Advantages of IR-based Communication and Sensing in Severe Environments

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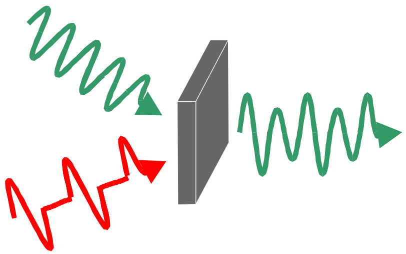
This research was supported by the Office of Naval Research (Award No. N00014-15-1-2393).

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

Applications of enabling system

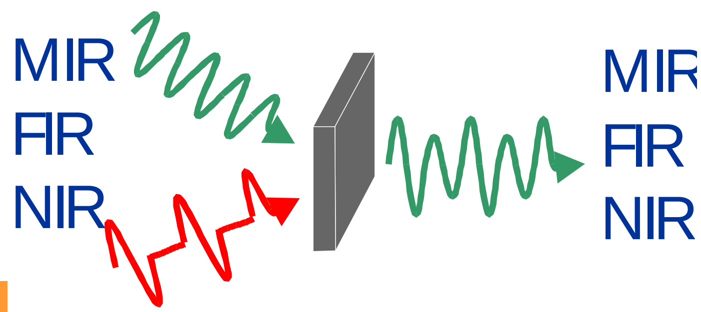
Key issues: Speed - Sensitivity - Resolution

Communication

Sensing

Observation

Switching



Guiding

Wavelength-Conversion

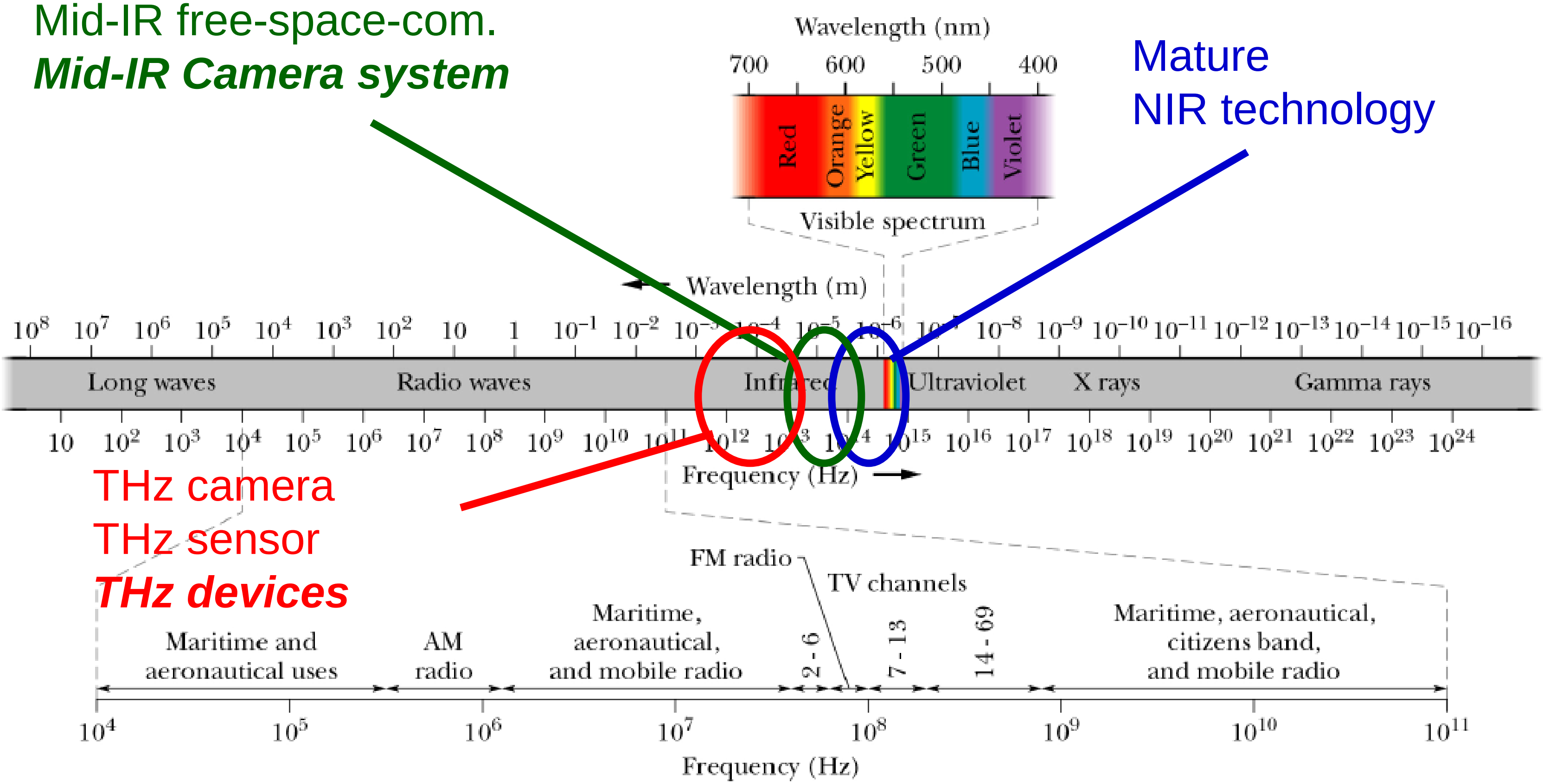
Configurable Optics

Testing

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

Mature
NIR technology

THz camera
THz sensor
THz devices



Overview

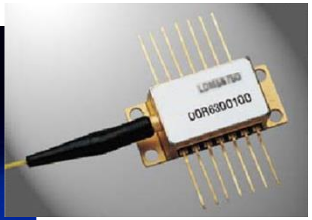
- Advantages of mid-infrared (or longer) wavelength propagation through challengine environments

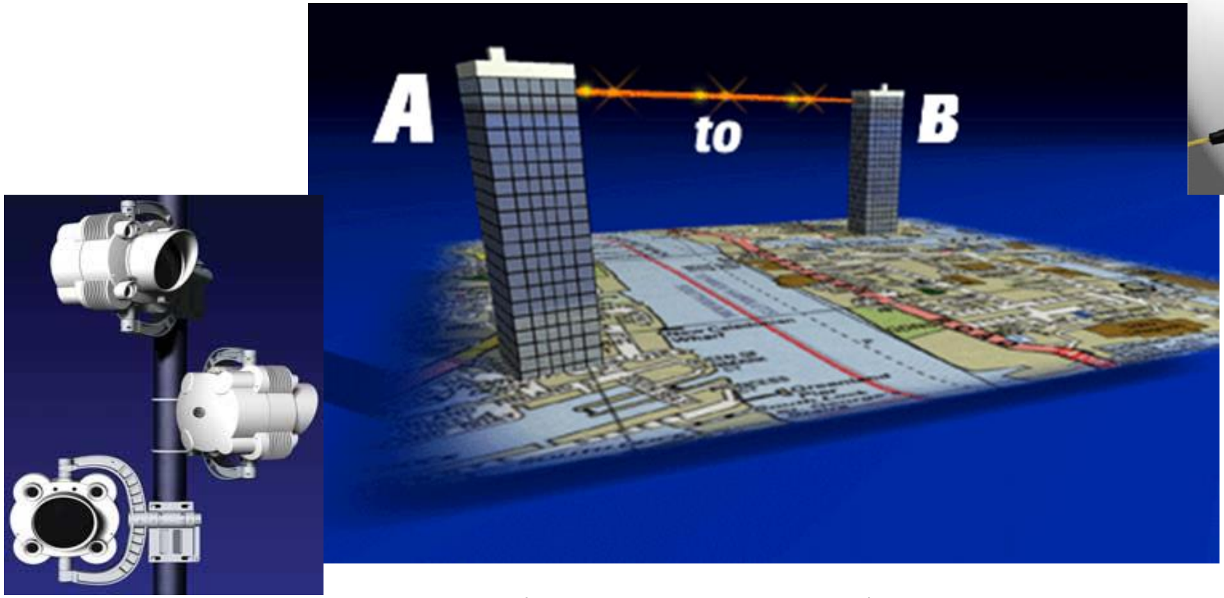
- An optical readout approach for sensors:
  - example UV-IR-THz-GHz camera

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)

Key issues for FSO Links

- Bandwidth
  - Commercially available systems work at 600MBit/s to 10GBit/s transmission rate – but future system should exceed these rates.
- Reliability
  - Network provider ask for a 99.999% availability, which is the biggest issue – especially under low visibility.
- Range
  - Between 100m and 10km are common in commercial systems.

Main FSO market:

"The Last Mile" from Network Provider to each household

Long range transmission through Atmosphere

Range and quality of a free space optical (FSO) transmission link limited by extinction losses:

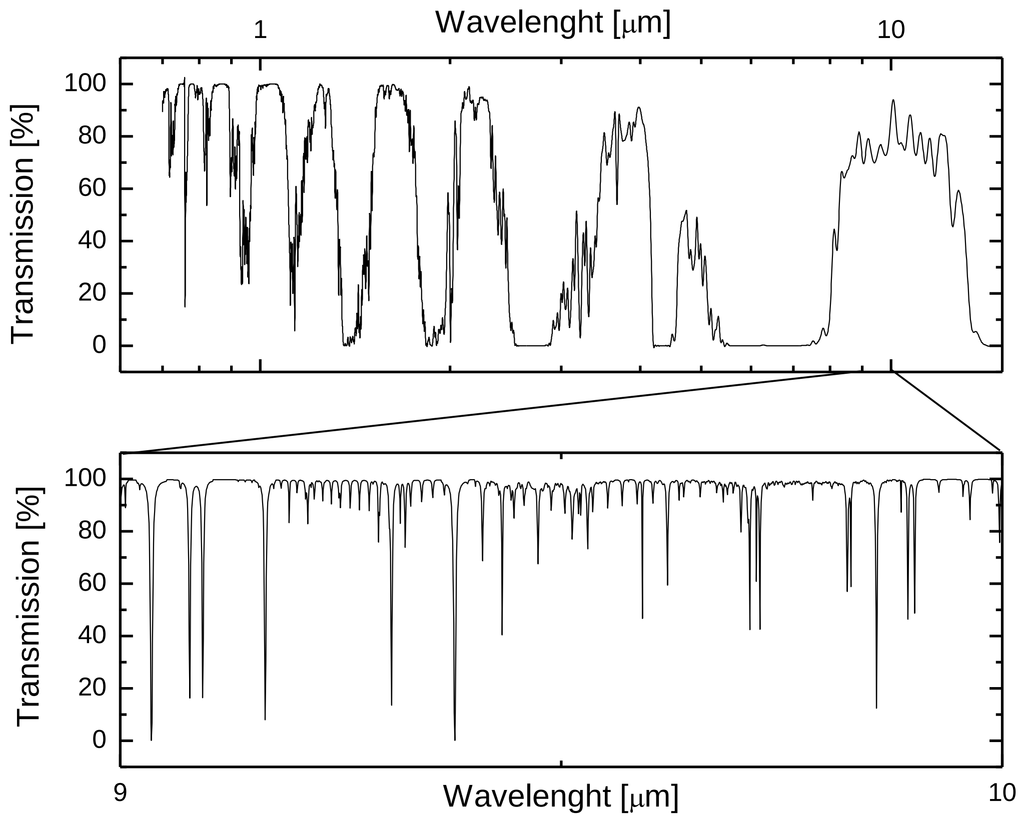
☺ 😐 ☹

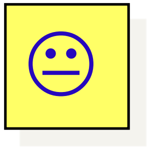
?

