Diffuse Terahertz Reflection Imaging using Quantum Cascade Lasers

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Outline

- Review of Imaging Techniques
  - Diffuse imaging
- Measurement of imaging resolution
- Demonstration of diffuse imaging of powders
  - Range of powdered materials
  - Range of particle sizes
  - Sensitivity to absorption coefficient and particle size
- Demonstration of diffuse imaging of concealed powders
- Discussion of imaging rates

Imaging Using Terahertz QCLs

Terahertz Imaging

- Transparency to non-polar materials
  - Non-invasive inspection and screening
- Non-ionising
  - Safe
- Spectral absorption features in many materials
  - Chemical finger-printing of drugs, explosives…
- Sub-mm wavelengths
  - Practical resolution
- Real-time video-rates possible
  - Removal of motion artefacts
  - Fast decision

THz Quantum Cascade Lasers

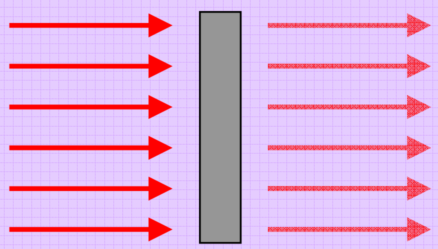
- High powers (~100 mW)
  - SNR, Transmission, Imaging rates
- Narrow linewidths (~30 kHz)
  - High spectral resolution
- Tunable
  - Atmospheric transmission
  - Spectral targeting
- Compact
- Room-temperature operation?
  - Getting there

Incoherent Imaging Modalities

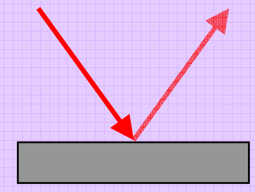
Reflection
(n)

Absorption
(α)

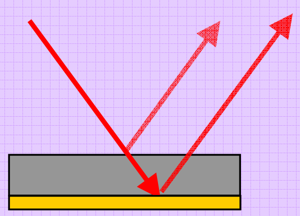
Scattering
(μ)



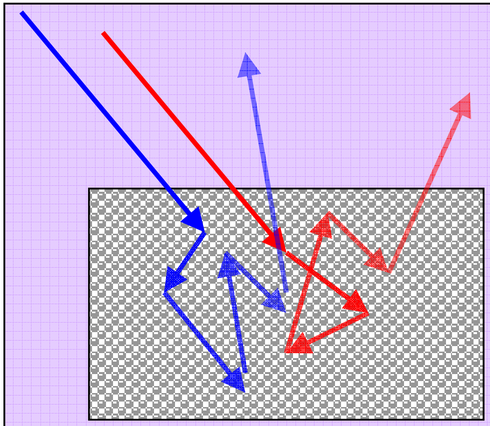
Transmission
(thin samples)
$\longrightarrow$ α, (μ)



Specular Reflection
(bulk samples)
$\longrightarrow$ n

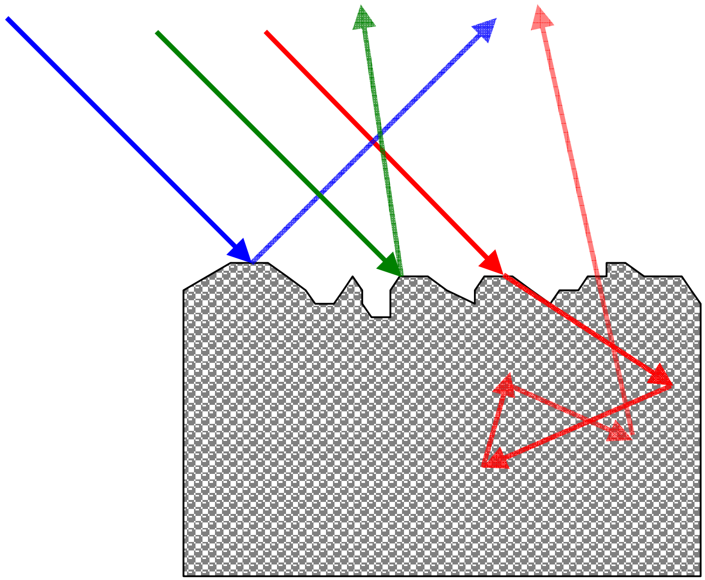


'Transflection'
(thin films)
$\longrightarrow$ α, (μ)



'Diffuse' Reflection
(rough surfaces, bulk samples, powders)
$\longrightarrow$ α, (μ)

