Measurements of partially spatially coherent laser beam intensity fluctuations propagating through a hot-air turbulence emulator and comparison with both terrestrial and maritime environments

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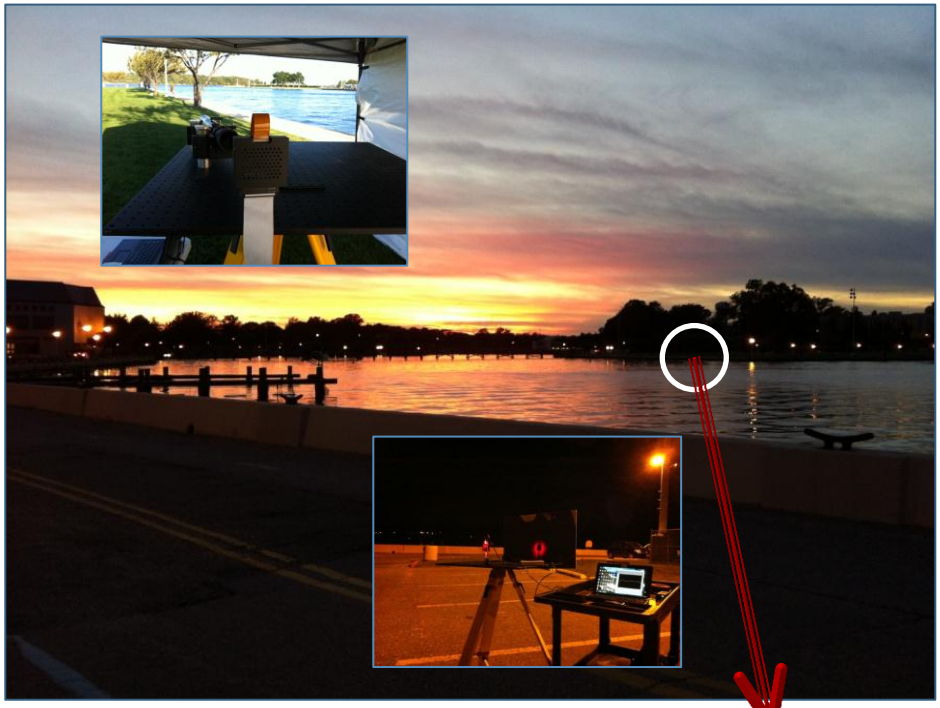
The Johns Hopkins University

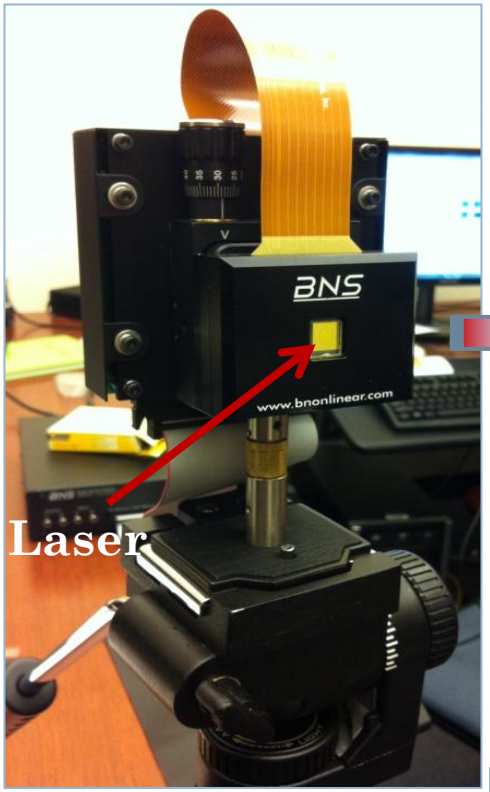
Field Tests – Overview

- Field Tests at USNA
- 314 meter over water link, HeNe (632.8 nm)
- 180 meter terrestrial link, IR (1550 nm)