- Losses due to transmission
  - Absorption
  - Scattering
    - ⇨Rayleigh scattering (particle radius < λ)
    - ⇨Mie scattering (particle radius ~ λ)
  - Scintillation

- Losses due to system
  - Beam spreading 😐
  - Transmitter & Receiver Losses ☹

Molecular absorption at sea level: “equal” windows in NIR/MIR





(Calculated with Hitran96)

Rayleigh scattering

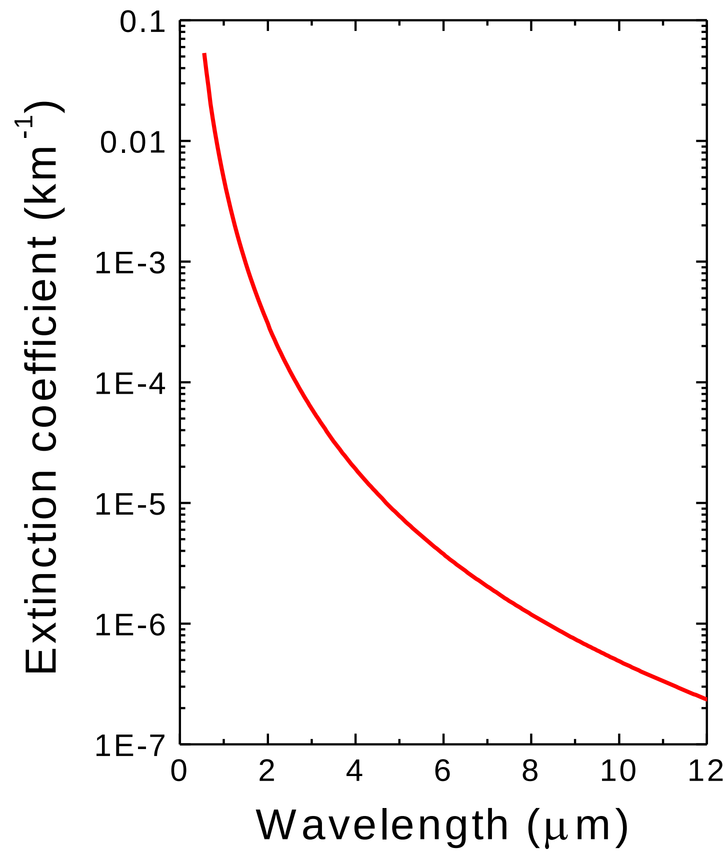
Extinction coefficient has strong λ^{-4}-dependence

- favors longer wavelengths with less extinction.

Comparison to 1.5μm to

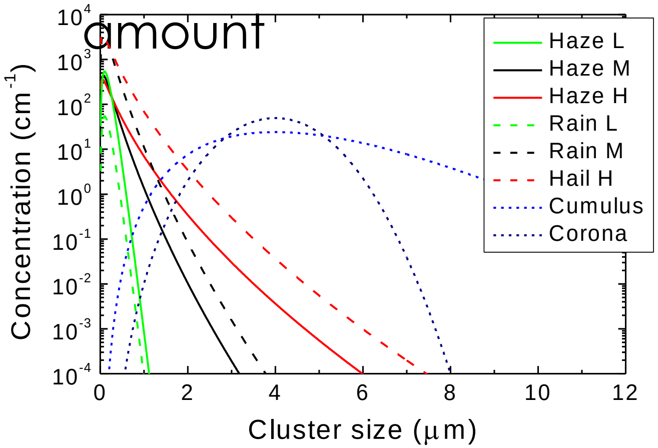
5μm : **~ 100x lower losses**

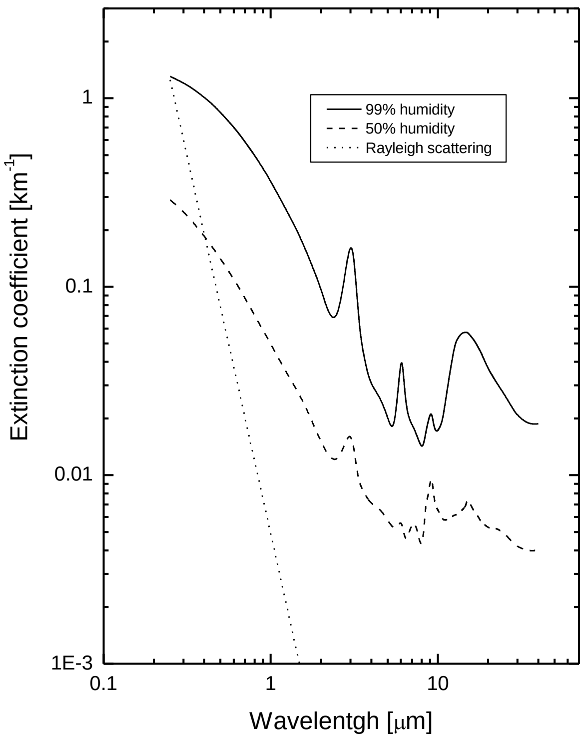
8.1μm : **850x lower losses**



Mie scattering

Distribution of particle size determines extinction amount





- Strongly dependent on weather and environment

Comparison to 1.5μm to 8.1μm :
18x lower losses

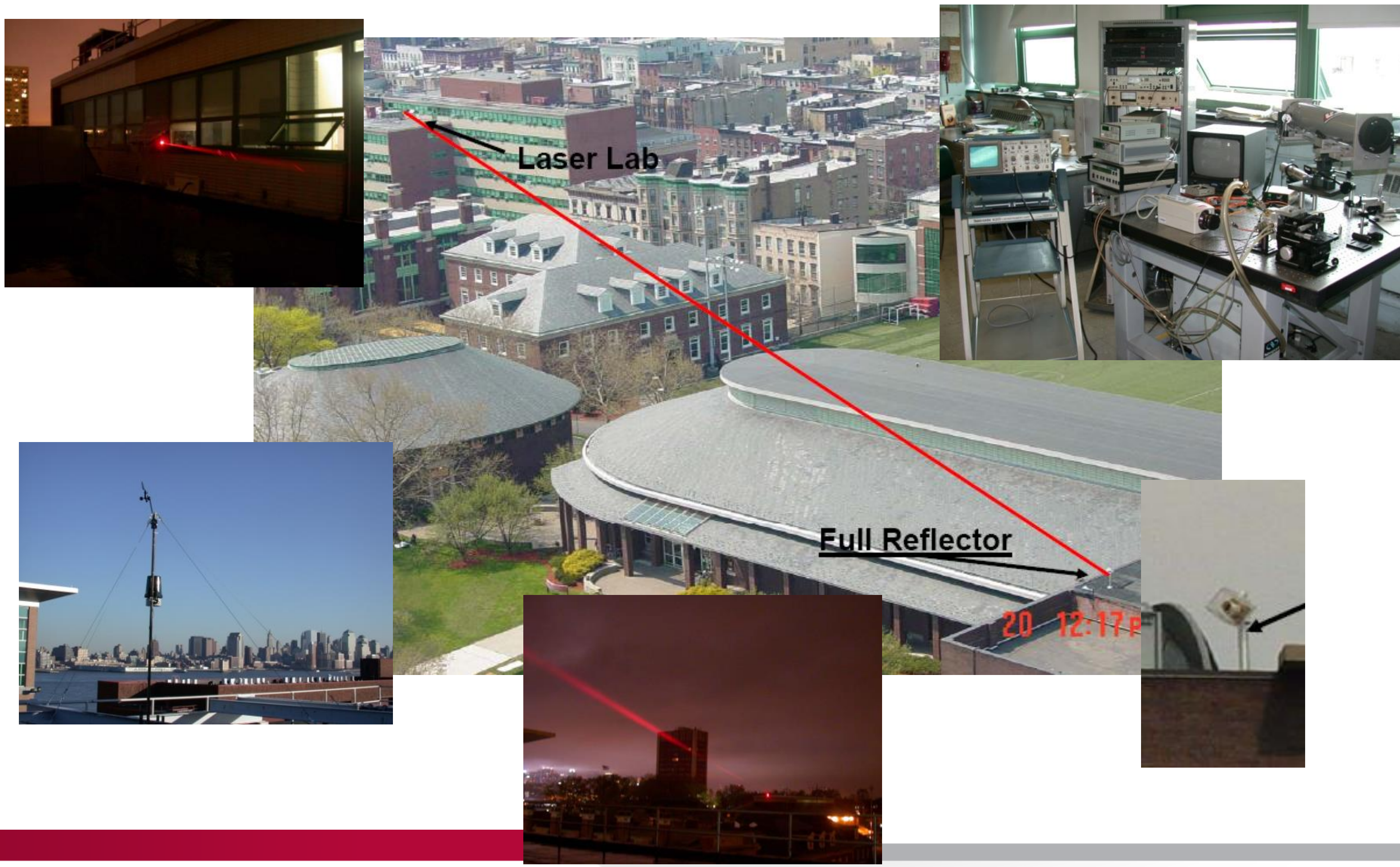
☺

BUT strongly weather dependent !!