Imaging of Powdered Samples



• Sub-surface scattering
+ Surface reflections

• Rms roughness $\sigma << \lambda$

$\longrightarrow$ Directional Specular

• Rms roughness $\sigma \sim \lambda, > \lambda$

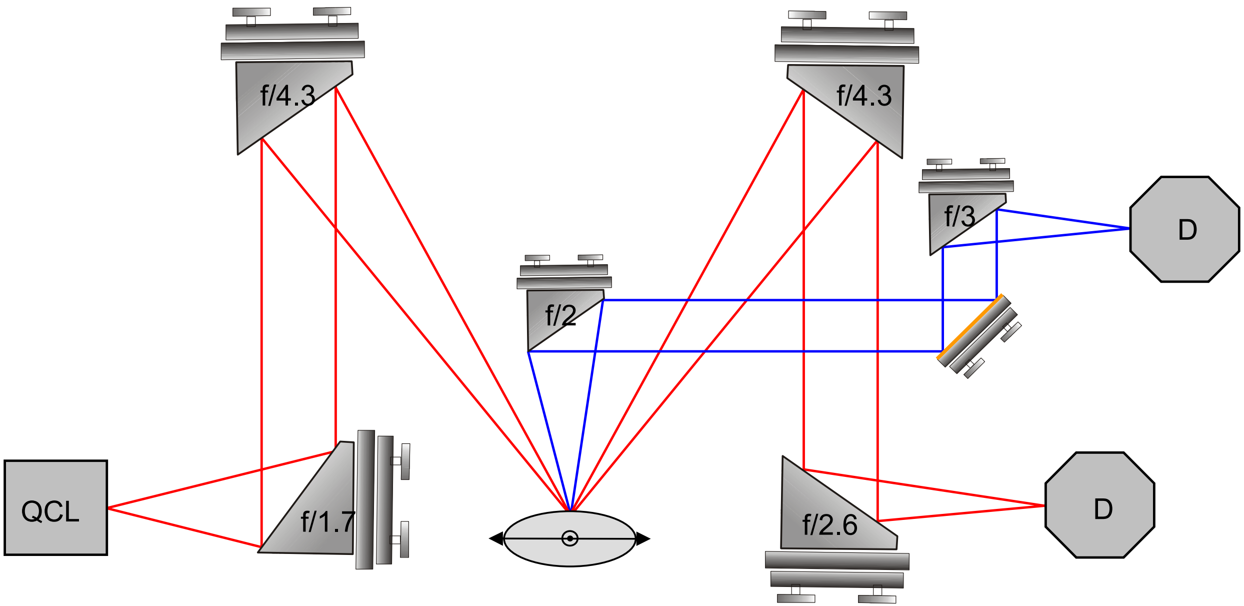
$\longrightarrow$ Non-directional Specular

('Diffuse-like')

• Contribution from sub-surface scattering greatest for:

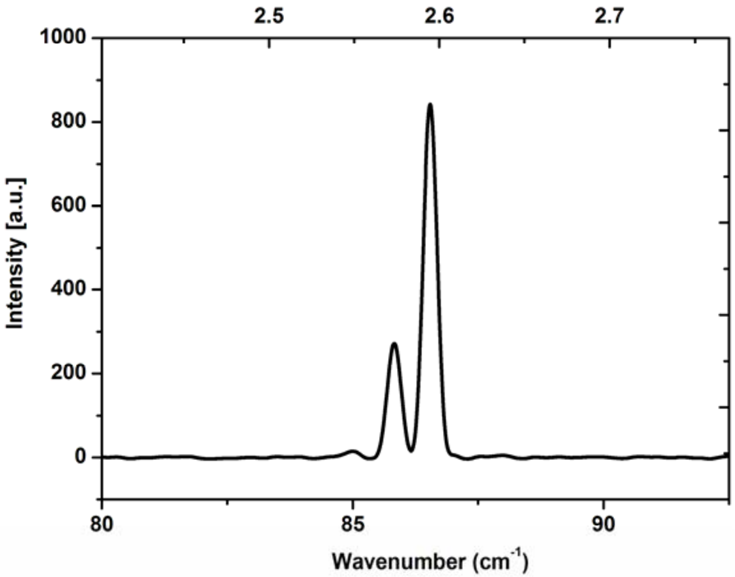
- Low refractive index (minimises surface reflections)
- Low absorption (maximises scattered power)
- Particle size $\sim \lambda$ (maximises scattering strength)
- Bulk samples (minimises unscattered transmission)