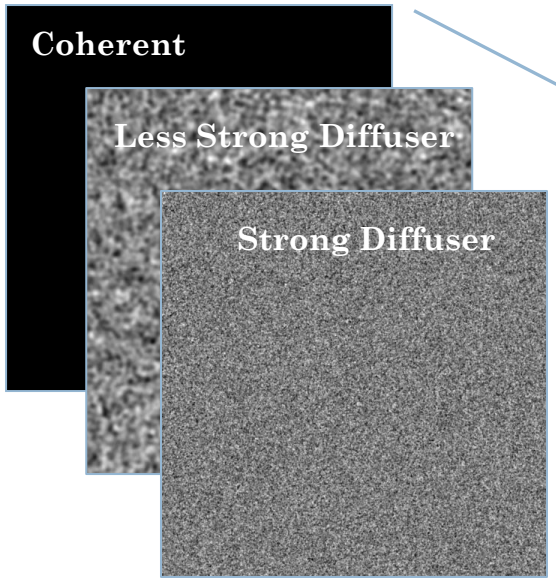


Phase Screen Construction

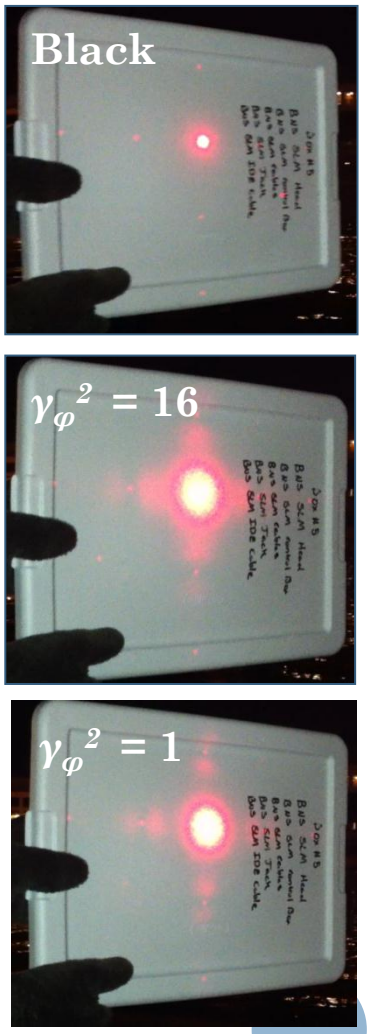
Spatial Light Modulator



Phase Screens



Beam with specified coherence properties



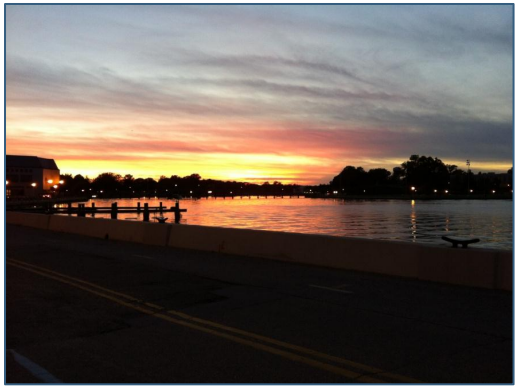
$R_\varphi(\rho) -$ *random function with Gaussian statistics, zero mean*

$$f_\varphi(\rho) = \exp\left(-\frac{\rho^2}{\gamma_\varphi^2}\right), \textit{window function}$$

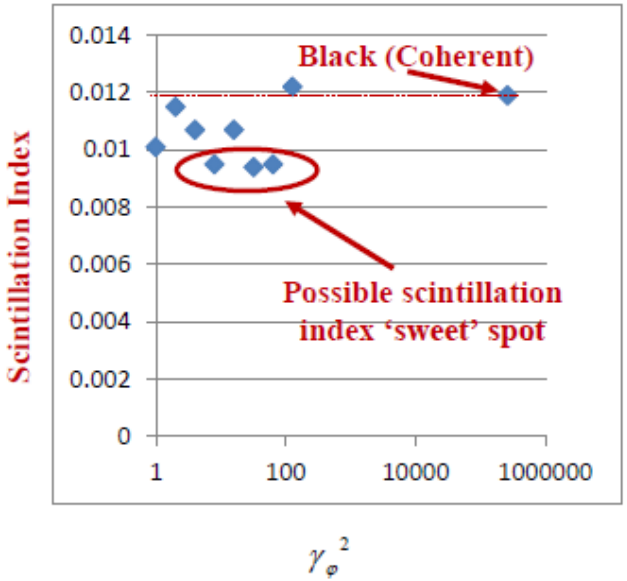
$$g_\varphi(\rho) = \int f_\varphi(\rho - \rho') R_\varphi(\rho') d^2\rho', \textit{convolution integral}$$