Differences RF – VIS / IR

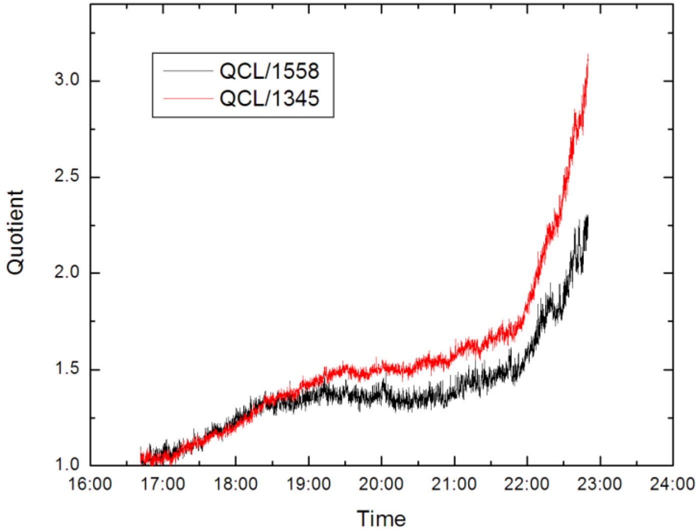
- RF
  - Typically not directed
  - Broadband distribution
    - Addressing many receivers
    - fast power drop
    - Good propagation condition
    - Multi-path
- Visible / IR
  - Typically directed
  - Targeted distribution
    - Adressing one (or few receivers
    - Good power delivery
    - Good propagation condition (depending on wavelength)
    - Single path

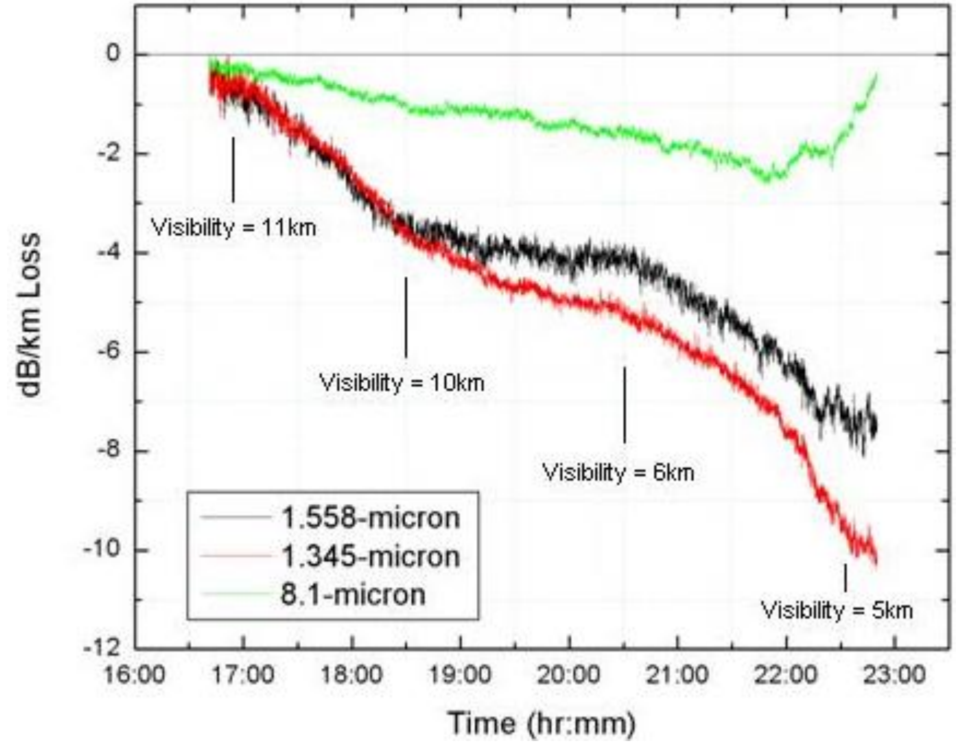
550m FSO link with >4 wavelength capability



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**

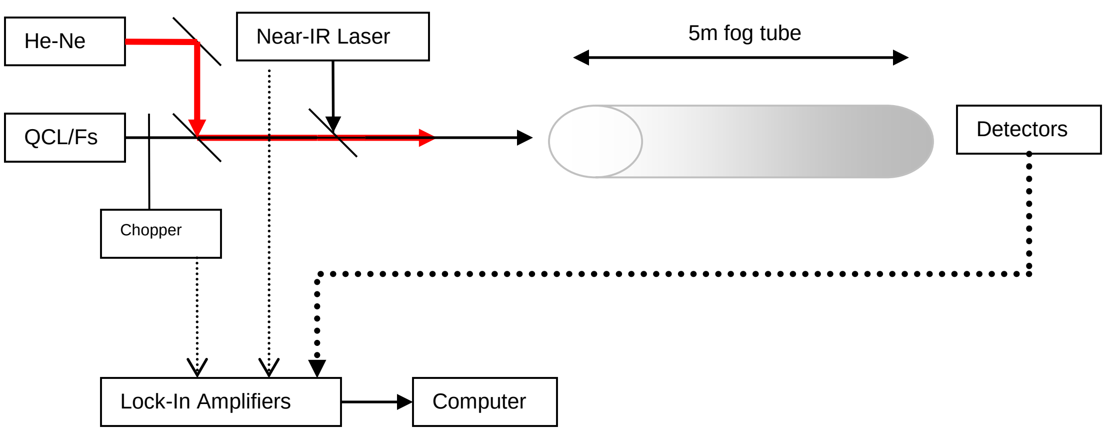


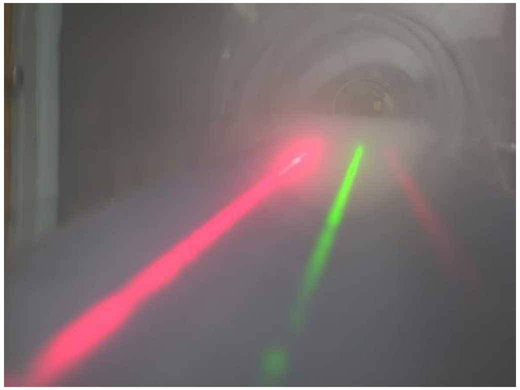


P. Corrigan, E.A. Whittaker, E.A. Whittaker, and C. Bethea, "Quantum cascade lasers and the Kruse model in free space optical communication", Optics Express 17, 4355-4359 (2009).

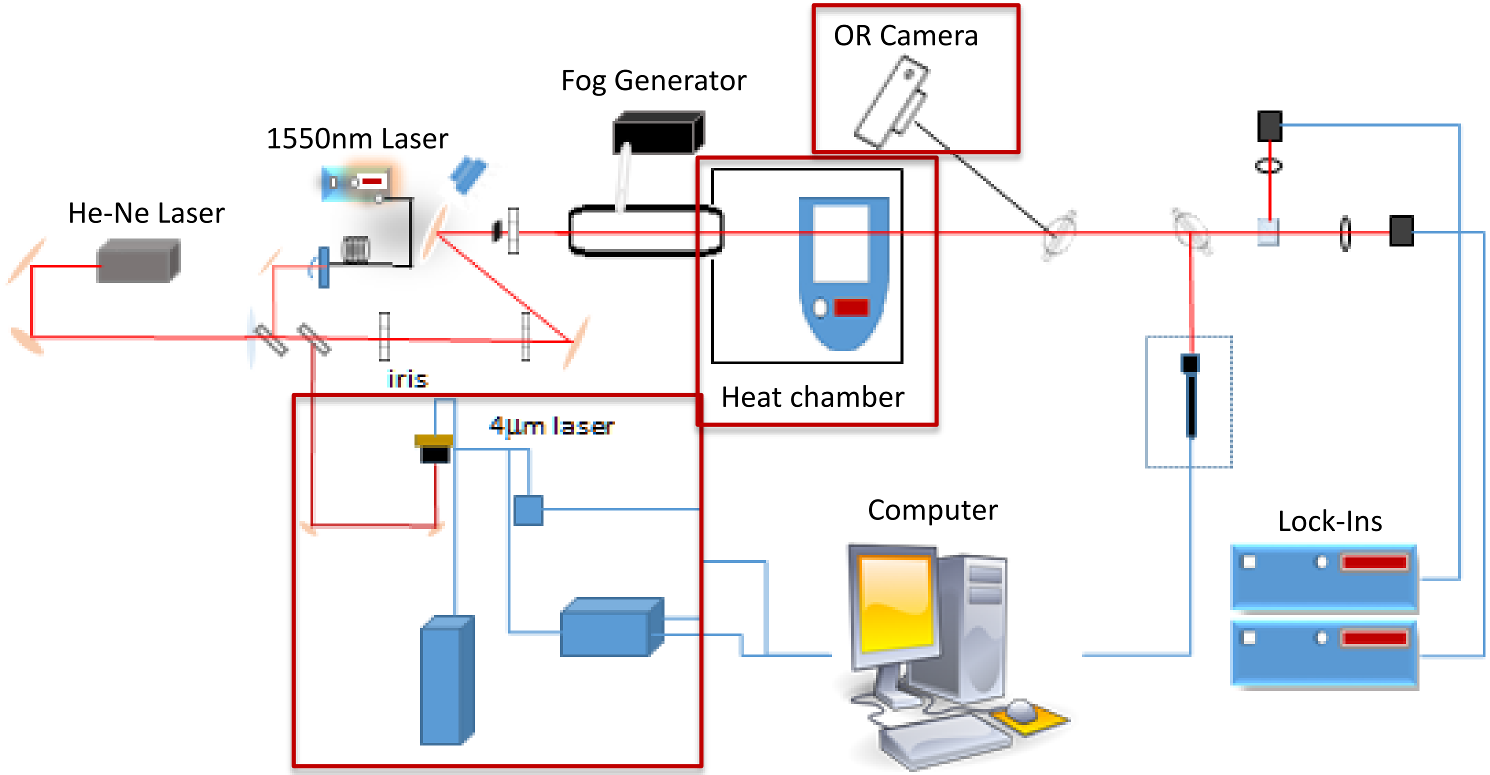
Indoor Transmission ("Fog Tube")

- 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.)