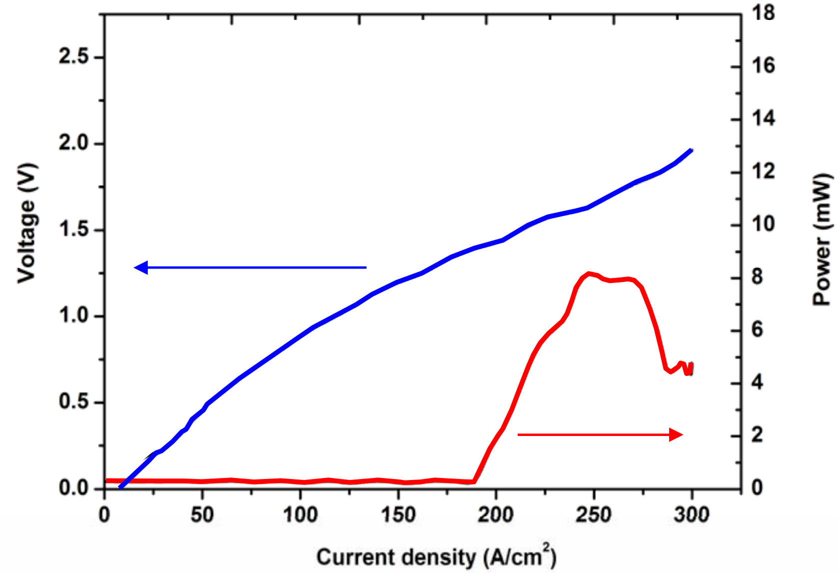
Imaging Apparatus



- Closed-cycle Pulse-Tube refrigeration to 5K
- Specular reflection ⟷ Refractive index
- Diffuse reflection ⟷ Absorption coefficient
- Simultaneous Bolometric and Pyroelectric detection
- Stand-off distance ~ **33 cm**
- Good resolution **(~300 μm)**, large depth-of-focus **(~12 mm)**

Bound to Continuum QCL





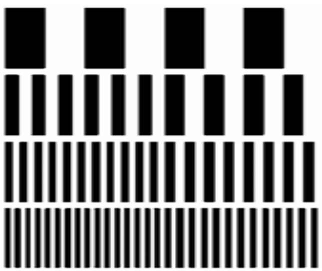
2.6 - 2.8 THz (106 - 115 µm)

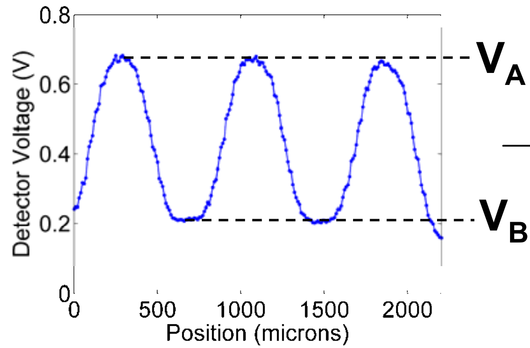
8 mW power (cw operation)

Dimensions: 1.75 mm x 145 µm

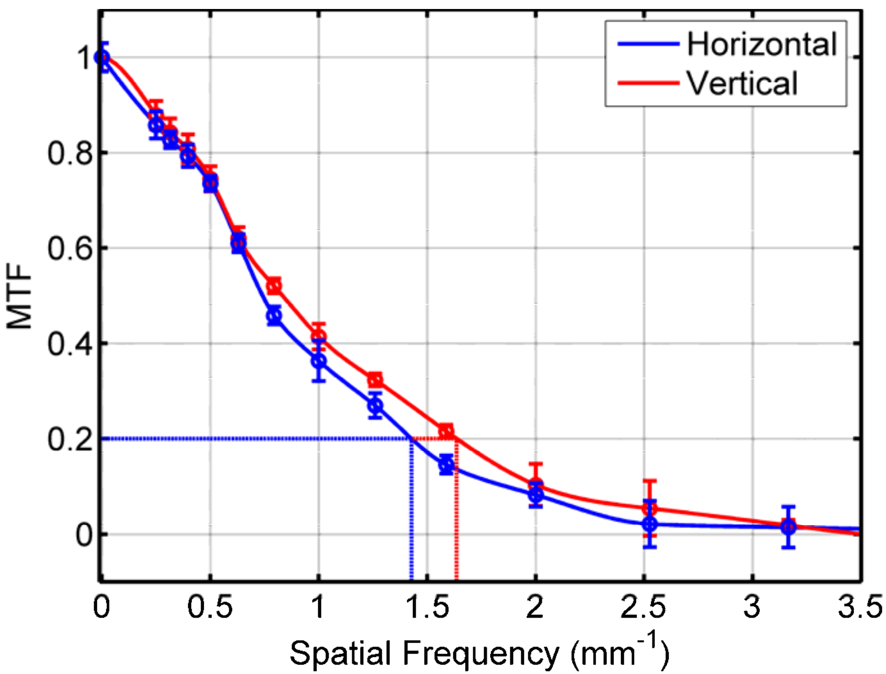
S. Barbieri *et al*., Appl. Phys. Lett., 85, 1674 (2004)