Gaussian Schell Model beam generation

Scintillation Index – over water link

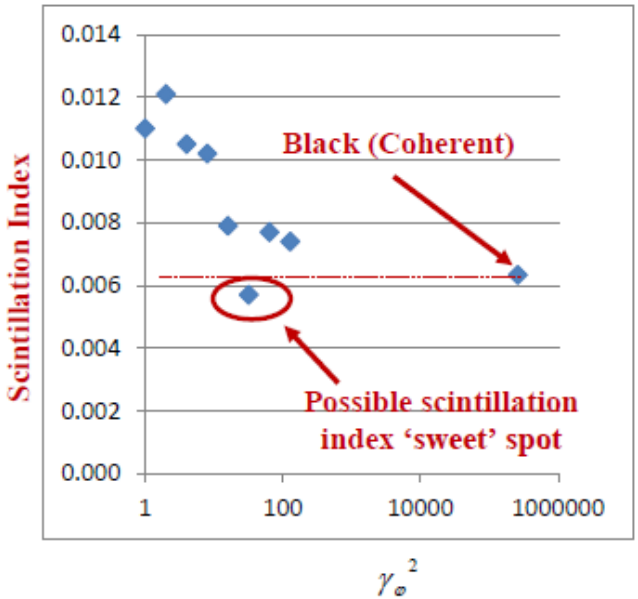


γ_φ^2 (pixels^2)	σ_I^2	% Diff.
Black (Coherent, ~512^2)	0.0119	N/A
1 (Strong diffuser)	0.0101	-15.1
2	0.0115	-3.4
4	0.0107	-10.1
8	0.0095	-20.2
16	0.0107	-10.1
32	0.0094	-21.0
64	0.0095	-20.2
128 (more weakly diffusing)	0.0122	2.5



Scintillation Index – Terrestrial link

γ_φ^2 (pixels^2)	σ_I^2	% Diff.
Black (Coherent, ~512^2)	0.0063	N/A
1 (Strong diffuser)	0.0110	73.7
2	0.0121	91.1
4	0.0105	65.8
8	0.0102	61.1
16	0.0079	24.7
32	0.0057	-10.0
64	0.0077	21.6
128 (more weakly diffusing)	0.0074	16.8