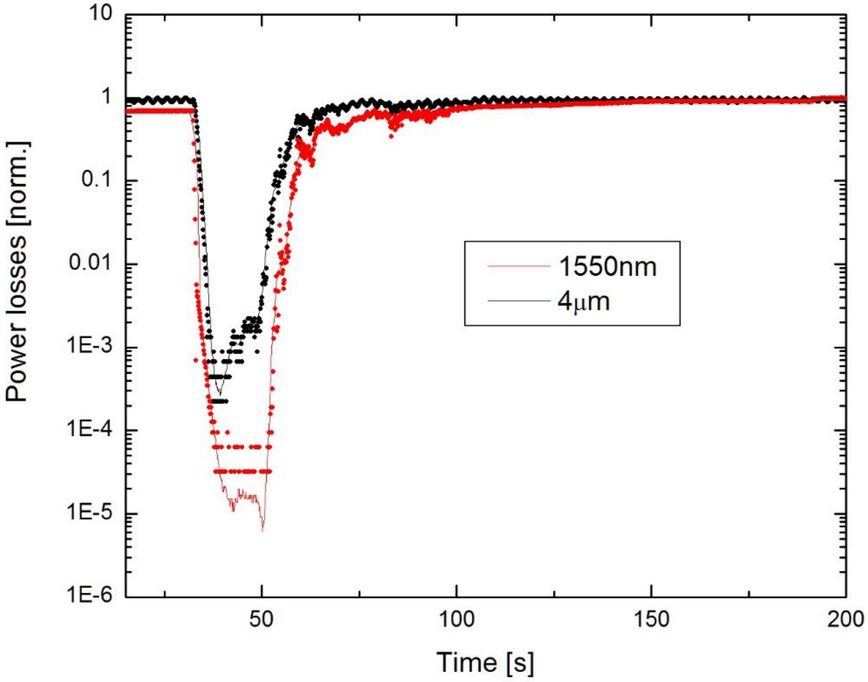


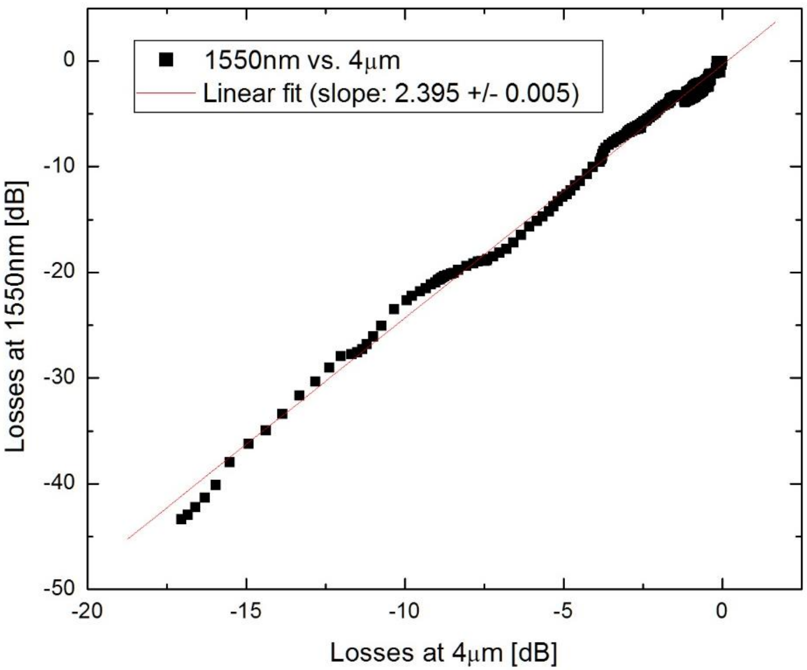
In-lab testbed for FSO propagation



- 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)

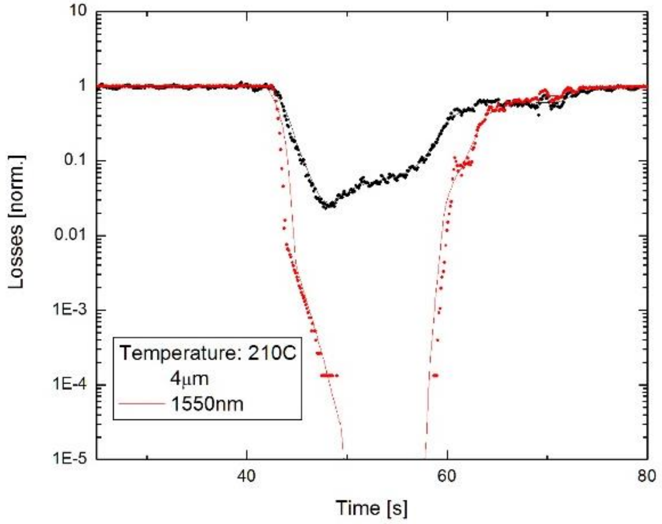
Comparison of simple scattering

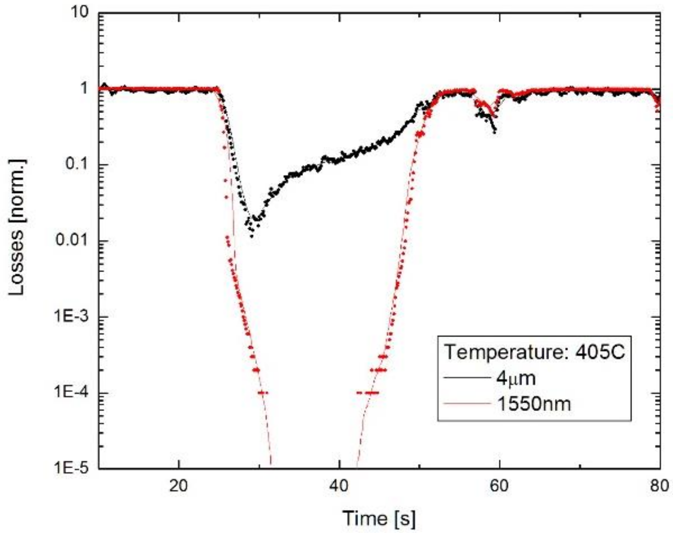


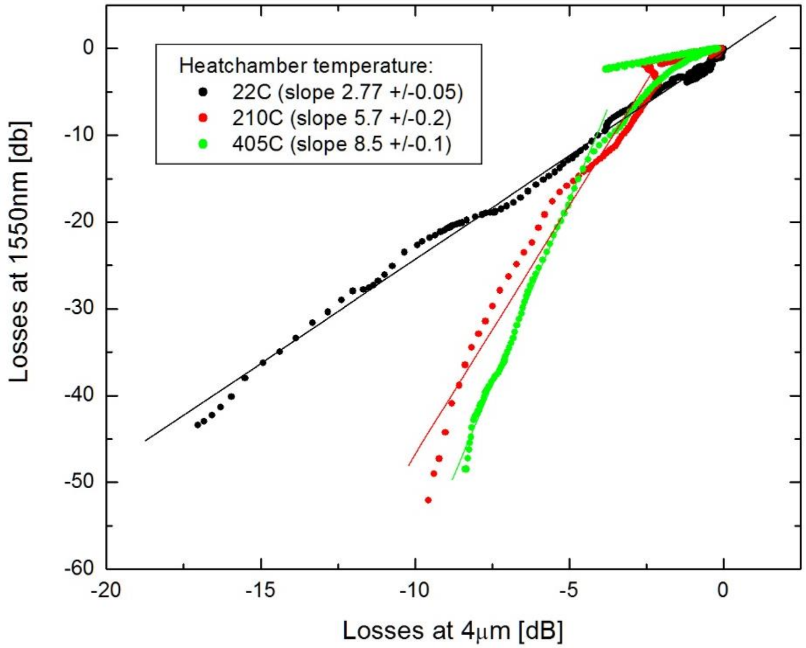


- Comparing losses over 40 dB dynamic range while aerosol concentration reduces.
- Comparison shows clear advantage of 4μm link
- Quantitative analysis shows ~(**1/2.4**) x dB loss (e.g., 40 dB vs 16 dB)

Scattering & Scintillation (reality)

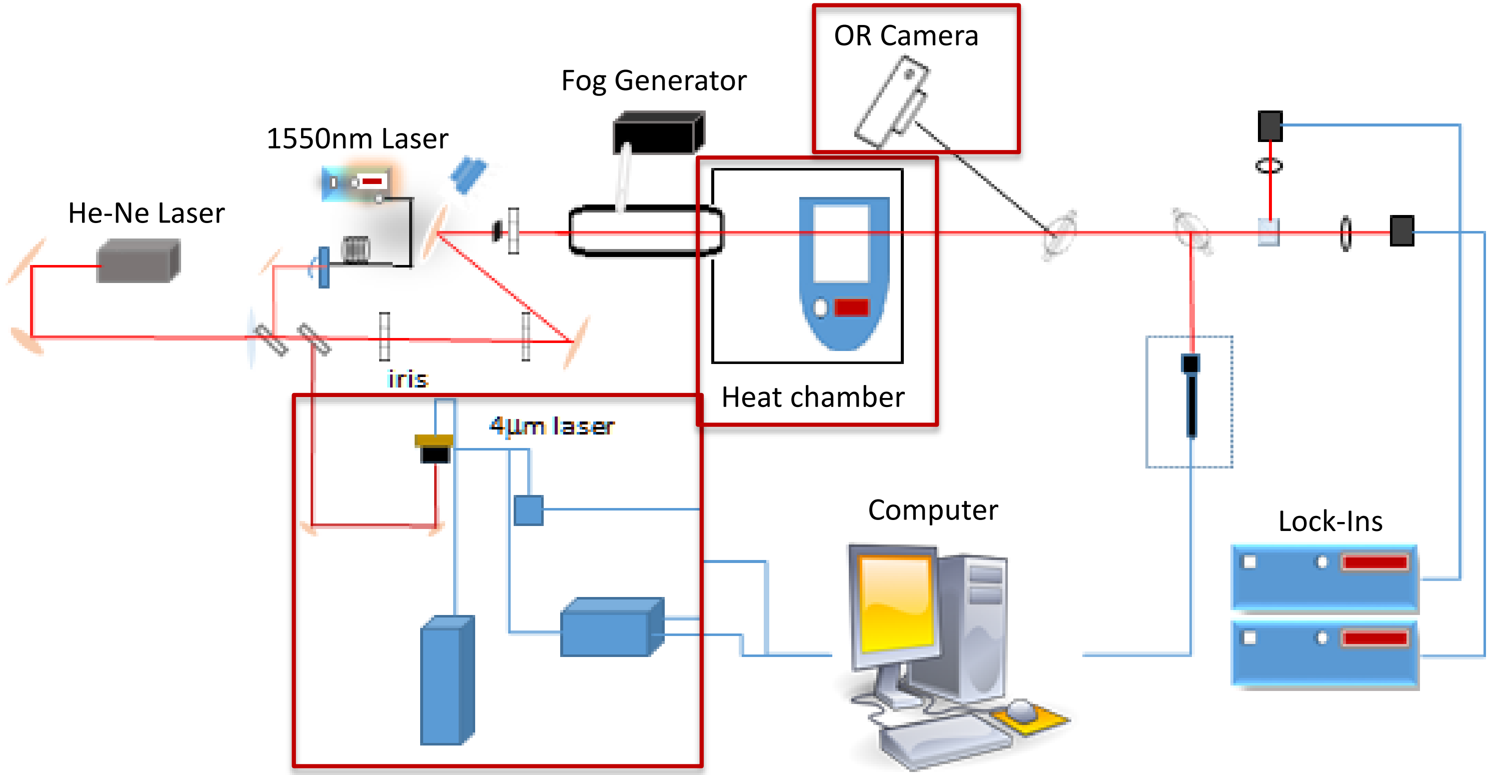






- Addition of scintillation (caused by heat from a heatplate) degrades transmission drastically
- **(1/8.5)** x dB loss under strong scintillation (50 dB vs 6 dB)
- New: losses per scatter scale with turbulence strength – cannot be treated as independent losses.