Transverse Optical Characterisation



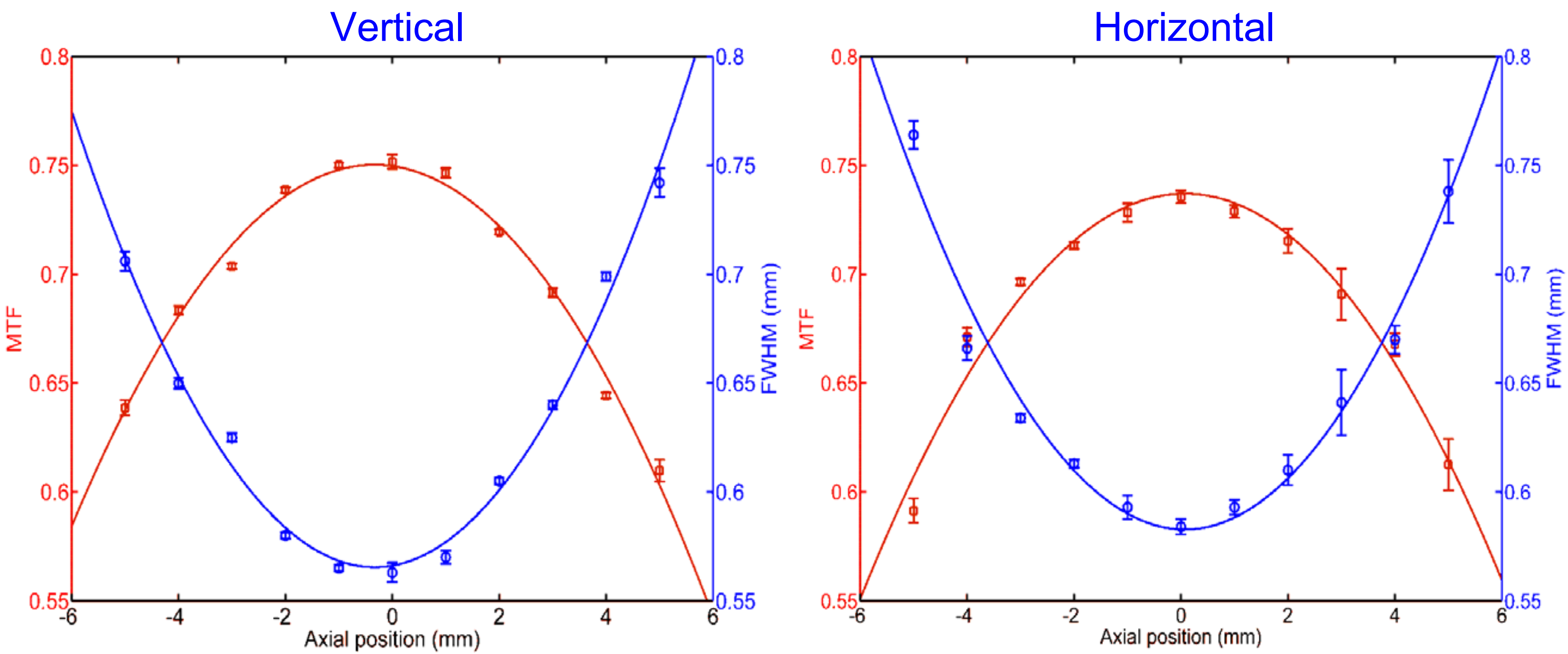


$$MTF \approx \frac{V_A - V_B}{V_A + V_B}$$



- Resolution at 20% MTF: **350 µm** and **305 µm**
- Circularly symmetric

Axial Optical Characterisation



- Depth-of-Focus = **12.3 mm** and **12.0 mm**
- Sub-millimeter beam for **> 16 mm** (5% of working distance)
- Sub-millimeter beam for **> 24 cm** for **5 m** stand-off distance

Diffuse-Specular Imaging at 2.8 THz

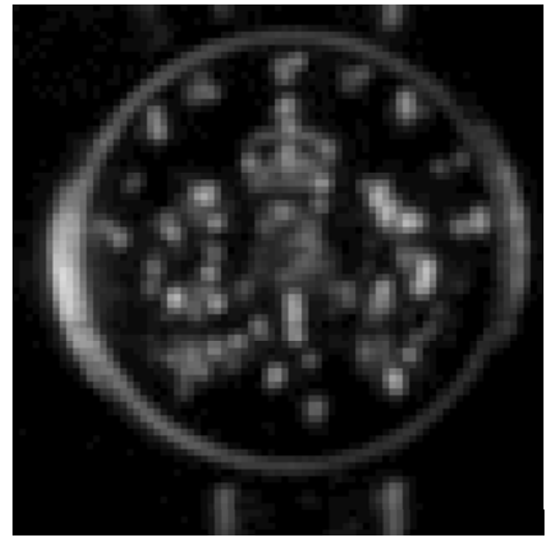
• 5-pence coin (UK) concealed behind HDPE FedEx envelope

