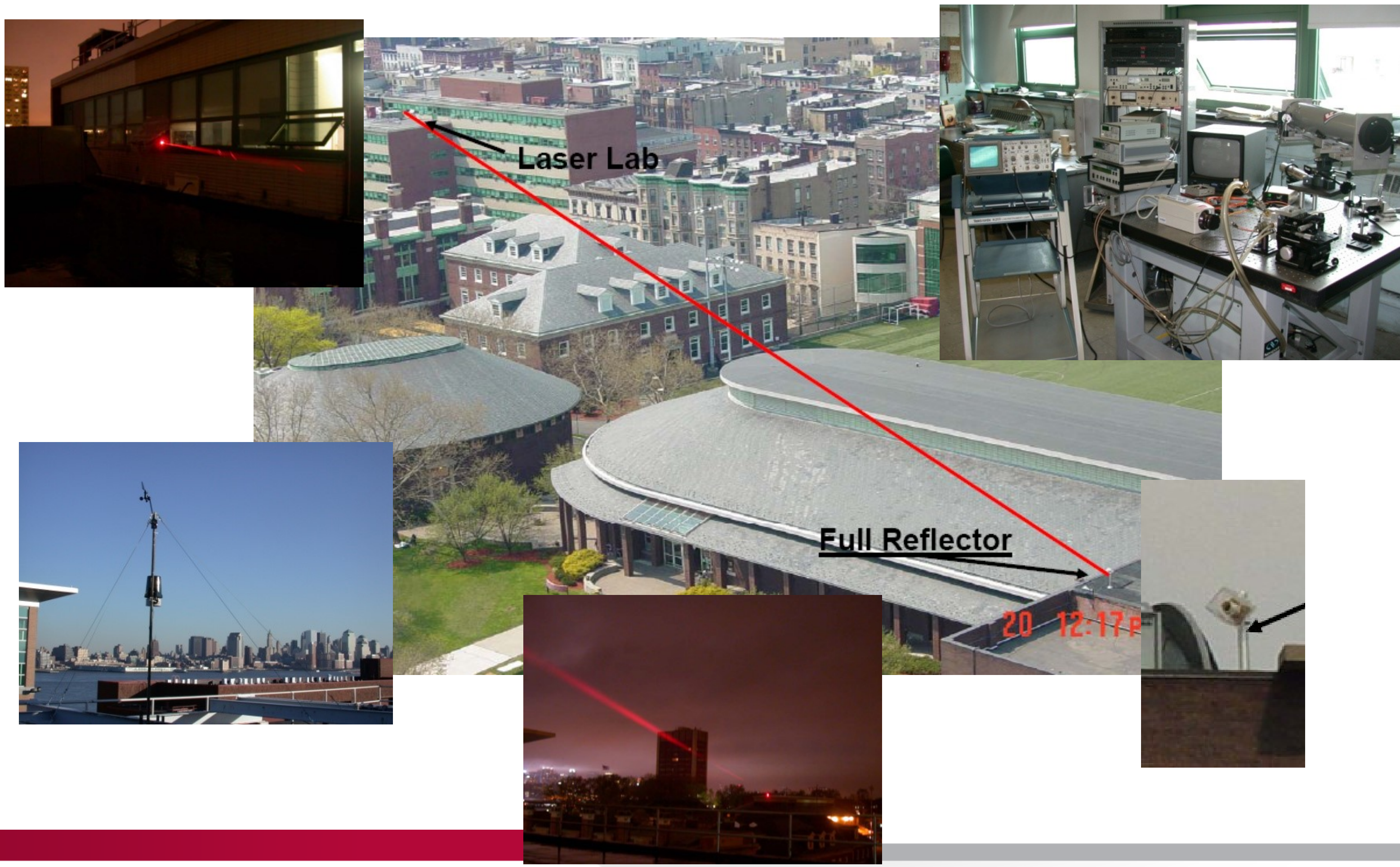
(Courtesy of Lightpoint)

Optimized wavelength

Navy Aerosol Model (NAM) for a distance of 30 km
Visibility 23 km: the observed monthly mean
Visibility 5 km: the average daily mean during an 8 day period in August

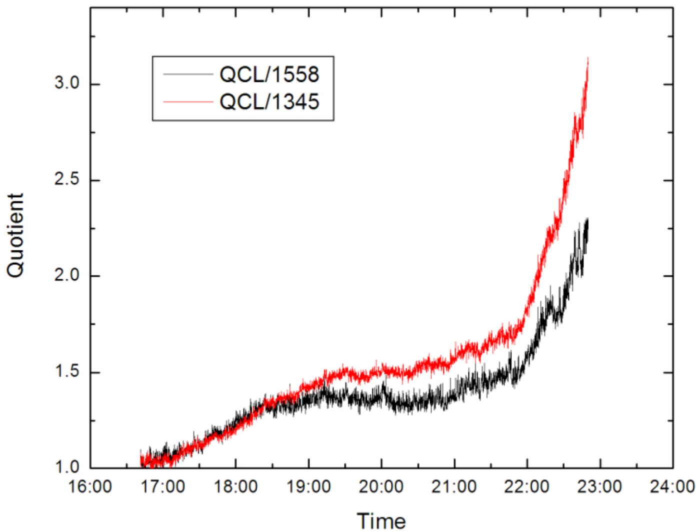


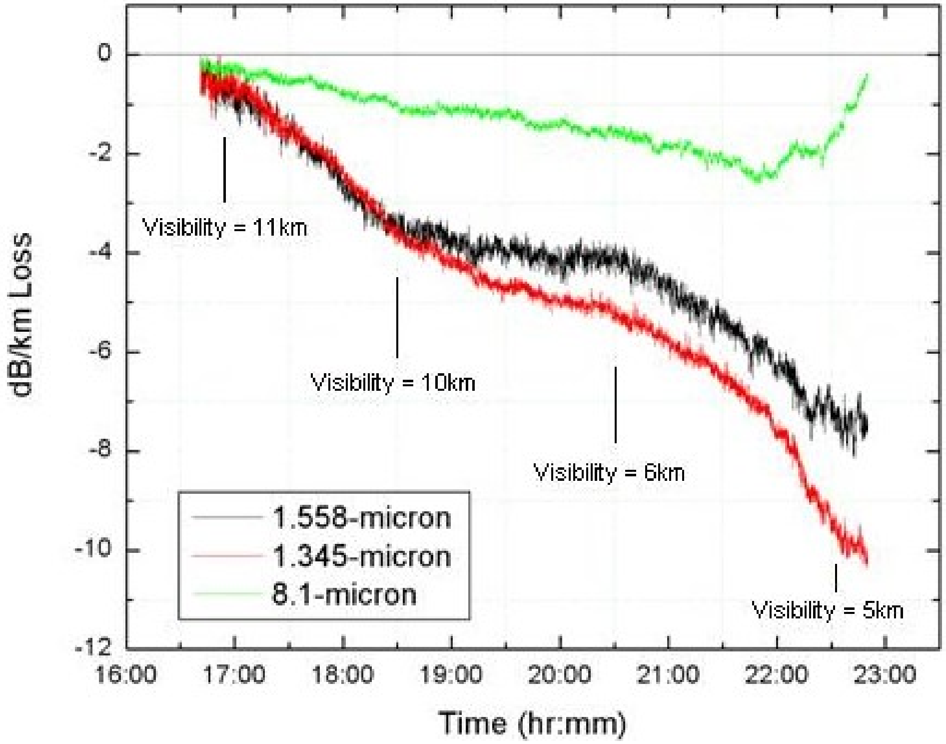
550m FSO link with >4 wavelength capability



Mid-IR Outdoor link measurment

- Mid-IR **Outperforms**
- **Up to x30 dB/km**
- Longest time sets
- Bimodal Fog
- Scavenging event at 22:00 with rain
- **x2 → x3 MORE Raw Power**