Turbulence Generator Mk I, Mod 0

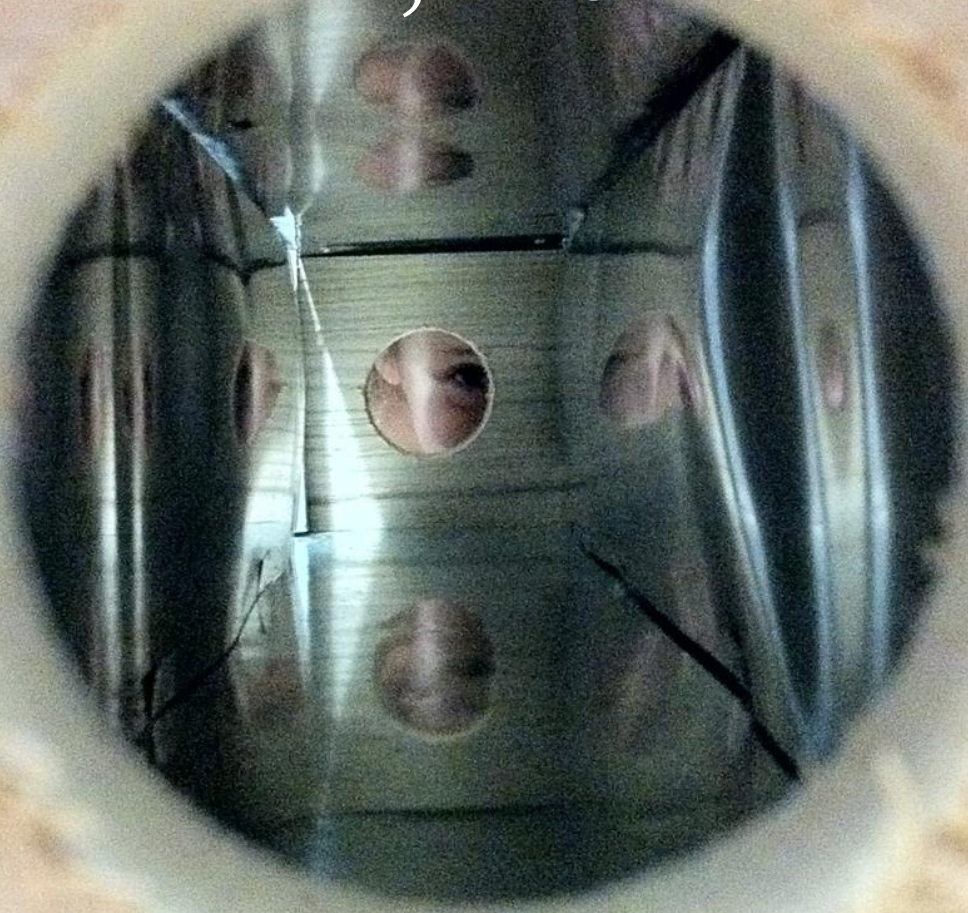
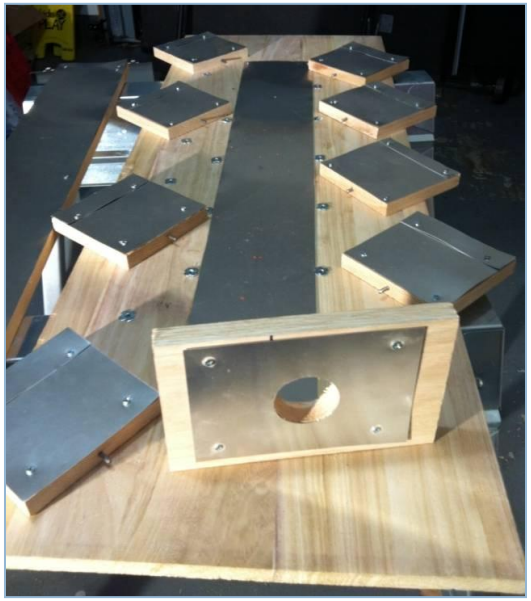
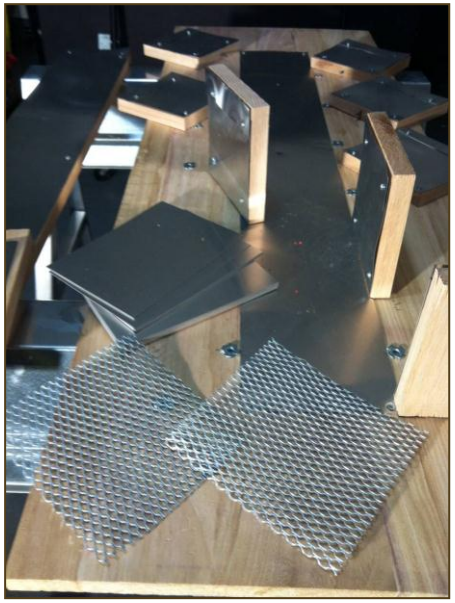
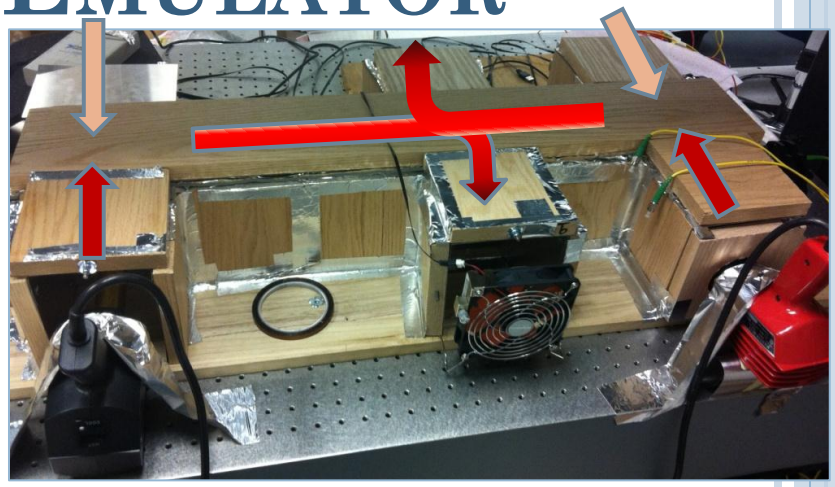


