# Measurements and Modeling to Overcome Shortcomings in the Atmospheric Channel Model

**Rainer Martini**
(rmartini@stevens.edu)

*Department of Physics and Engineering Physics*
*Stevens Institute of Technology*

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

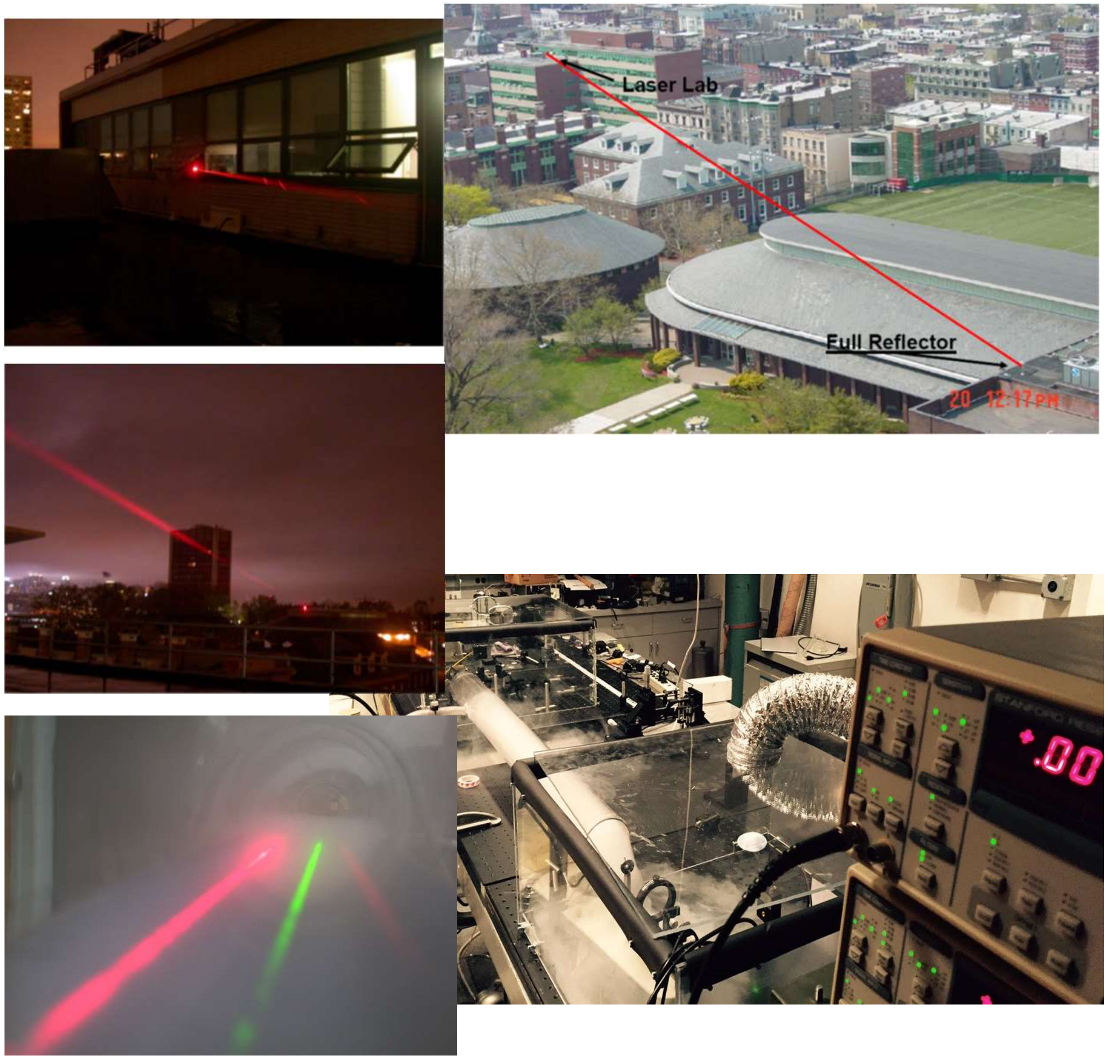
# Status quo – and its challenges

- Achilles heel for free-space optical communication: Reliability – especially in low visibility conditions.
- Today (successful) approaches: active beam and phase front steering, power level adaption, sophisticated modulation schemes, etc.
- Alternative: make optimal use of the atmospheric transmission channel!
- **Challenge: only few measuremensts existing and reliability of existing models for longer wavelength (>2$\mu$m)**
- **Status quo: 3 main ingredients for atmospheric channel models:**
  - **Mie-Kruse model linking visibility to transmission losses**
  - **Turbulence based losses (scintillation and beam wander) modeled based on Rytov variance**
  - **Losses (szintillation, absorption and scattering) are calculated and treated independently**