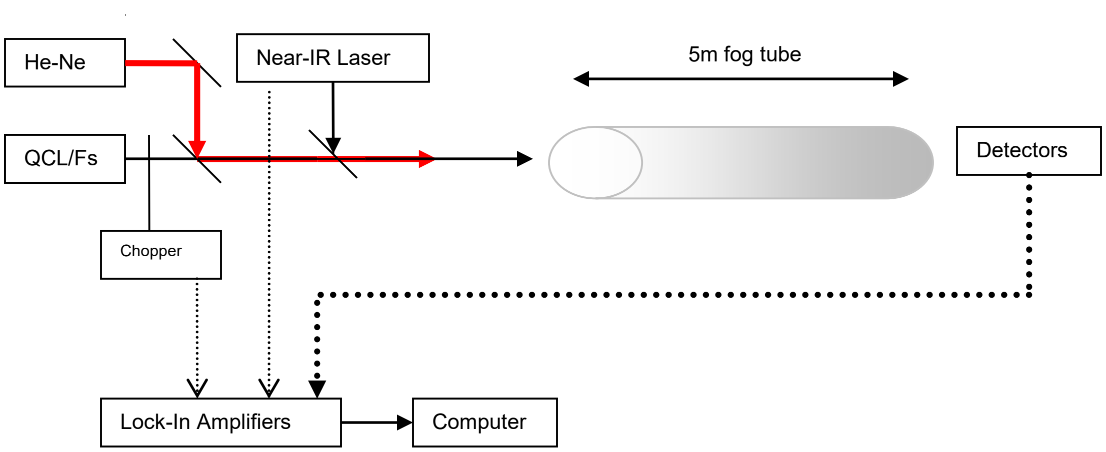


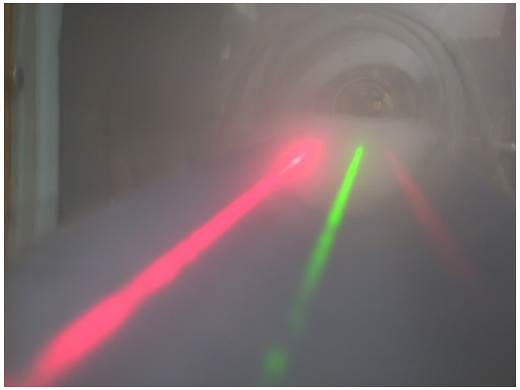


P. Corrigan, E.A. Whittaker, E.A. Whittaker, and C. Bethea, "Quantum cascade lasers and the Kruse model in free space optical communication", Optics Express 17, 4355-4359 (2009).

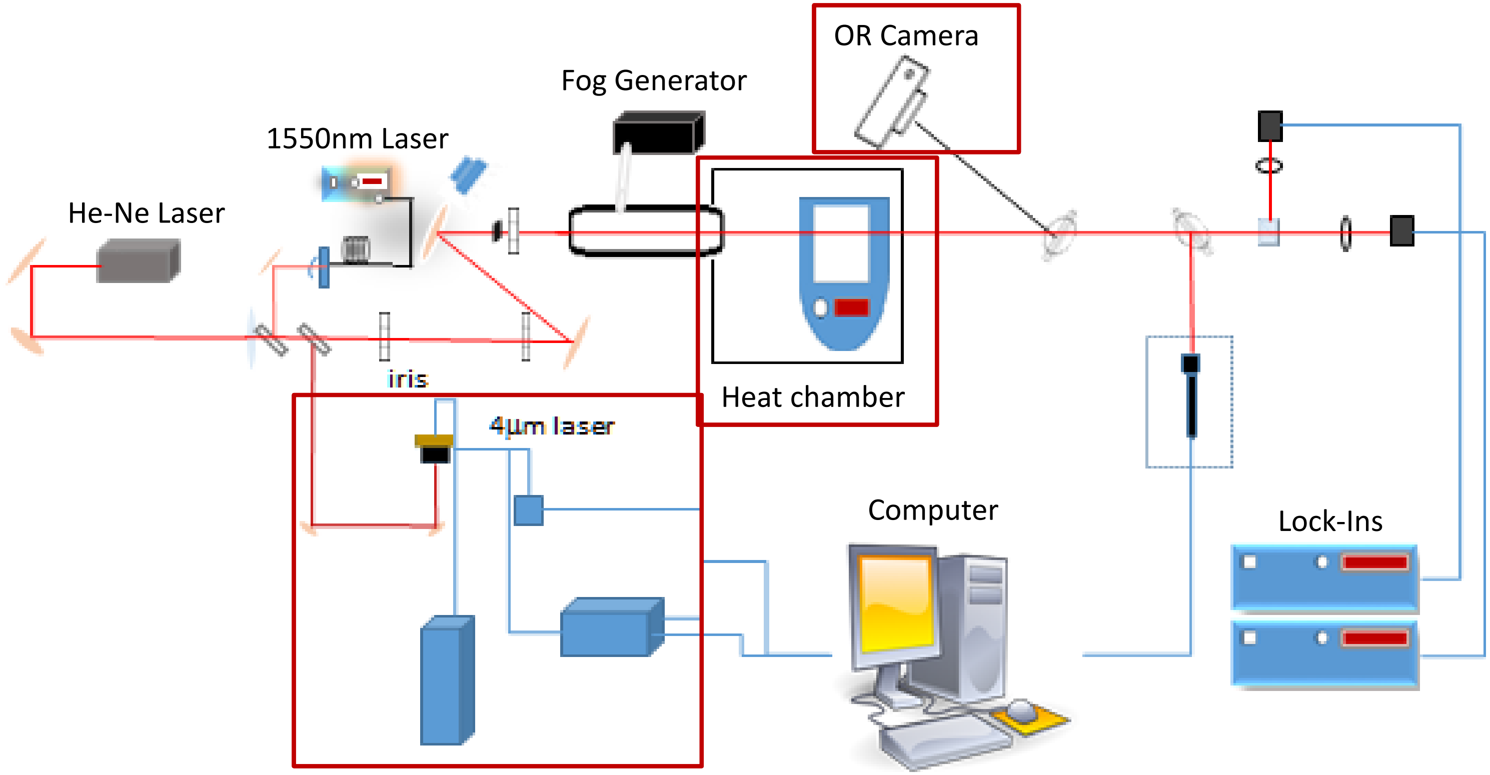
Indoor Transmission ("Fog Tube")

- Only get a few "good" fog days a year!
- Make use of propylene glycol based Synthetic Fog
  - ⇨ Slightly (~5%) absorbing at 8.1μm
  - ⇨ Transparent at 1.31 & 1.55 μm
- Reproducible losses up to 20db/5m (4,000dB/km, <10m vis.)