Optical

17 mm

Specular

Diffuse-like



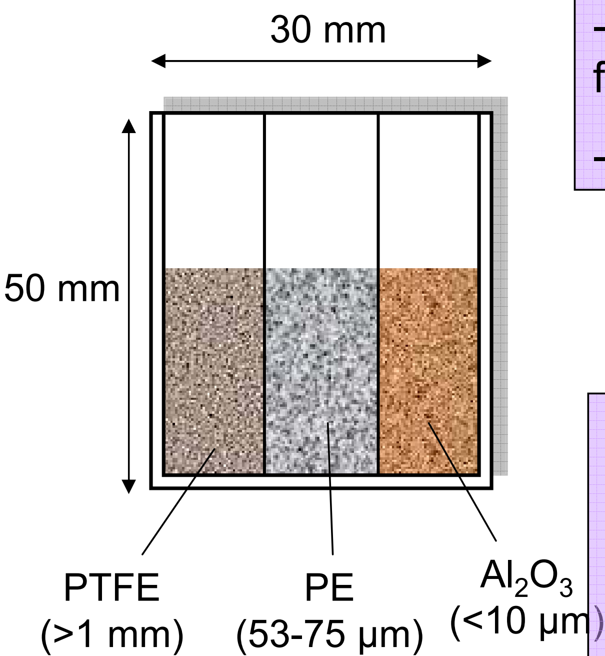
• Specular image shows **smooth mirror-like surfaces** as high intensity

• Diffuse-like image reveals non-directional specular reflections from **rough surfaces**

• **Simultaneous** acquisition of specular and diffuse-like images

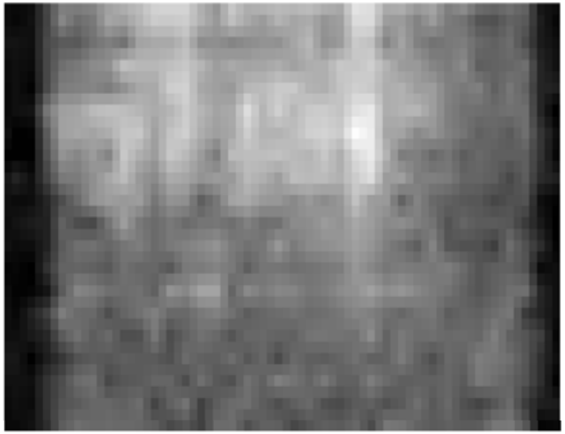
- **180 x 108 pixels**; **27-min** acquisition time (translation-limited)

Diffuse Imaging of Powders at 2.8 THz



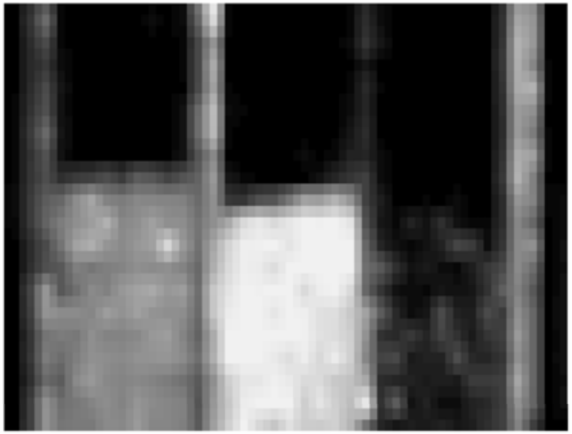
Specular image:

- **Strong reflections** from lid of box
- Powders not resolved



Diffuse image:

- **No contribution** from lid of box
- Large intensity for low-absorbing powders
- Lower intensity for absorbing powder



Diffuse Imaging of Powders at 2.8 THz

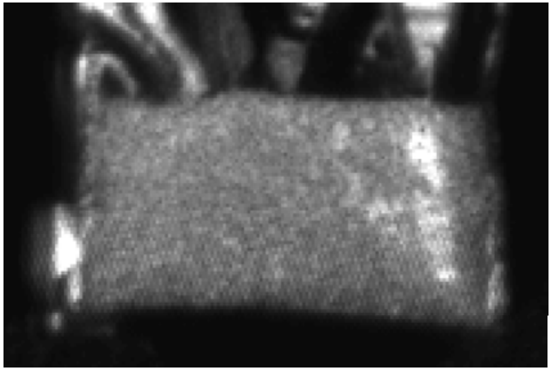
Material	Particle size (μm)	Normalised image intensity
PE	53-75	1.00
PTFE	>1000	0.49
Polystyrene	6	0.33
PTFE	1	0.22
Lactose	>1000	0.13
Al_2O_3	< 10	0.12
Perspex	5	0.09
Sucrose	>1000	0.07