# Approach: multi-wavelength testbeds

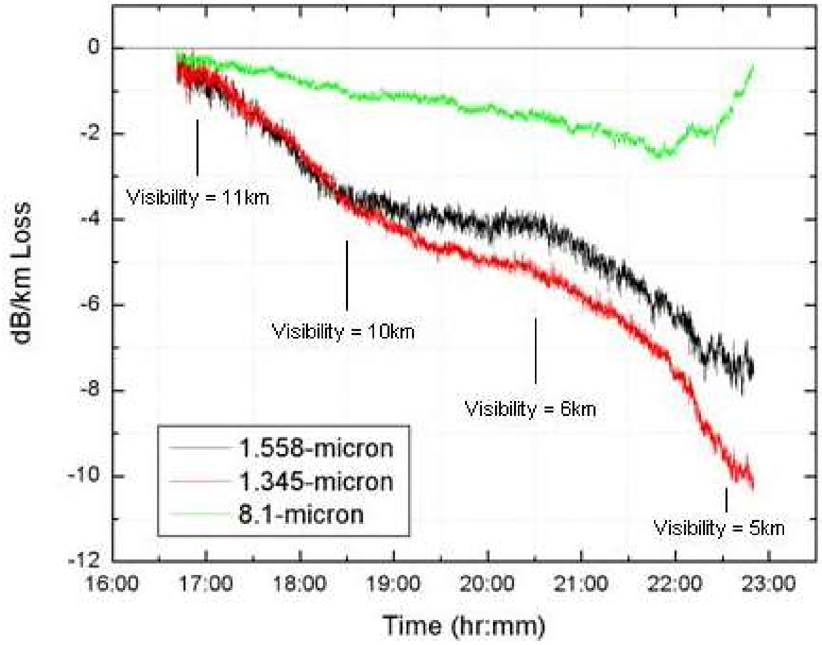
Measuring multi-spectral propagation losses and effects, comparing NIR (1300nm, 1550nm) with MIR (4μm, 8μm) properties

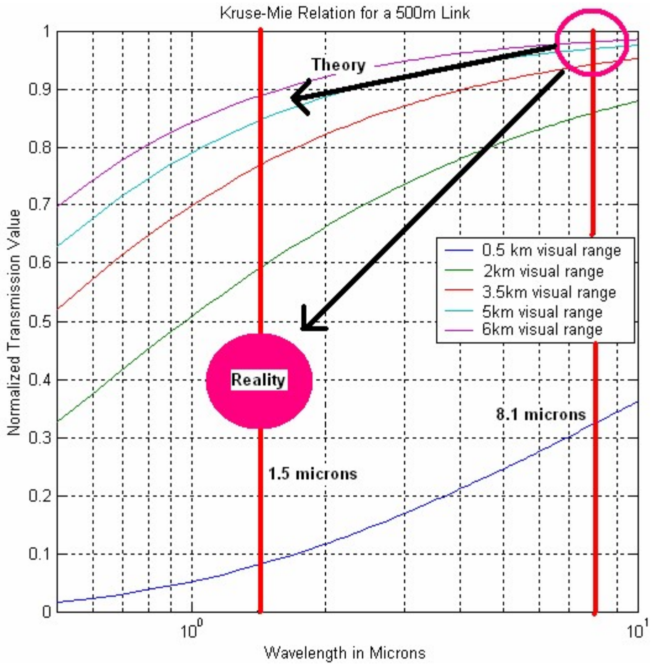
- Outdoor testbed (500m link)
- Indoor testbed (simulating realistic link losses)
  - Scattering losses up to 50dB
  - Turbulence in controlled environment
  - Direct beam wander measurement
  - New: scattering and turbulence effect measured simultaneous