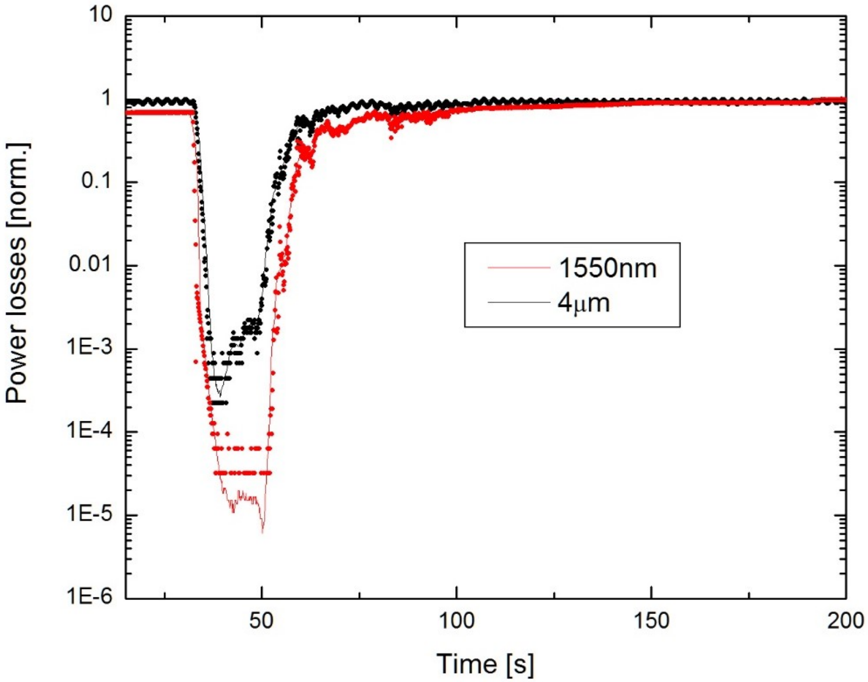


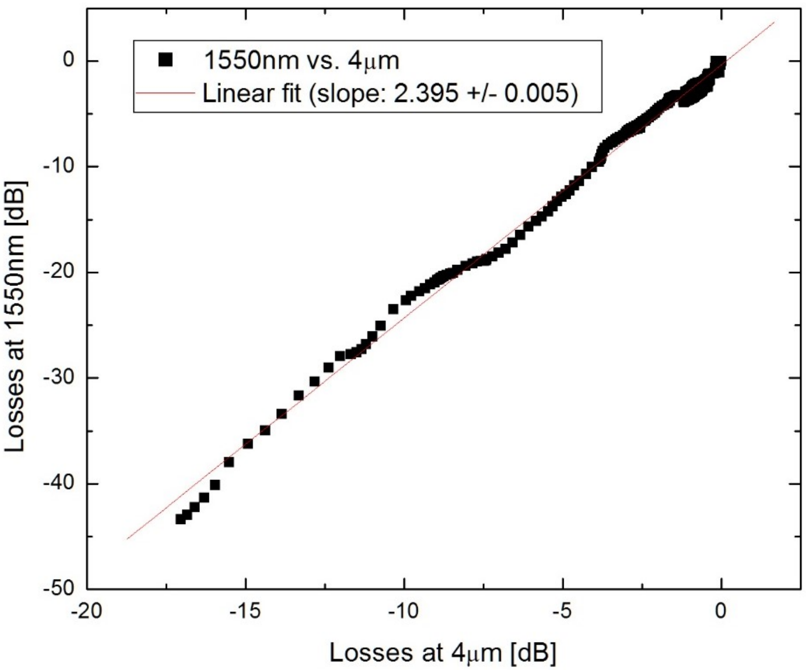
In-lab testbed for FSO propagation



- Measuring transmission and beamwander at 1550nm, 4μm (+ extension possible)
- Controlled addition of turbulence (~500m at $C_n^2 = 2*10^{-16} m^{-2/3}$)
- Controlled addition of water based aerosol (losses up to -50 db)

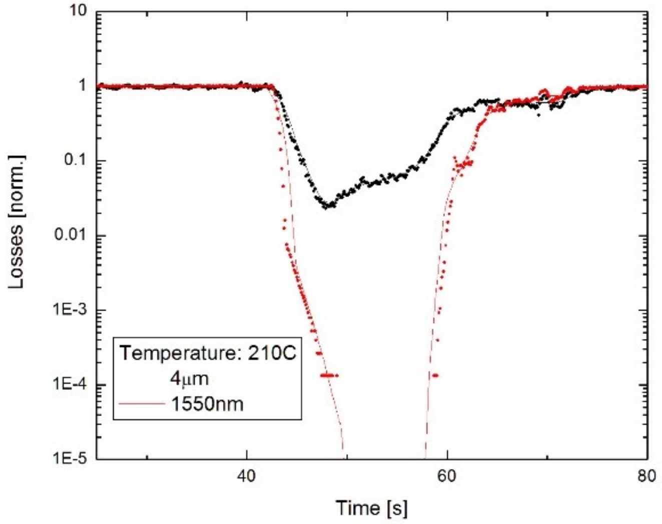
Comparison of simple scattering

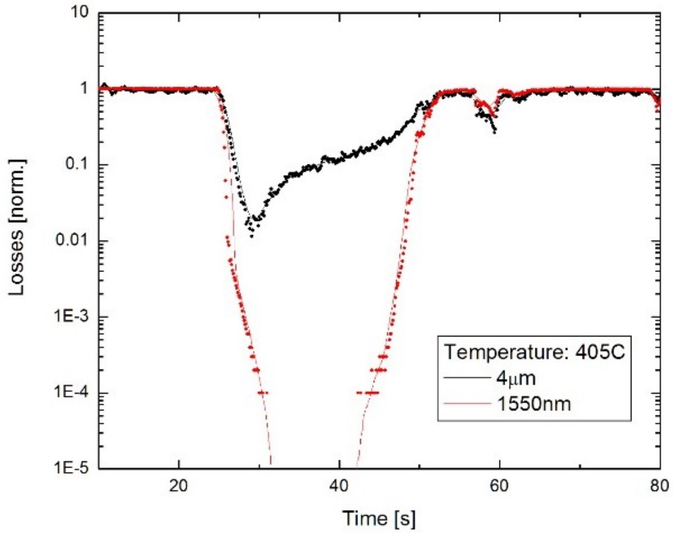


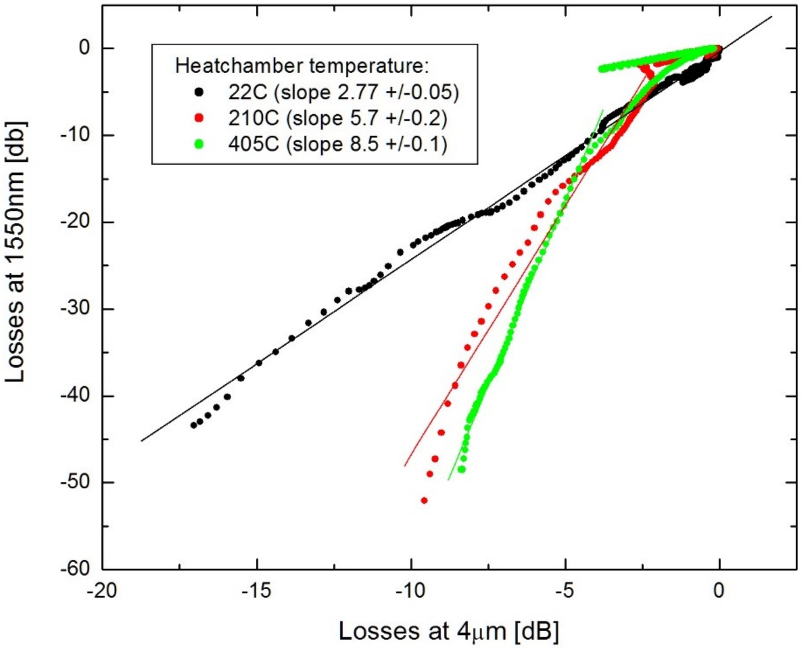


- Comparing losses over 40 dB dynamic range while aerosol concentration reduces.
- Comparison shows clear advantage of 4μm link
- Quantitative analysis shows ~(**1/2.4**) x dB loss (e.g., 40 dB vs 16 dB)

Scattering & Scintillation (reality)