- **Sensitivity to absorption coefficient and particle size**

Diffuse Imaging of Concealed Powders

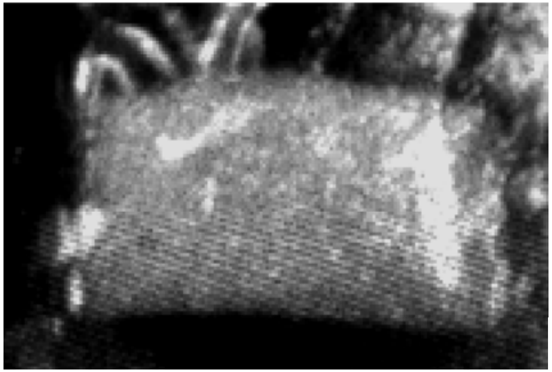
• Polyethylene powder (53-75 μm) in re-sealable polythene bag

Unconcealed

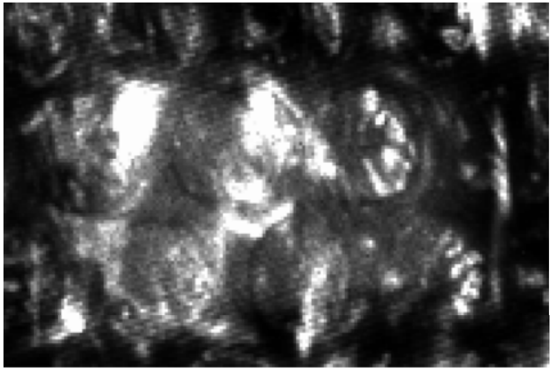


35 mm

FedEx HDPE envelope



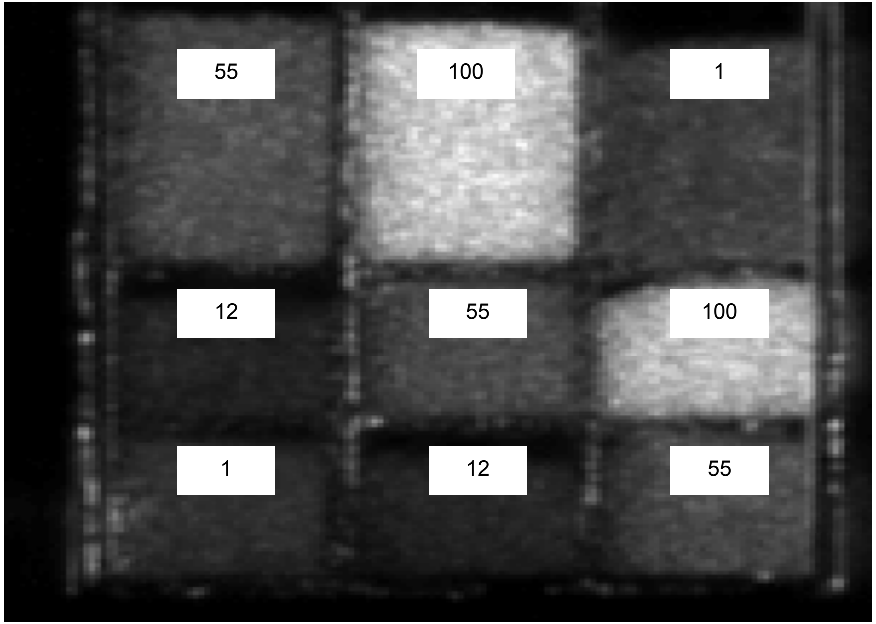
FedEx padded envelope



- Specular highlights from creases in bag
- Small contribution from concealing materials
- Convex air pockets partially distort powder
- **180 x 108 pixels** (45 mm x 27 mm) in **27 mins**
- Estimated minimum acquisition time ~ **2 mins** (~**7 secs** for 1-mm pixels)