In-lab testbed for FSO propagation



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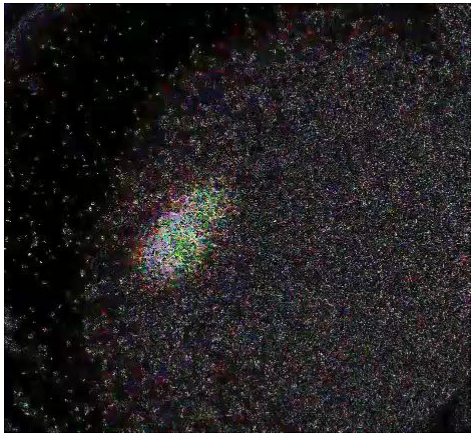
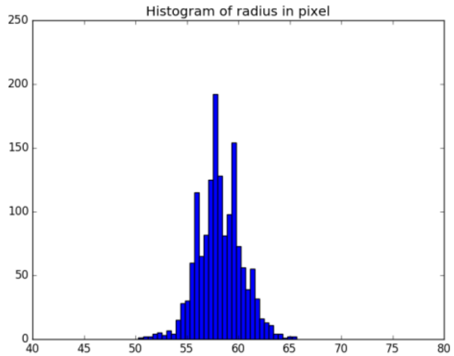
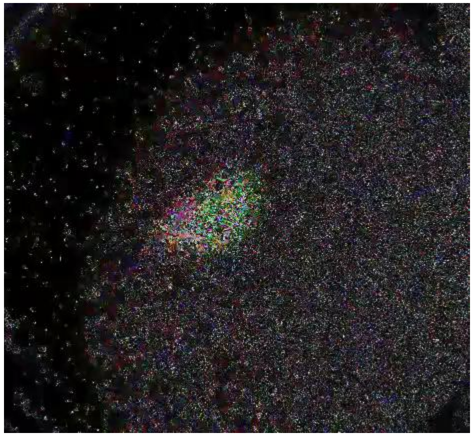
1550nm beam dynamics under scintillation

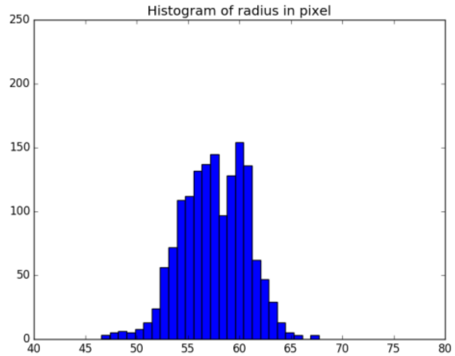
Air temp 22C



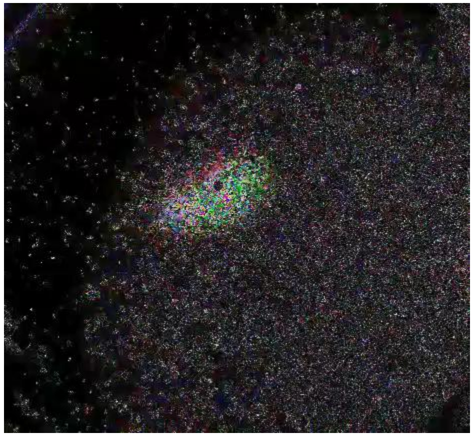


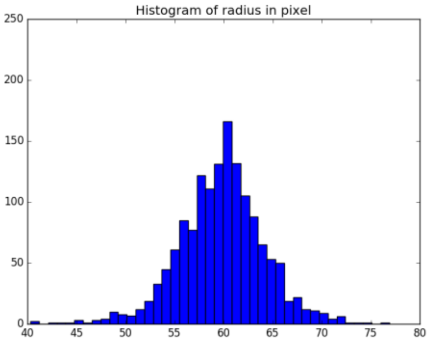
Air temp 30C





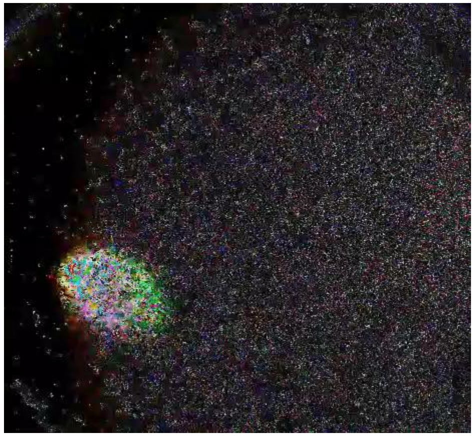
Air temp. 70C

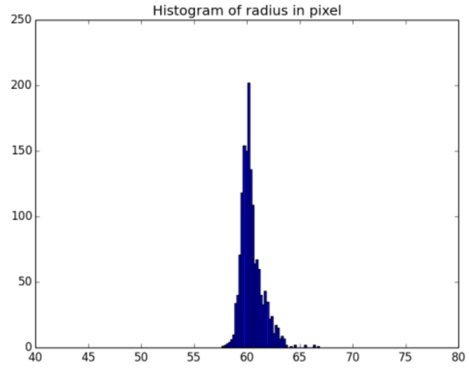




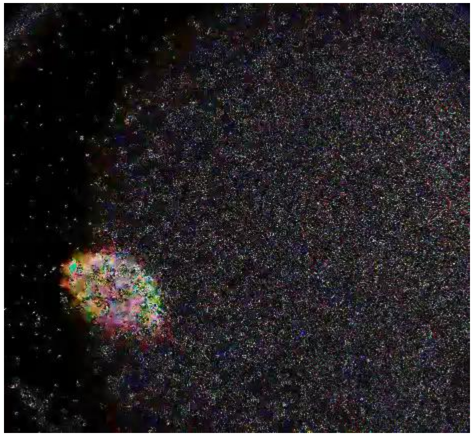
Movies of 4μm beam profile under scintillation (preliminary)

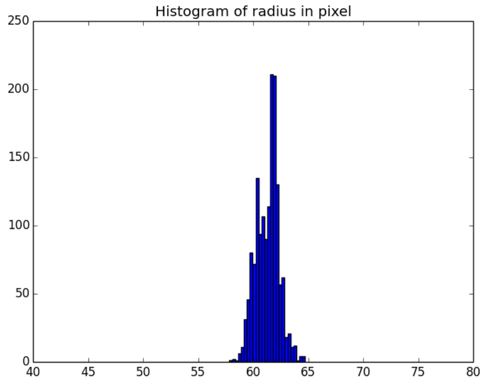
Air temp 22C



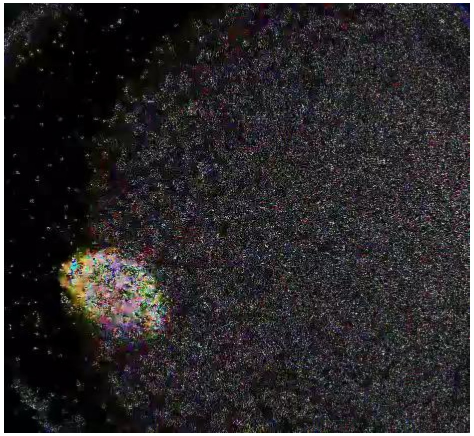


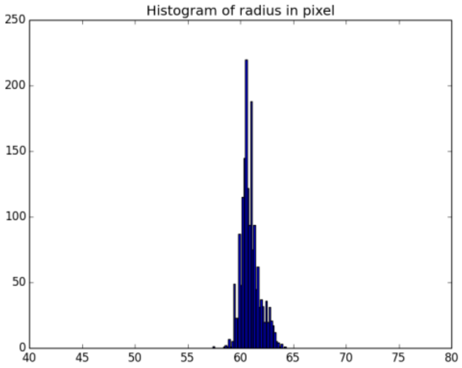
Air temp 30C



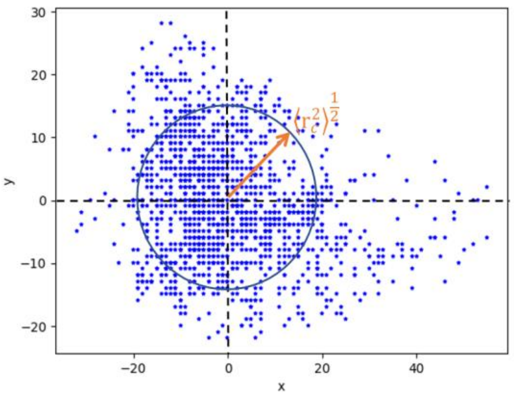


Air temp. 70C



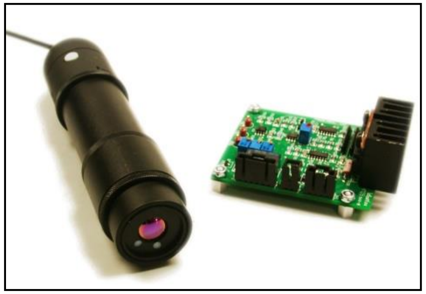


Beamwander analysis: Deduction of C_n^2 and comparison



Air Temp.	22 °C	30 °C	70 °C
C_n^2 (1550nm)	4.936×10^{-13}	1.222×10^{-11}	2.929×10^{-11}
$\langle r_c^2\rangle^{1/2}$ (1550nm)	2.710×10^{-5}	1.859×10^{-4}	3.141×10^{-4}
$\langle r_c^2\rangle^{1/2}$ (4000nm, expected)	2.242×10^{-5}	1.538×10^{-4}	2.598×10^{-4}
$\langle r_c^2\rangle^{1/2}$ (4000nm, experiment)	1.797×10^{-5}	1.818×10^{-5}	2.484×10^{-5}