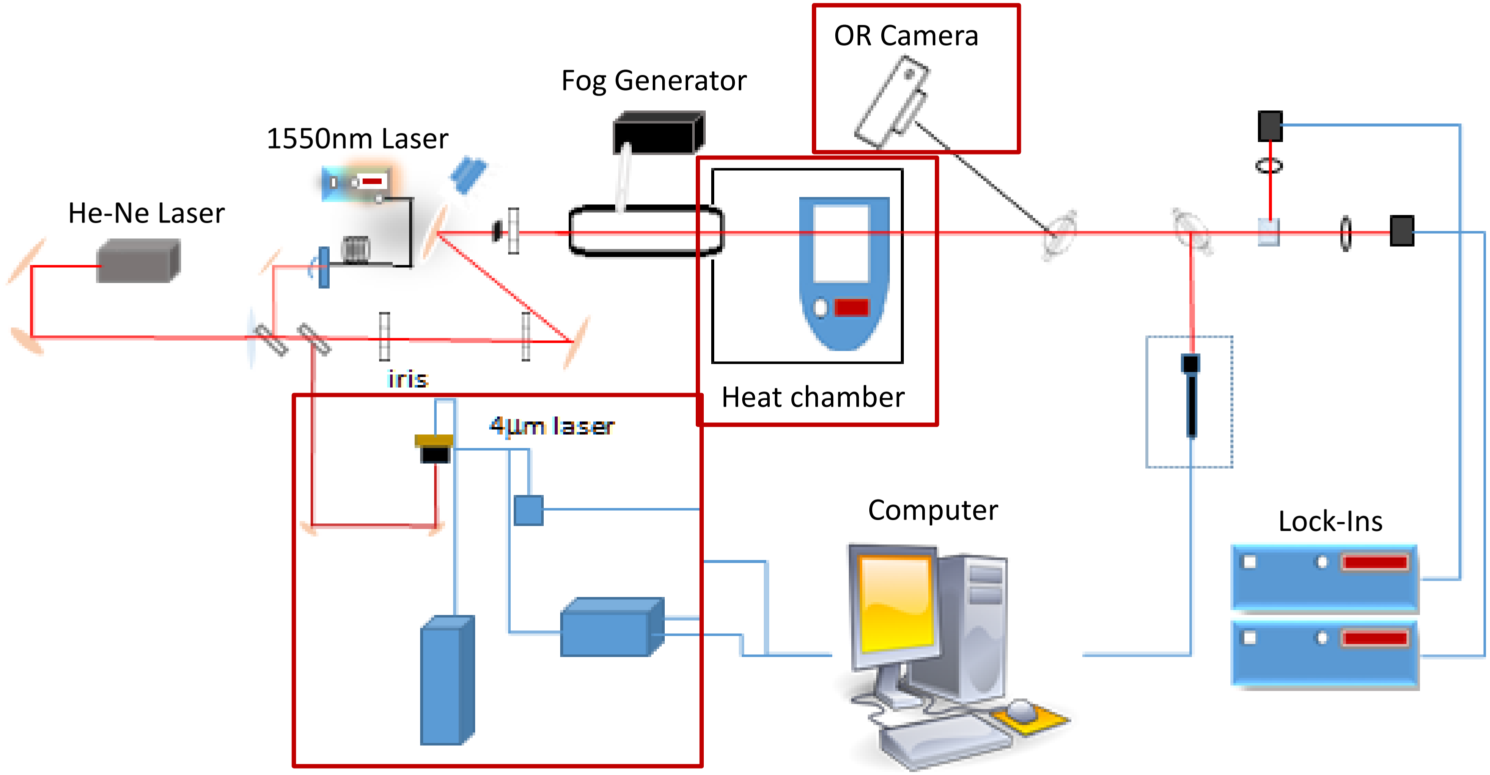






- Addition of scintillation (caused by heat from a heatplate) degrades transmission drastically
- **(1/8.5)** x dB loss under strong scintillation (50 dB vs 6 dB)
- New: losses per scatter scale with turbulence strength – cannot be treated as independent losses.

In-lab testbed for FSO propagation



- Measuring transmission and beam wander at 1550nm, 4μm (+ extension possible)
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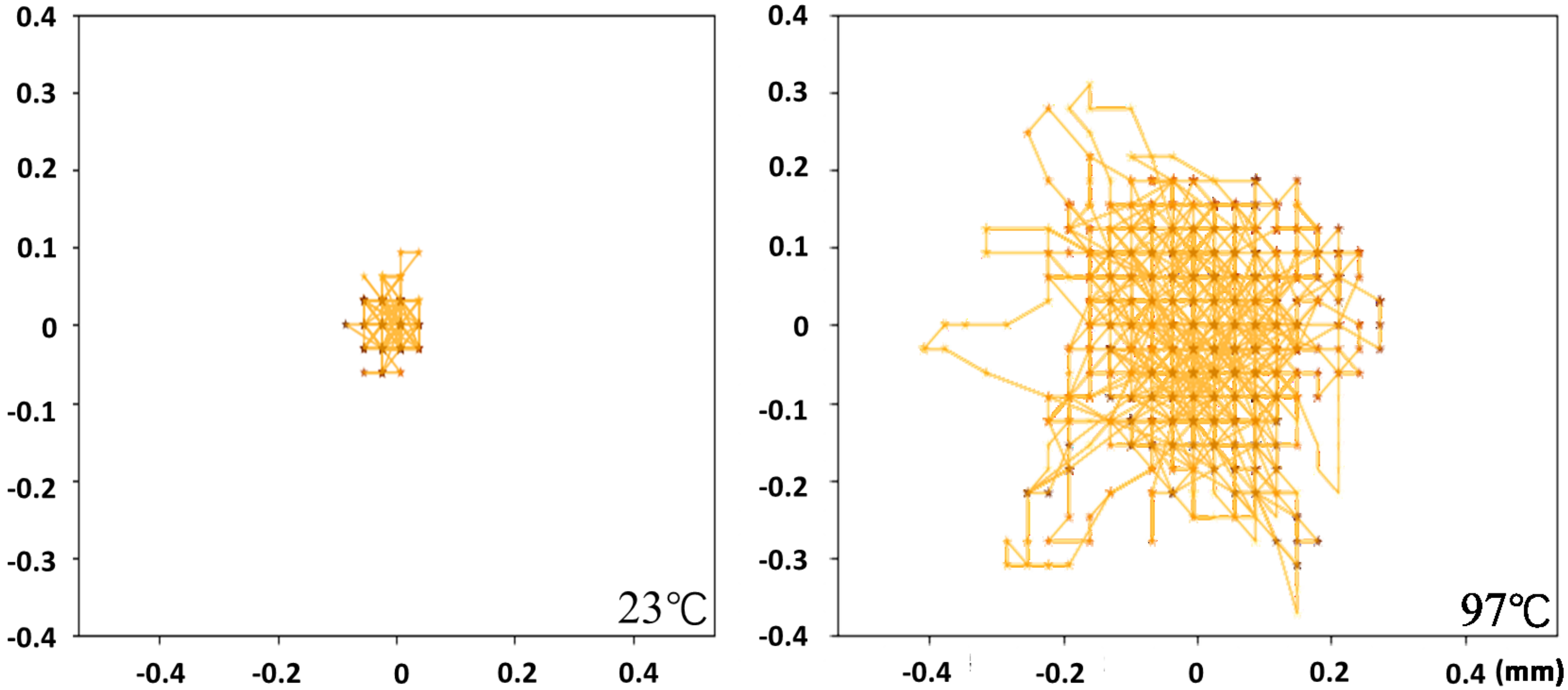
Observed beam wander

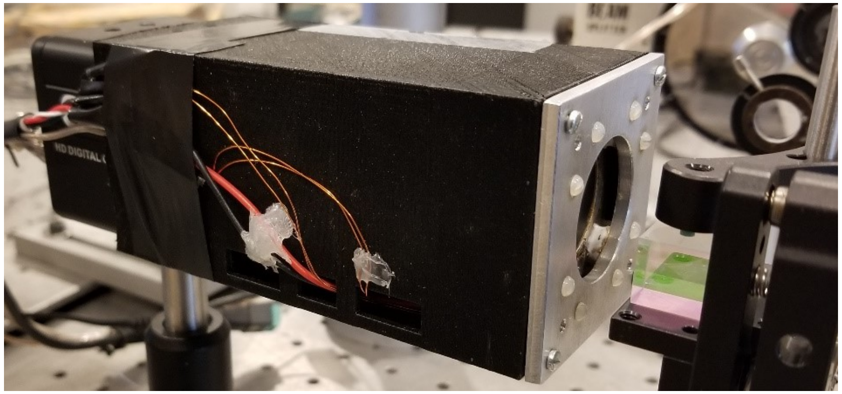


Typical beam wander pattern $r_w(t)$ for a near-IR beam at 23℃ (left) and 97 ℃. The beam wander can cover an area of up to six times larger at the highest temperature.