Diffuse Imaging of Different Particle Sizes

• PTFE (Teflon) powders (~1 g) in polystyrene sample holder



Particle sizes shown in μm

•**Sub-surface scattering** dominates

• Largest intensity for 100 μm powder

- Largest Mie scattering coefficient
- Largest back-scattered power

• Smallest intensity for 1 μm and 12μm powders

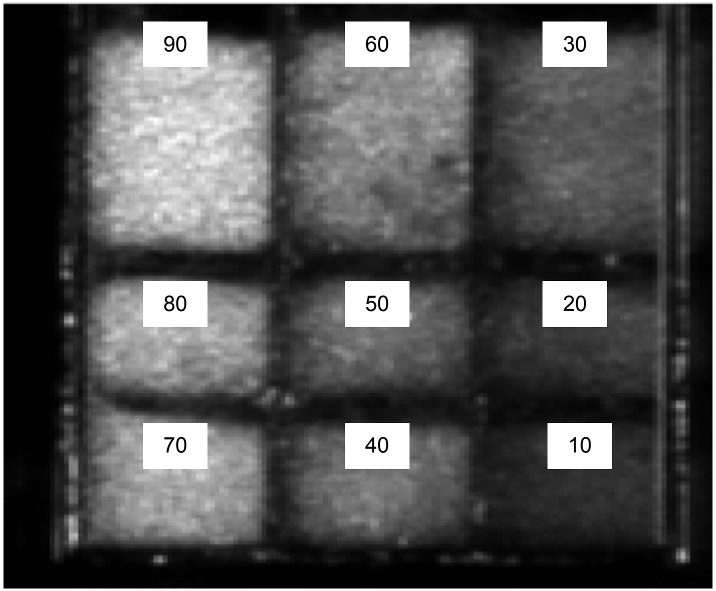
- Smallest Mie scattering coefficients

• $I_{1\mu m} > I_{12\mu m}$

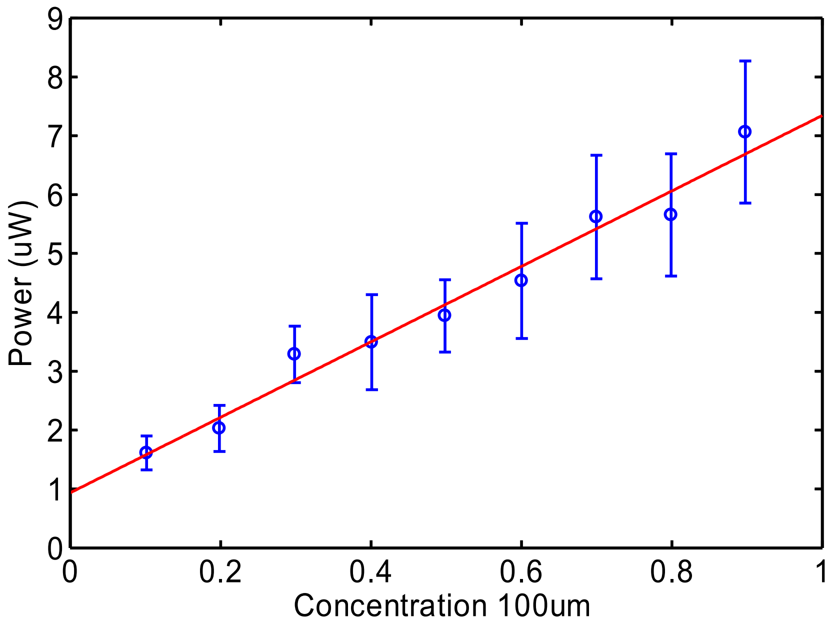
- Evidence for agglomeration?

Diffuse Imaging of Different Particle Sizes

- PTFE (Teflon) powders (~1 g) in polystyrene sample holder
- Admixtures of 100 μm and 12 μm powders



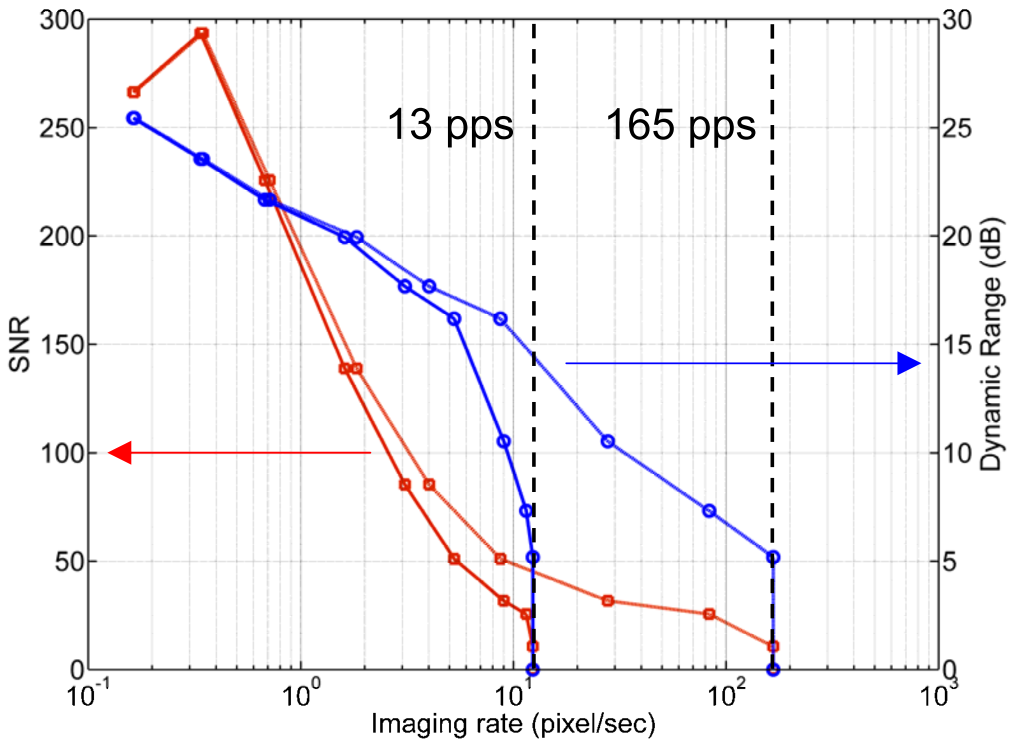
% concentration of 100 μm powder shown



- Linear dependence on effective scattering coefficient $\mu_{eff} = c\mu_{100} + (1-c)\mu_{12}$