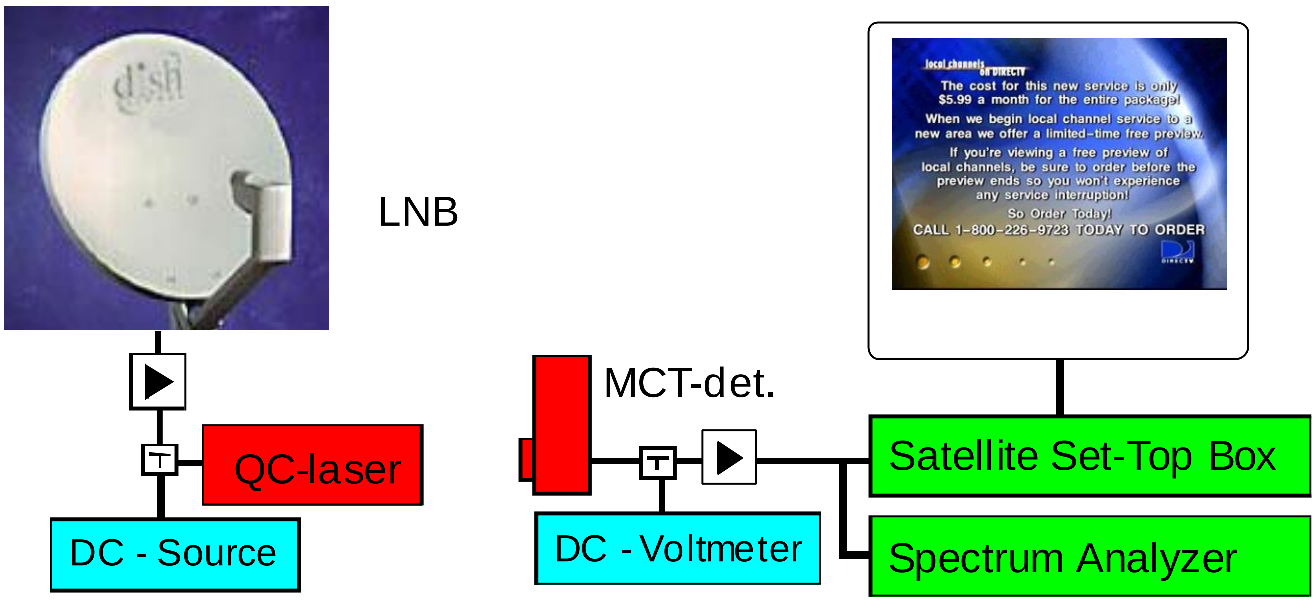
Air Temp.	22 °C	30 °C	70 °C
C_n^2 (1550nm)	4.31E-12	1.15E-11	2.96E-11
$\langle r_c^2\rangle^{1/2}$ (1550nm)	1.00E-04	1.81E-04	3.18E-04
$\langle r_c^2\rangle^{1/2}$ (4000nm, expected)	4.07E-05	7.33E-05	1.29E-04
$\langle r_c^2\rangle^{1/2}$ (4000nm, experiment)	4.78E-05	9.86E-05	1.54E-04



- Using novel broadband camera, NIR and MIR beam position and size can be monitored at 30fps
- Beamwander measurement allows for estimation of C_n^2 based on Rytov based calculation (max comparable to 500m at $C_n^2 = 2*10^{-16} m^{-2/3}$)
- C_n^2 calculated for 1550nm, allows for beamwander estimate for other wavelengths (4μm)
- Preliminary observation shows MIR beam wander overestimated, others right on spot – depending on wavelength and beam spot size…

QC laser link - electrical setup

- Digital encoded satellite TV data with QPSK encoding
- Data distributed over 750 MHz – 1.45 GHz



➲ Monitoring of signal strength and quality

Summary

- OR Camera allows real time observation of laser beam size and movement at 1550nm and 4μm
- Observed beamwander at 4μm one order of magnitude smaller compared to Rytov based prediction.
- MIR link experience much lower (as expected).
- Observed drastic increase in losses (22dB -> 50dB) for NIR link when Aerosols and turbulence are present at the same time.
- Losses scale with density of aerosol partical and turbulence – hints at more efficient scattering in presence of turbulence.

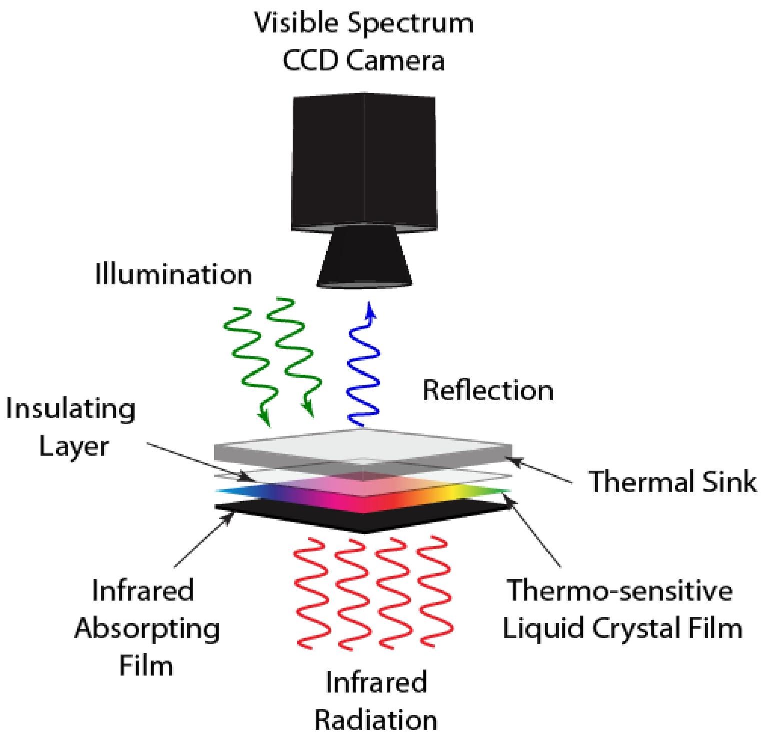
Overview

- Advantages of mid-infrared (or longer) wavelength propagation through challengine environments
- An optical readout approach for sensors:
  - example UV-IR-THz-GHz camera

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?



<u>Process of Wavelength Transformation</u>

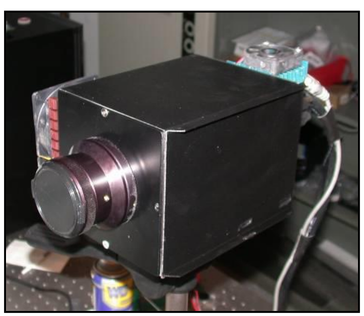
1. Photons incident on an absorbing film (radiative detection)
2. Film converts the energy of the photons into heat
3. Thermo-Sensitive Polymer Reacts to Heat through an change in optical properties
4. Probe the optical changes with a camera.

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….



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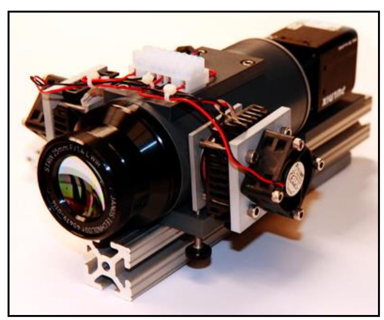

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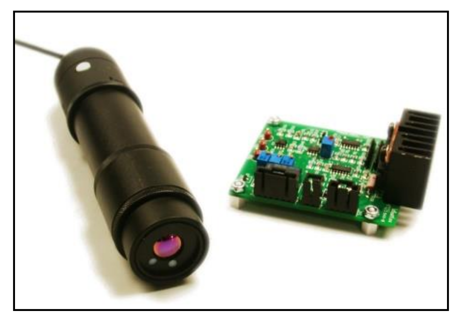
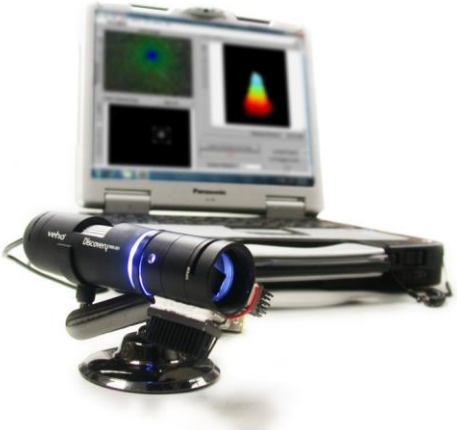
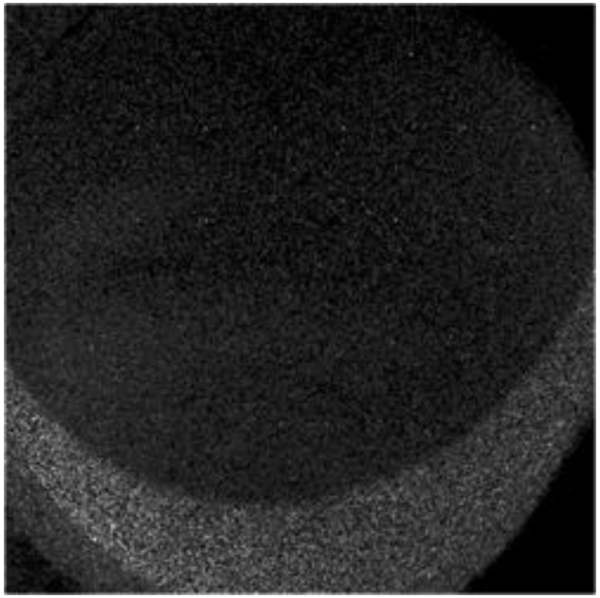
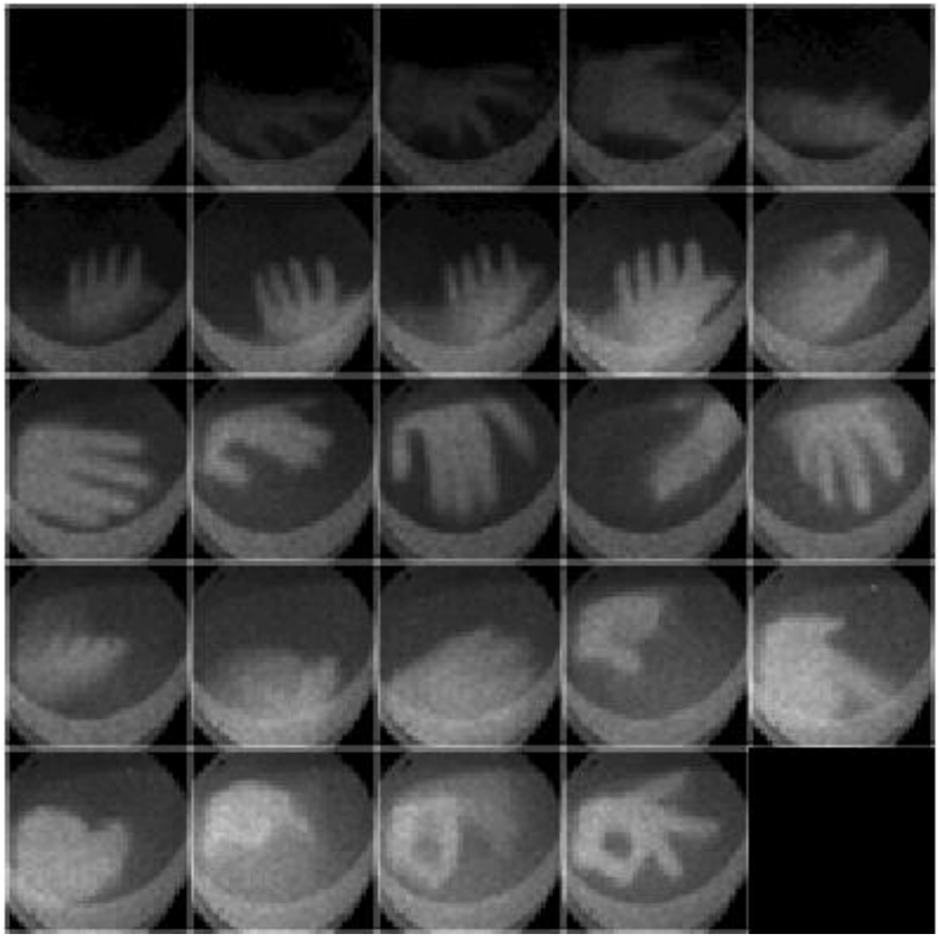