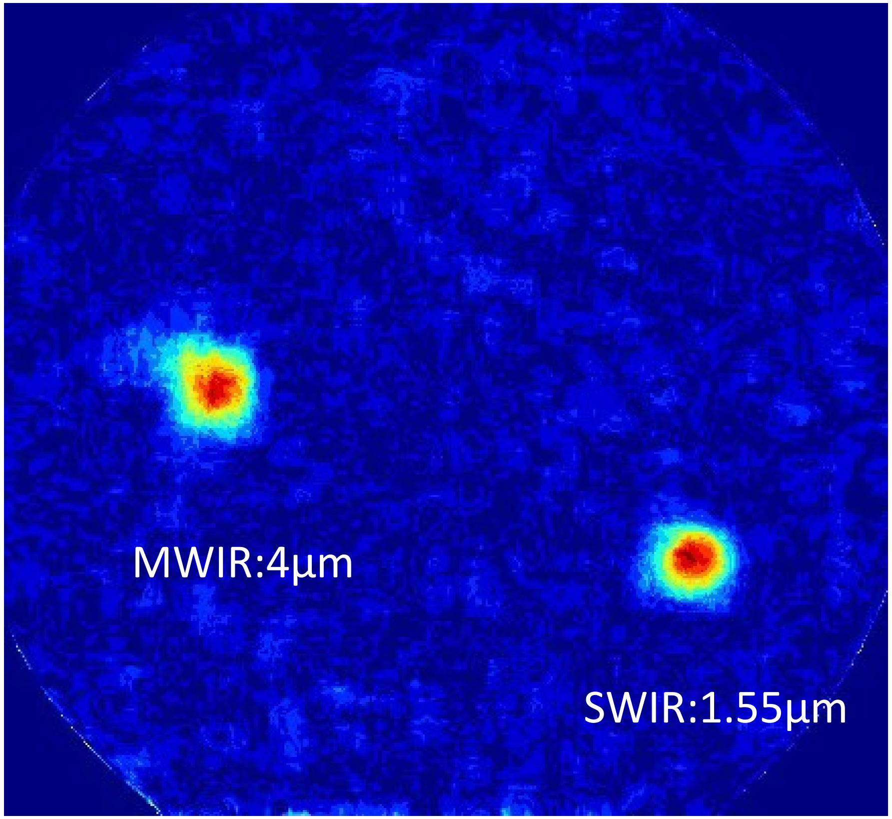
-> Yet: was it all due to turbulence in the joined beam path?

Enabler: Large area camera

- ❑Big detection area with multiwavelength sensitivity
- ❑Allows for simultaneous detection

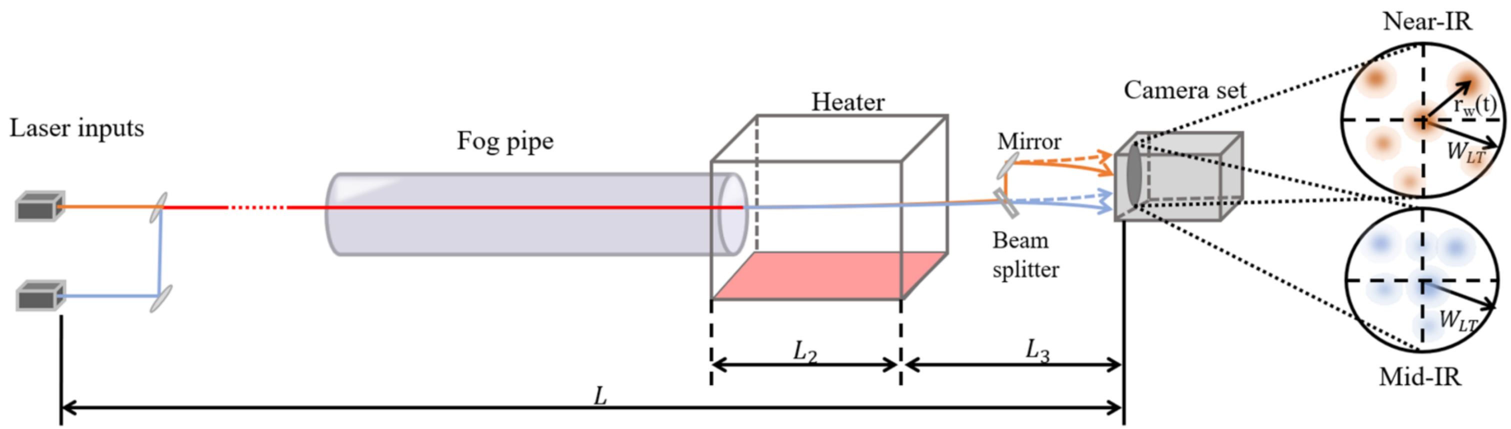


The detector size is 25mm in diameter while the CMOS image sensor is 6mm diagonal.



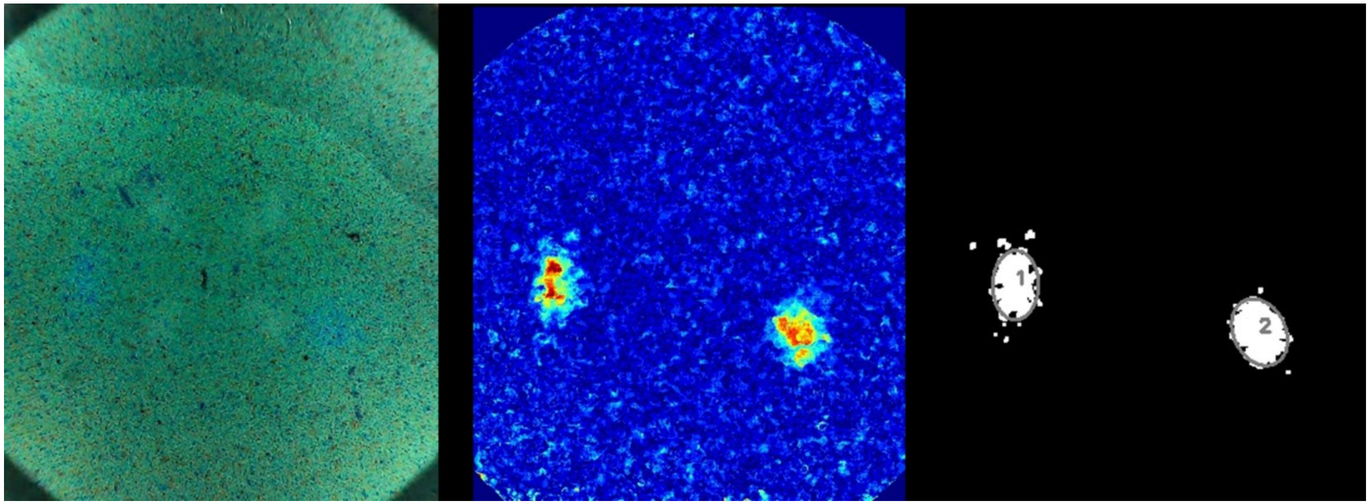
Color mapped hue image

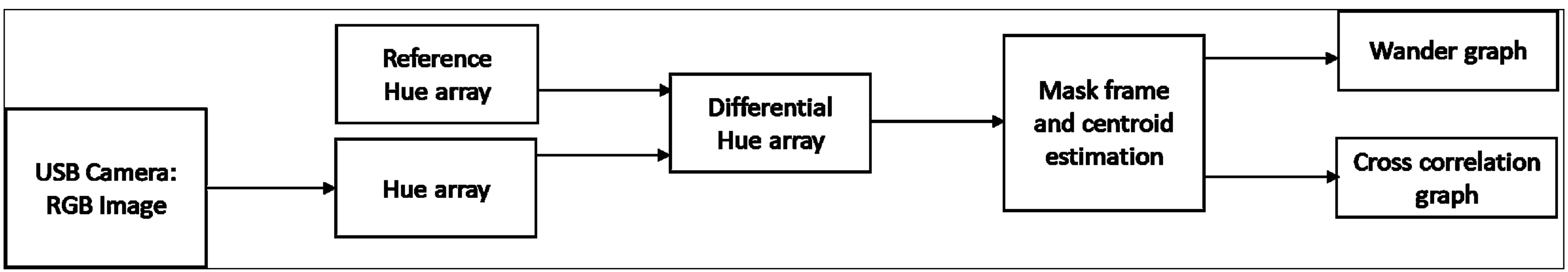
Changed simplified setup



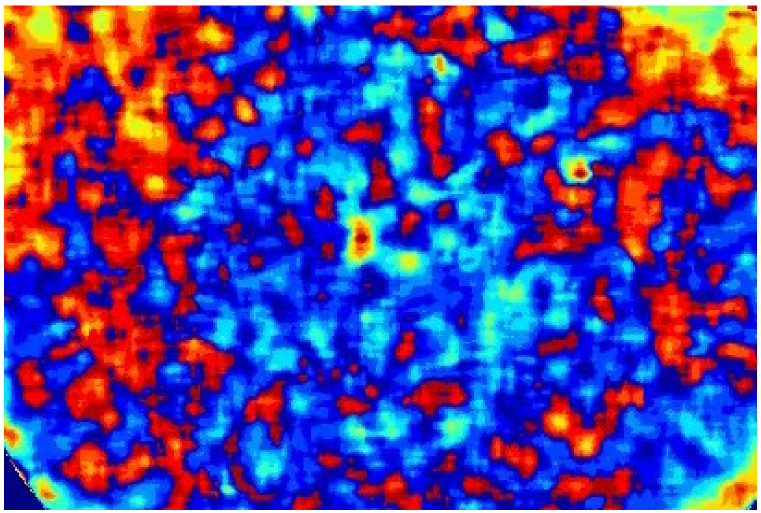
The near-IR and mid-IR beams are carefully aligned to have a nearly identical beam path through the fog pipe and scintillation box so the same scattering and scintillation condition are guaranteed