Image Acquisition Rate

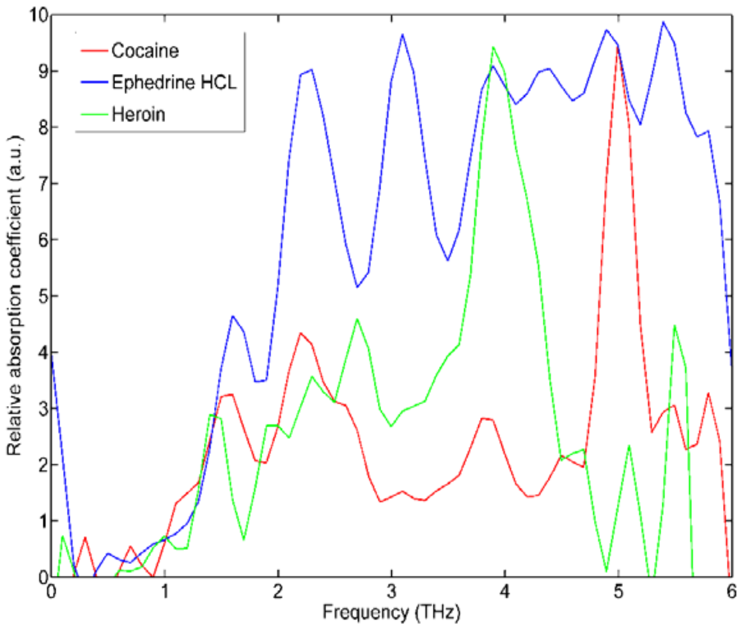
- Compromise between **acquisition rate** and **SNR**, **Dynamic range (DR)**
- 6 ms **processing time** per pixel (~165 pps)
- 75 ms **translation time** (~13 pps)
- **Pixel averaging time**

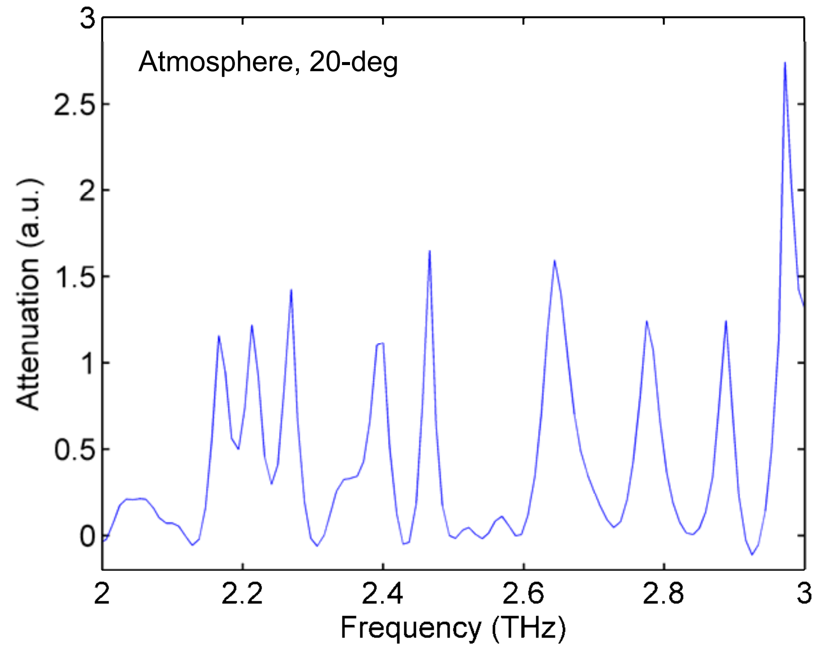


For 53-75 µm PE powder (through atmosphere):

- Peak SNR ~ 300
- Peak DR ~ 25 dB

Multi-wavelength Stand-Off Imaging for the Identification of Illicit Materials





A. Burnett, W. Fan

- **Weak wavelength-dependence** of scattering strength and surface reflections
- **Strong wavelength-dependence** of absorption coefficient
- Target transmission windows in atmosphere

Summary

- Diffuse imaging modality
  - Bulk samples
  - Powders
  - No specific sample alignment
- **Sub-mm** resolution, **>24-cm** depth-of-focus over **5-m** stand-off distance
- Diffuse imaging of a range of concealed powders
  - Sensitivity to particle size
  - Linear dependence on effective scattering coefficient
  - Sensitivity to absorption coefficient
- Extension to multi-wavelength imaging for identification of materials

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