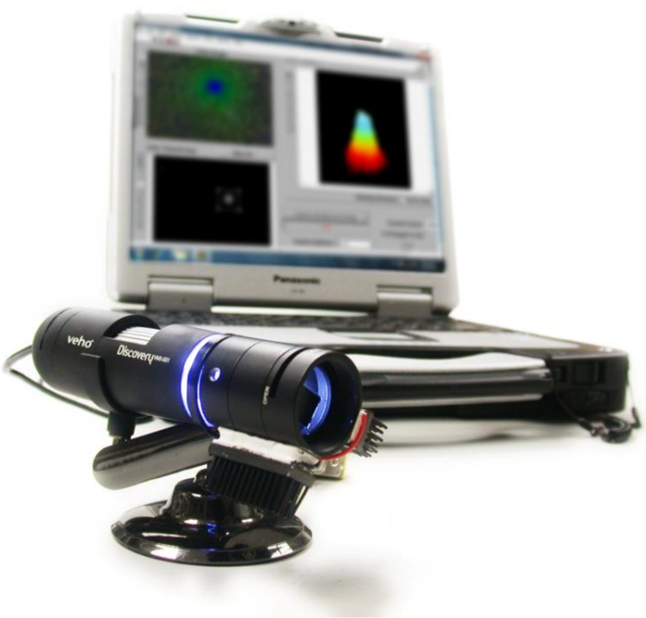
First tests with hand…..

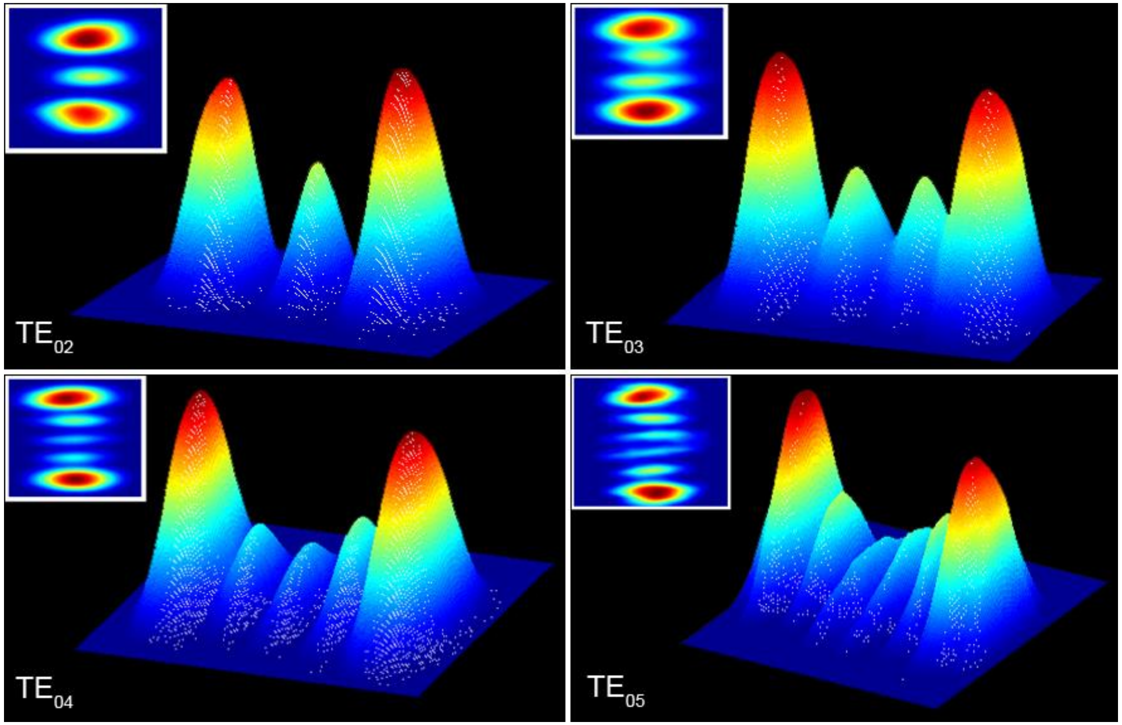




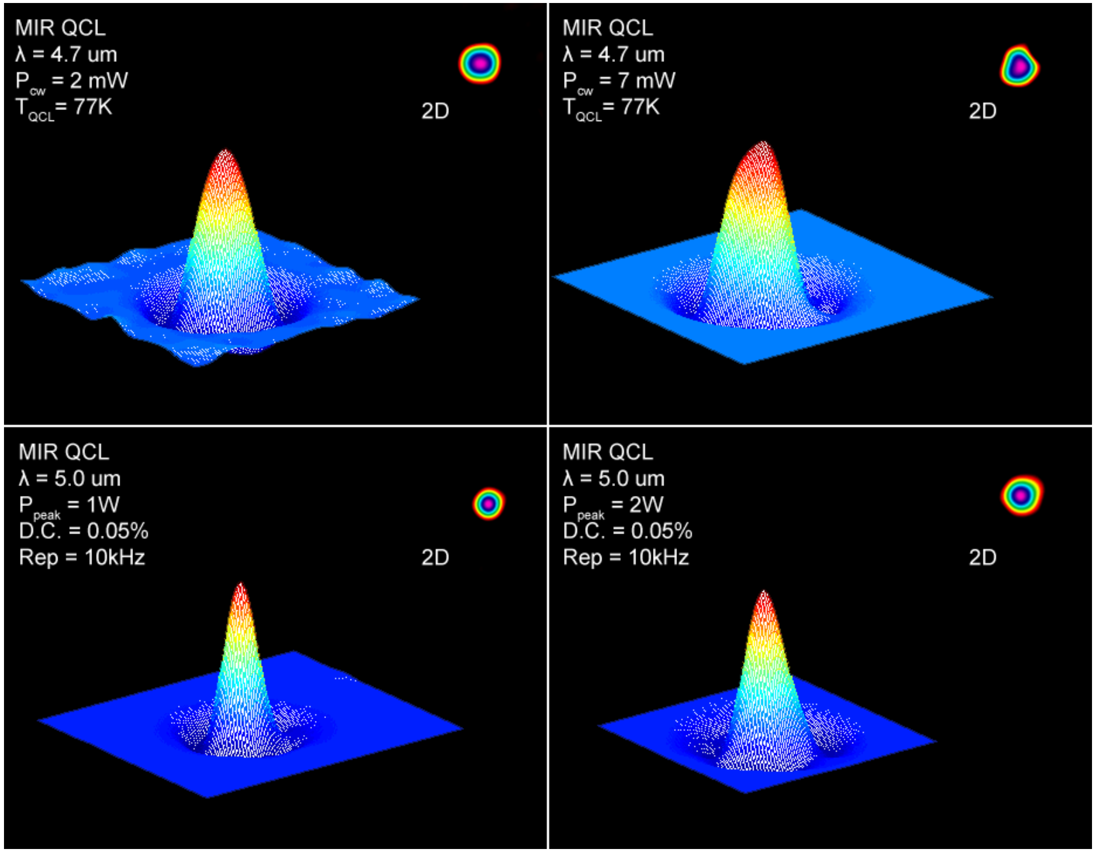


NIR Laser mode imaging



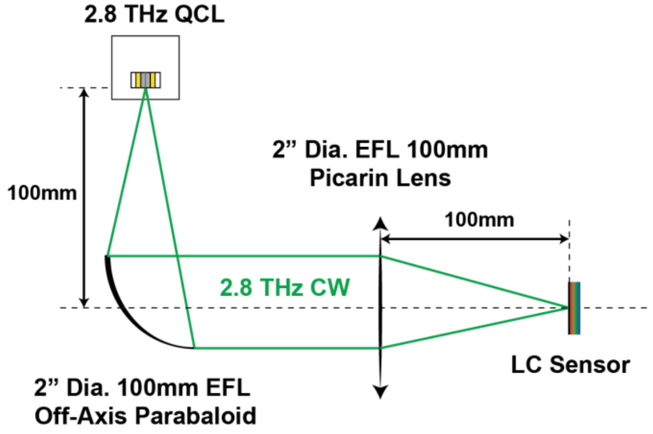


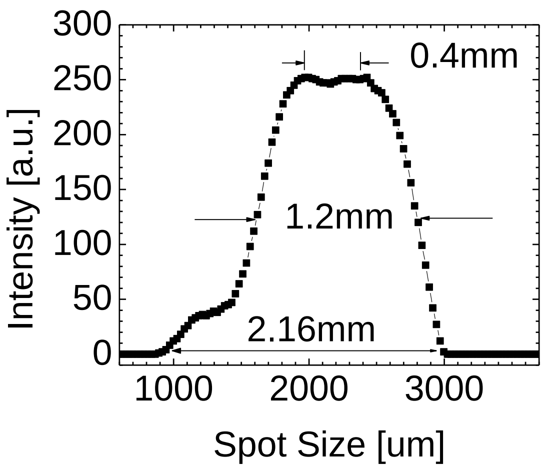
Laser modes MIR QCL

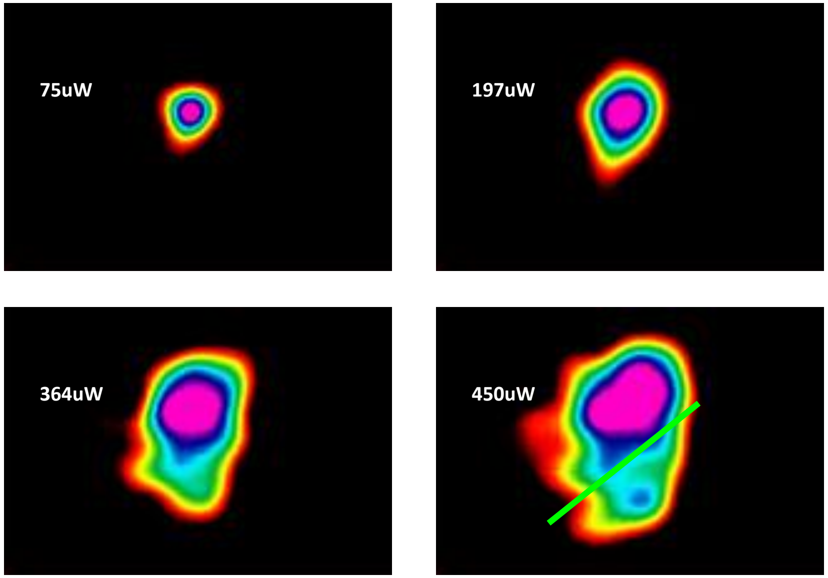


We would like to thank Claire Gmachl from Princeton University for her assistance in these measurements