Image processing and analysis

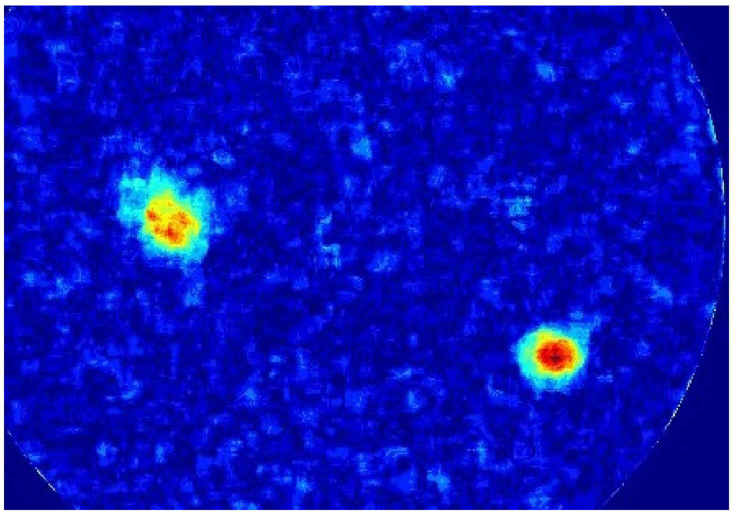




Simultaneous detection at different temperature

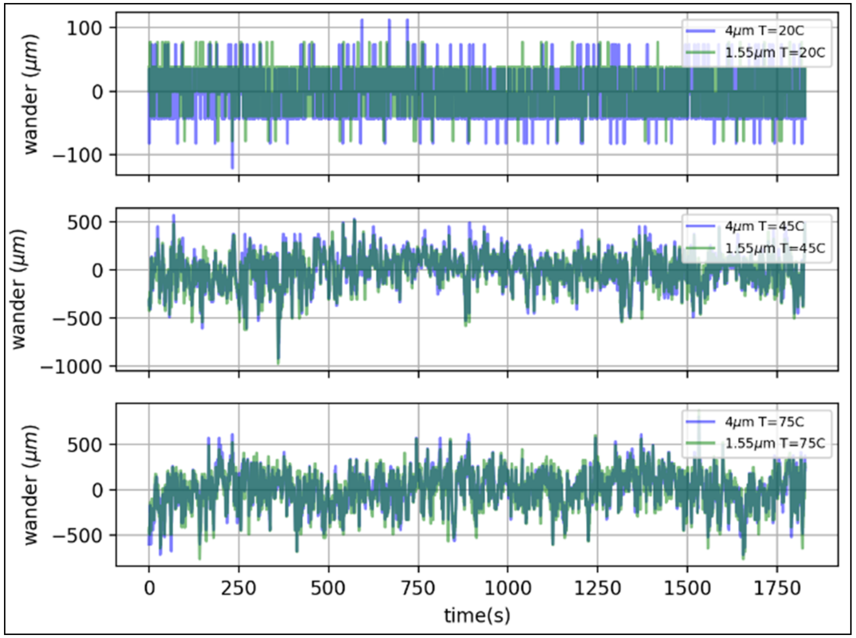


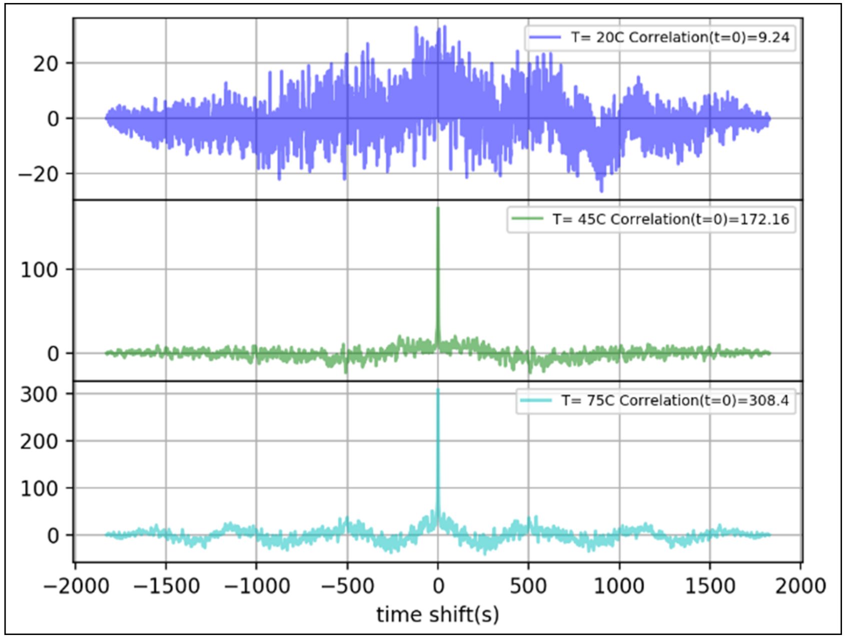
Room temperature



Air temperature 100C

Correlation analysis

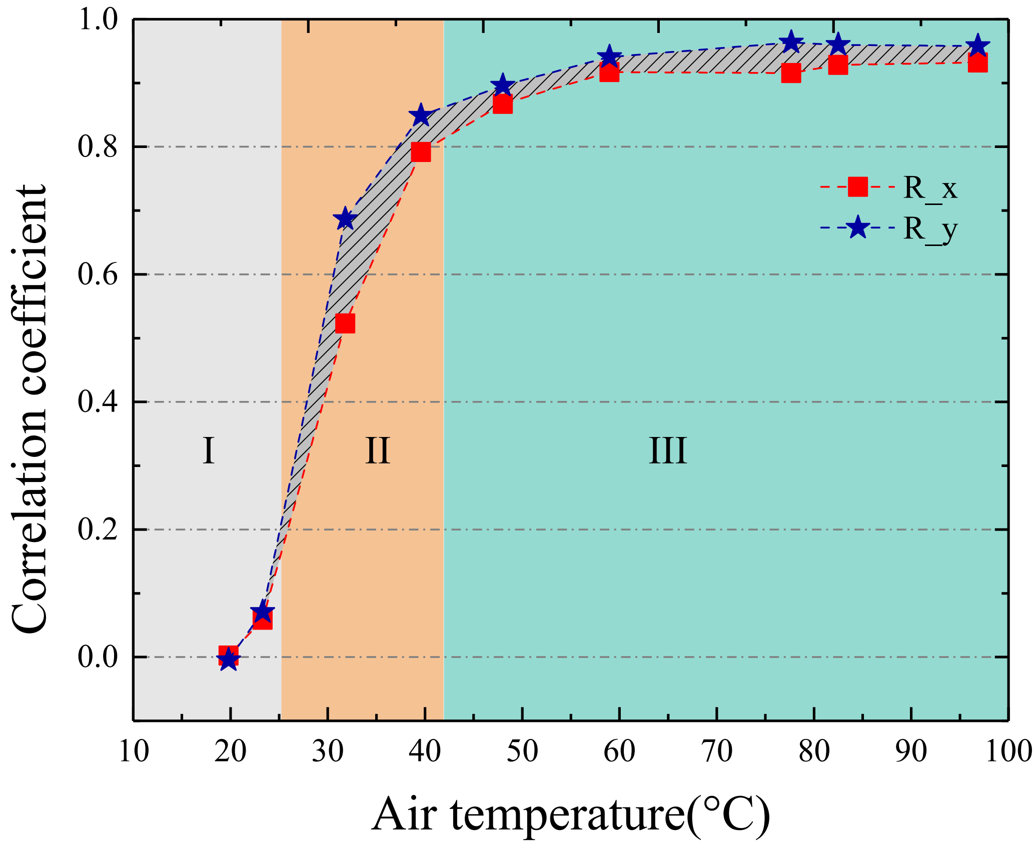




Beam wander along horizontal axis of polymer sensor for 4μm and 1.55μm laser about its mean at 25°C, 45°C and 75°C air temperature.