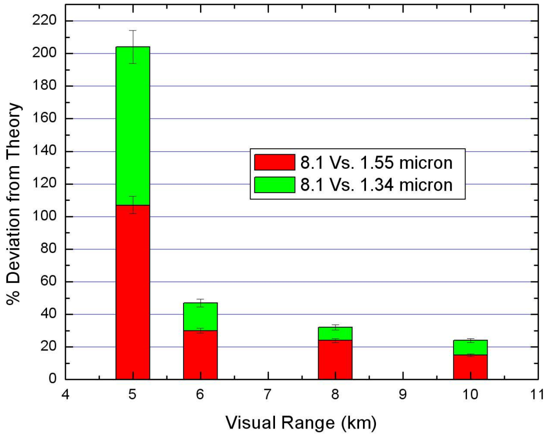


# Mid-IR Outdoor link measurment

- Mid-IR **Outperforms NIR links**
- **Up to x30 dB/km**
- Bimodal Fog
- Scavenging event at 22:00 with rain
- **Kruse Mie overestimating MIR losses**



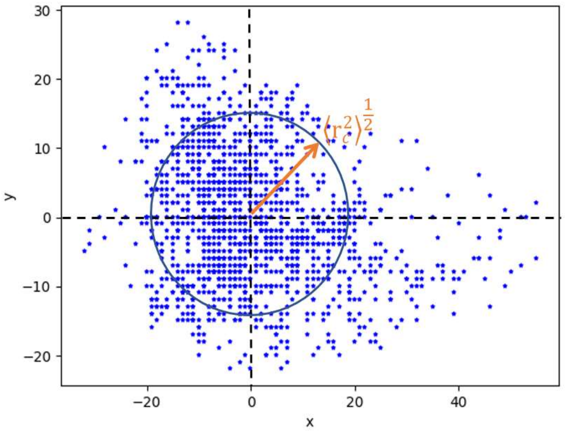




P. Corrigan, E.A. Whittaker, E.A. Whittaker, and C. Bethea, "Quantum cascade lasers and the Kruse model in free space optical communication", Optics Express 17, 4355-4359 (2009).

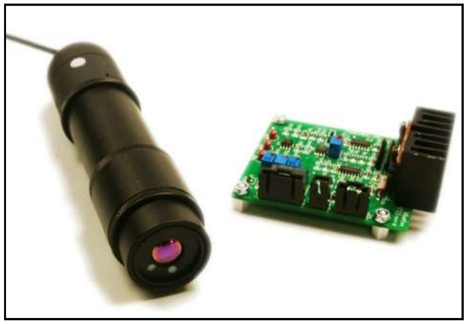
$1.818 \times 10^{-5}$

# Beamwander analysis: Deduction of $C_n^2$ and comparison



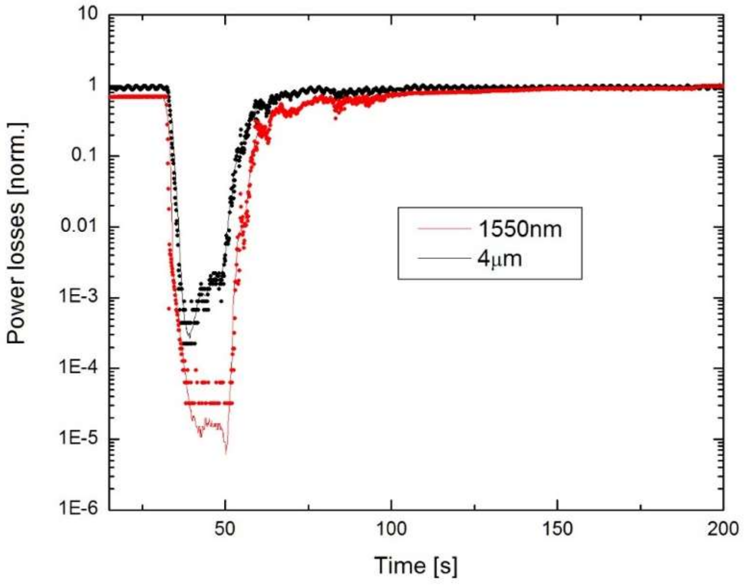
| Air Temp. | 22 °C | 30 °C | 70 °C |
|---|---|---|---|
| $C_n^2$ (1550nm) | $4.936 \times 10^{-13}$ | $1.222 \times 10^{-11}$ | $2.929 \times 10^{-11}$ |
| $\langle r_c^2 \rangle^{1/2}$ (1550nm) | $2.710 \times 10^{-5}$ | $1.859 \times 10^{-4}$ | $3.141 \times 10^{-4}$ |
| $\langle r_c^2 \rangle^{1/2}$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