2.8 THz Quantum Cascade Laser







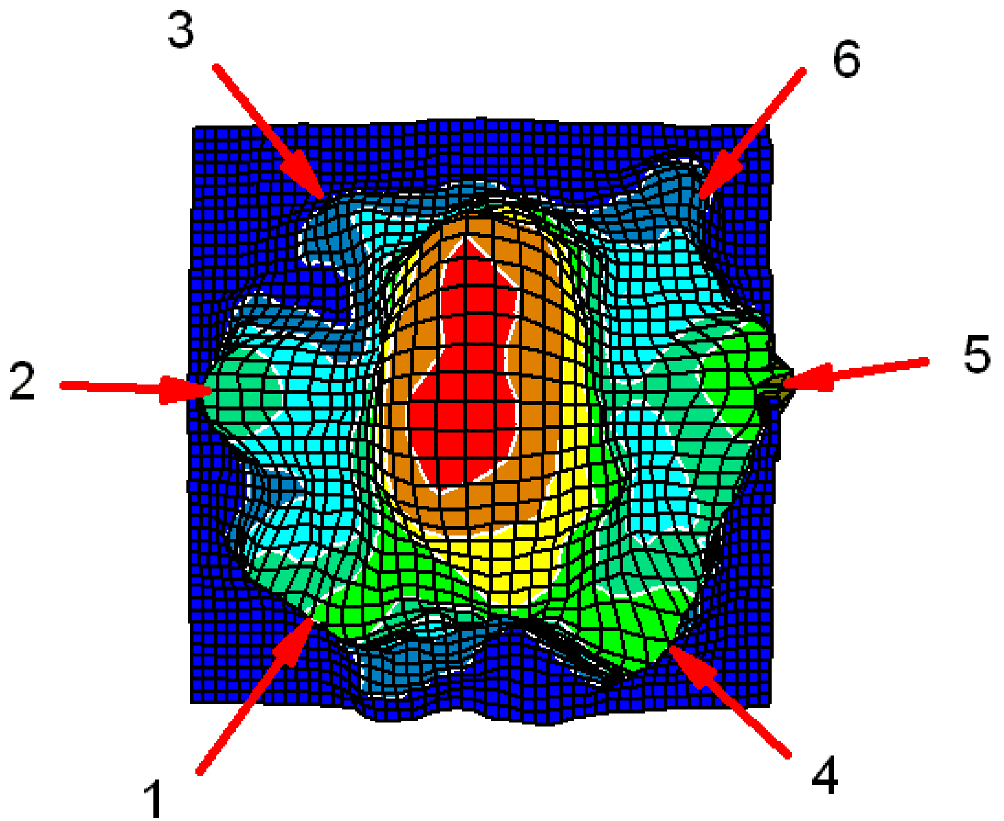
Measurements performed at Sandia National Laboratory, Albuquerque, NM

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

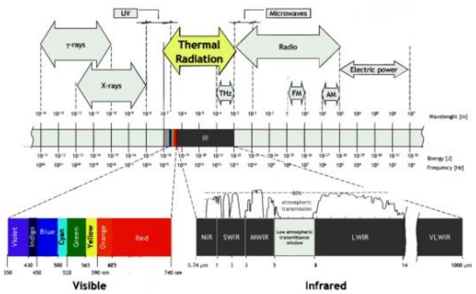
- Source:
  Antenna driven by 7mW, 110GHz

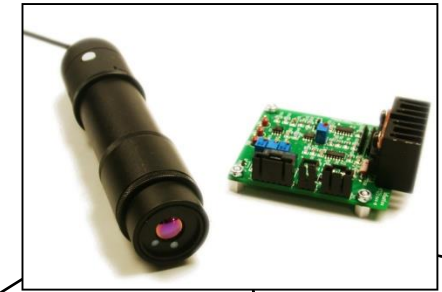
- Increased absorption through water layer

- To my knowledge first 100GHz camera



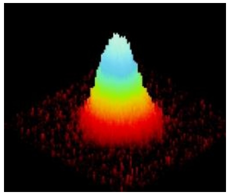
Laser beam imaging (Multi Spectral!)



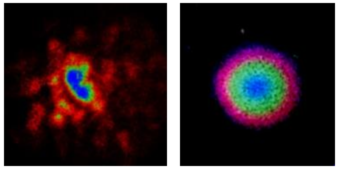


Proof of multi-spectral capability in form of laser beam profiler:
One device for all lasers

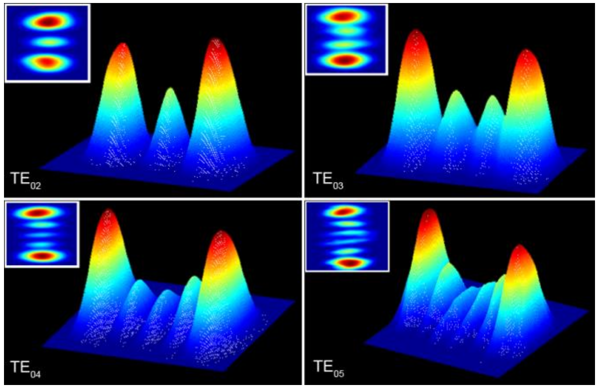
VIS - NIR



1mW DPSS **Green Laser**

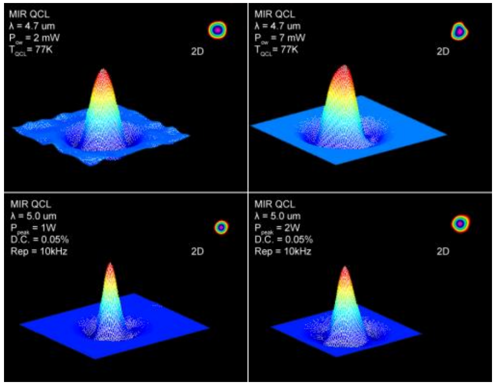


Fiber Pigtailed 1.3um
(left) Damaged (right) Repaired

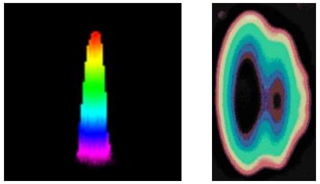


Ring Cavity **800nm Ti:Sapphire** laser at 300uW CW tuned to higher order modes.

MIR to LWIR

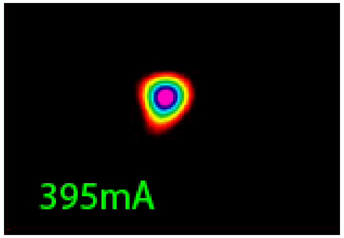


Mid IR QCL (top row) CW @77K (bottom row) Pulsed @ Room Temperature

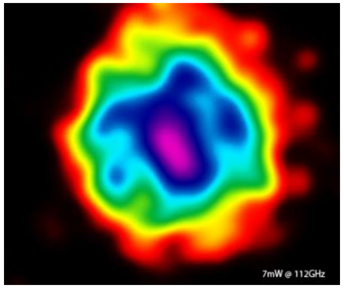


LWIR QCL & C02 laser

THz and GHz



THz QCL from 75uW to 450uW



GHz Horn Antenna 7mW @ 112GHz
* Used a film of water as the absorber

Beyond MIR: FIR camera - applications

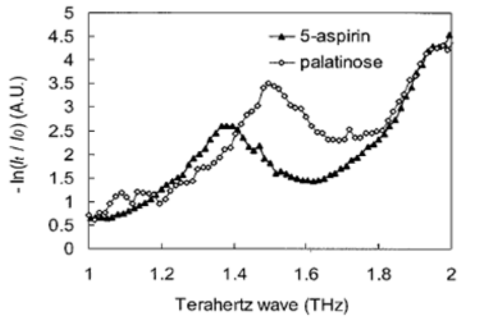
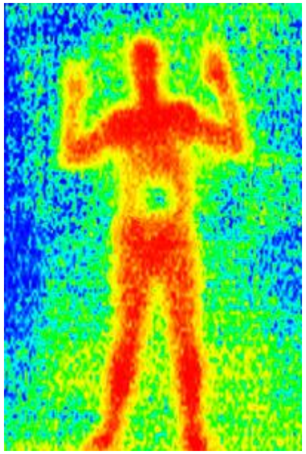


Fig. 3. Spectral curves of 5-aspirin and palatinose. I_o and I_t are incident and transmitted intensities, respectively.



FIR (THz) spectroscopy

- ***Explosive Detection***
- Biological species (Virus,DNA)
- Chemical species (via Water)
- Recognition of metal / ceramics
- Not influenced by most packing materials (plastic, paper,…)
- QCL available (since 3 years)!

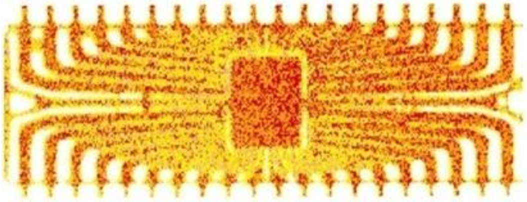


Plate I. THz image of a packaged semiconductor integrated circuit (plastic packaging).

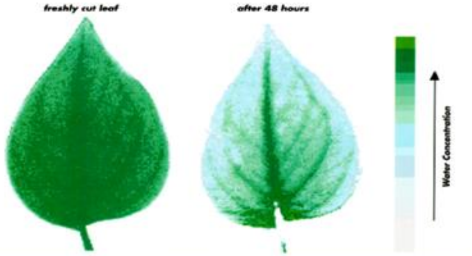


Plate II. Left: THz image of a fresh leaf. Attenuation of THz radiation through the leaf is largely due to water within the leaf. Right: THz image of the same leaf after 48 h. Water has clearly evaporated from the leaf, except from the stems of the leaf. At the far right is the color scale indicating the relative water concentration within the leaf; darker green corresponds to higher water concentration.

Thank you – and any questions?

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