Cross Correlation between 4μm and 1.55μm normalized laser wander at 25°C, 45°C and 75°C.

Correlation analysis II

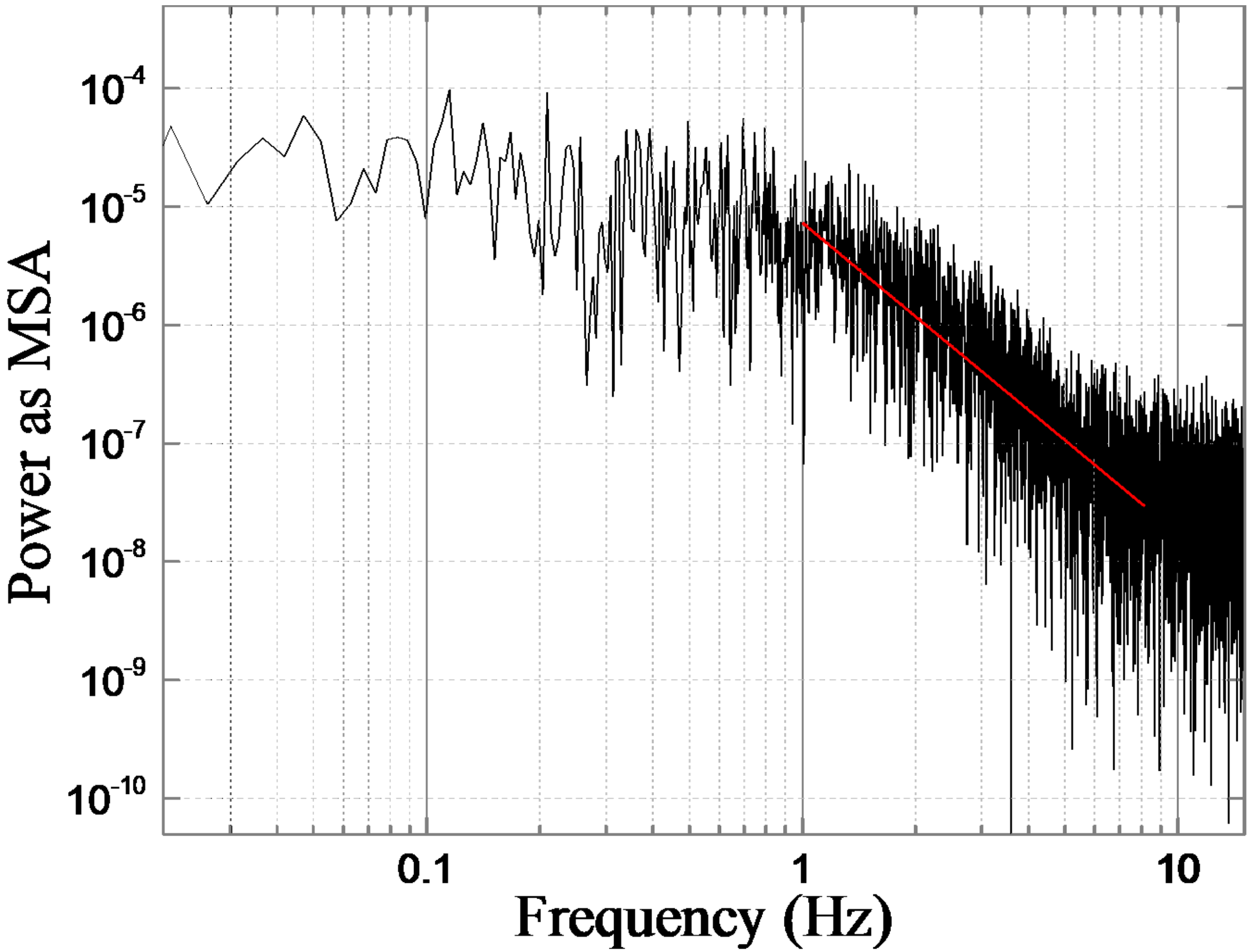


Pearson's correlation coefficient R is calculated for the beam wander $r_w(t)$ along x and y-axis,

Three regimes:

Regime III is the only high correlation and stable regime where we can compare the effect of varying environmental condition on the propagation and draw conclusions about the resilience of a link based on its wavelength.

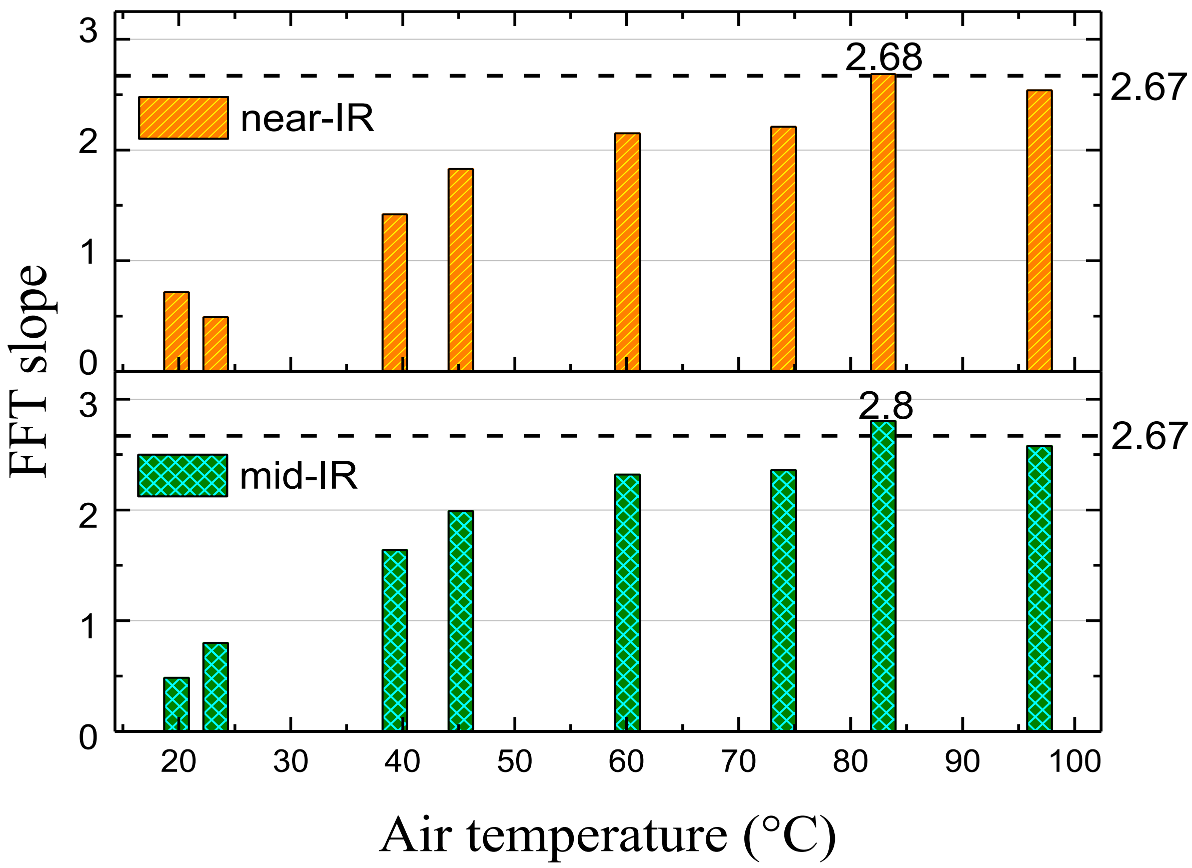
Camera detection allows for noise spectral analysis