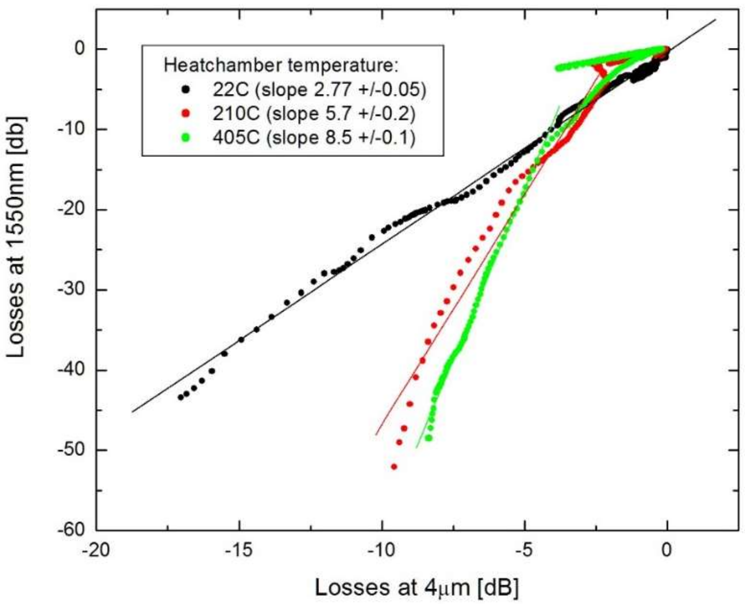
| Air Temp. | 22 °C | 30 °C | 70 °C |
|---|---|---|---|
| $C_n^2$ (1550nm) | 4.31E-12 | 1.15E-11 | 2.96E-11 |
| $\langle r_c^2 \rangle^{1/2}$ (1550nm) | 1.00E-04 | 1.81E-04 | 3.18E-04 |
| $\langle r_c^2 \rangle^{1/2}$ (4000nm, expected) | 4.07E-05 | 7.33E-05 | 1.29E-04 |
| $\langle r_c^2 \rangle^{1/2}$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

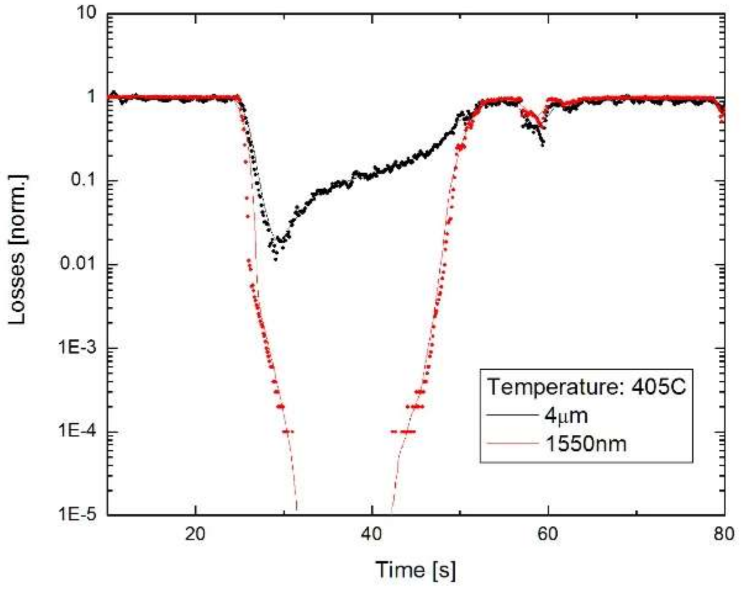


- Using novel broadband camera, NIR and MIR beam position and size can be monitored at 30fps
- Beamwander measurement allows for estimation of $C_n^2$ based on Rytov based calculation (max comparable to 500m at $C_n^2 = 2 * 10^{-16} m^{-2/3}$)
- $C_n^2$ calculated for 1550nm, allows for beamwander estimate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

# Scattering & Scintillation (reality)







- Comparison shows clear advantage of 4μm link
- 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 – maybe not treated as independent losses.
- **Behavior not clear: more measurements needed!**