FFT of the beam wander at 83℃ for near-IR, the slope is -2.68

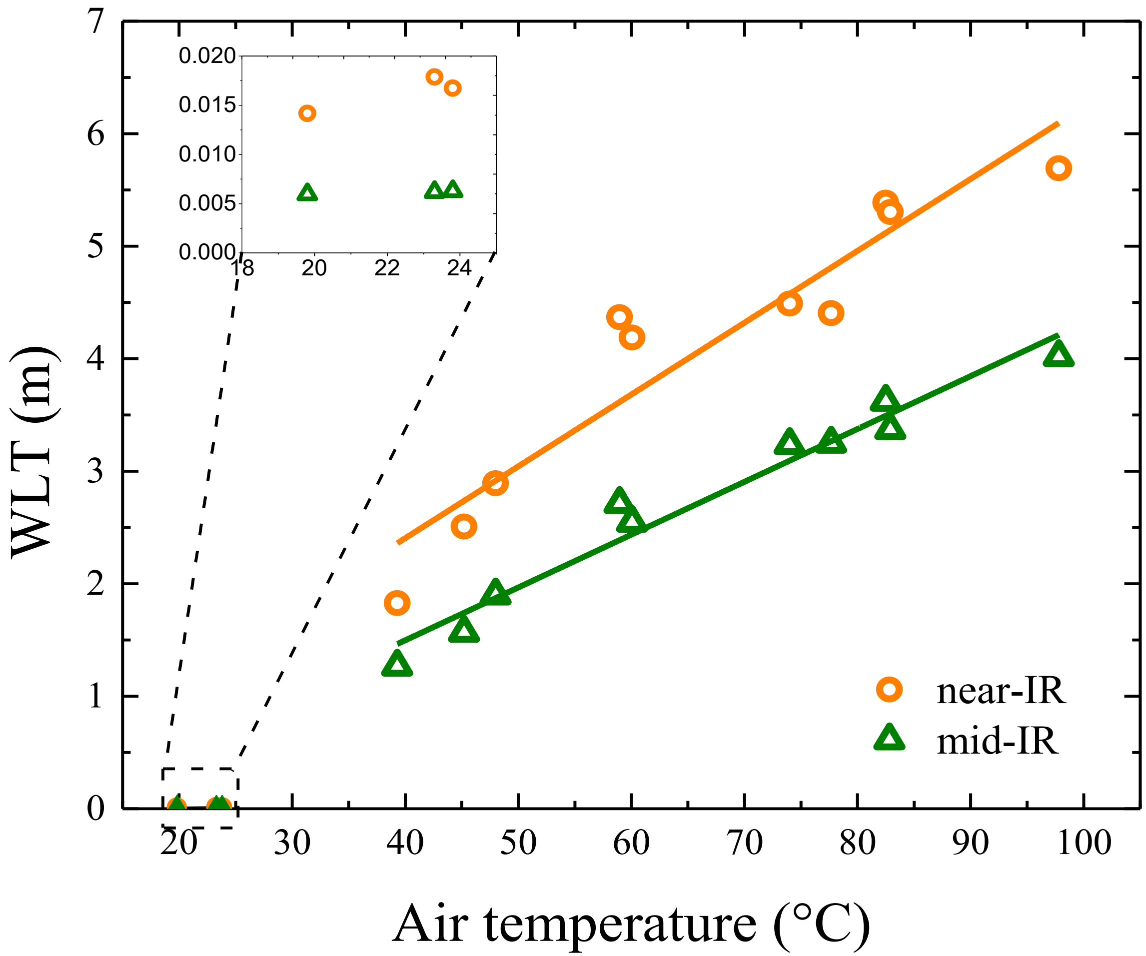
Theoretical value for the slope for a Obukhov-Kolmogorov turbulence can be calculated to -8/3 (~ -2.67)

FFT slope analysis for



The absolute values of the FFT slope in regime III are close to the value of expected for Obukhov-Kolmogorov turbulence, yet at each temperature the mid-IR beam has a higher value than the near IR beam

Effective beam spot at 1km



The estimation of W_{LT} with L=1km can be observed in the figure.

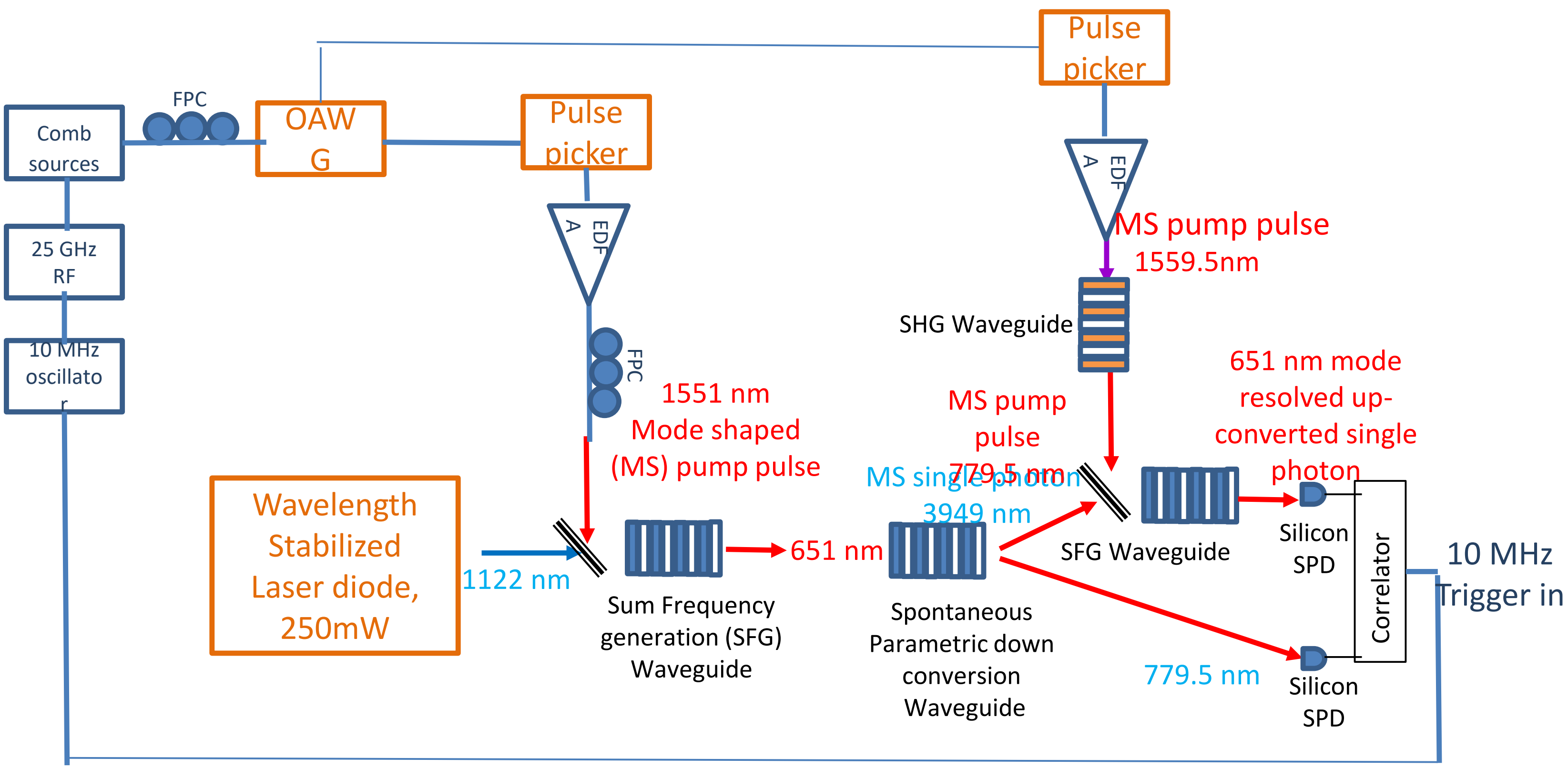
The efficient spot radius is 4 m for mid-IR and 5.7m for near-IR at 97 ℃

-> NIR beam area increased by slightly more than 100% due to beam wander

Summary

- The turbulence in our setup is close to the ideal Obukhov-Kolmogorov turbulence with high correlation between beams at high temperature.
- The higher slopes of near-IR than mid-IR indicate higher noise fluctuation is present in the near-IR beam propagation.
- The scattering effect is simulated leveraging discrete ordinate method. Combining both the scintillation and scattering effect, the power at the receiver for mid-IR is 71.2%, but it drops to 37.4% for near-IR

Future: explore Quantum sensing / communication at MIR wavelength



Generation of mode shaped single photon at 4 micron

Thank you – and any questions?

This research was supported by the Office of Naval Research (Award No. N00014-15-1-2393).