Photo looking down through turbulence generator, daughter Aurora pictured

Initial Turbulence Emulator







- Hot and cool air meet and mix
- Red Oak, aluminum flashing, modular

Theory

High delta T → High C_n^2

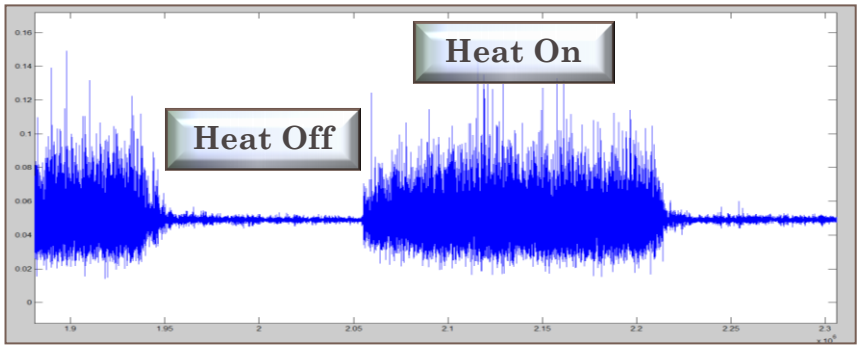
$$C_n^2 = (77.8 * 10^{-6} \frac{P}{T^2})^2 C_T^2$$

$$C_T^2 = \frac{\langle (T_1 - T_2)^2 \rangle}{R^{2/3}}$$

$$\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}}, Rytov\ variance$$

$$\sigma_I^2 = \frac{(\langle I^2 \rangle - \langle I \rangle^2)}{\langle I \rangle^2}, scintillation\ index$$

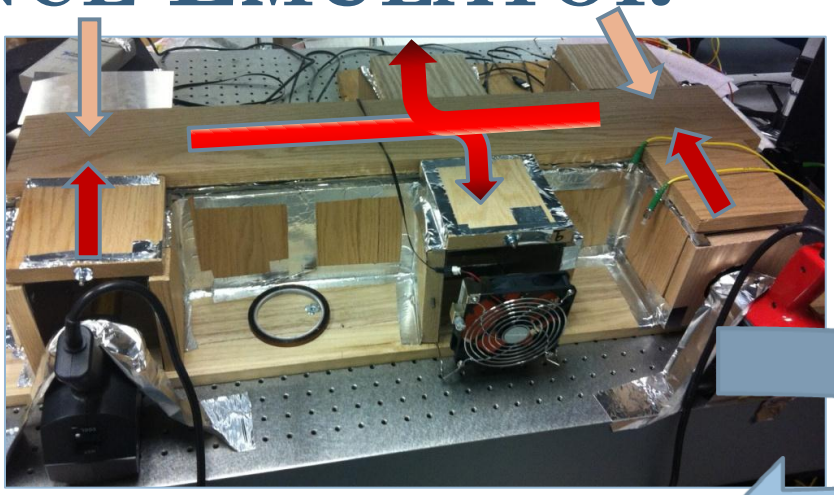
Results



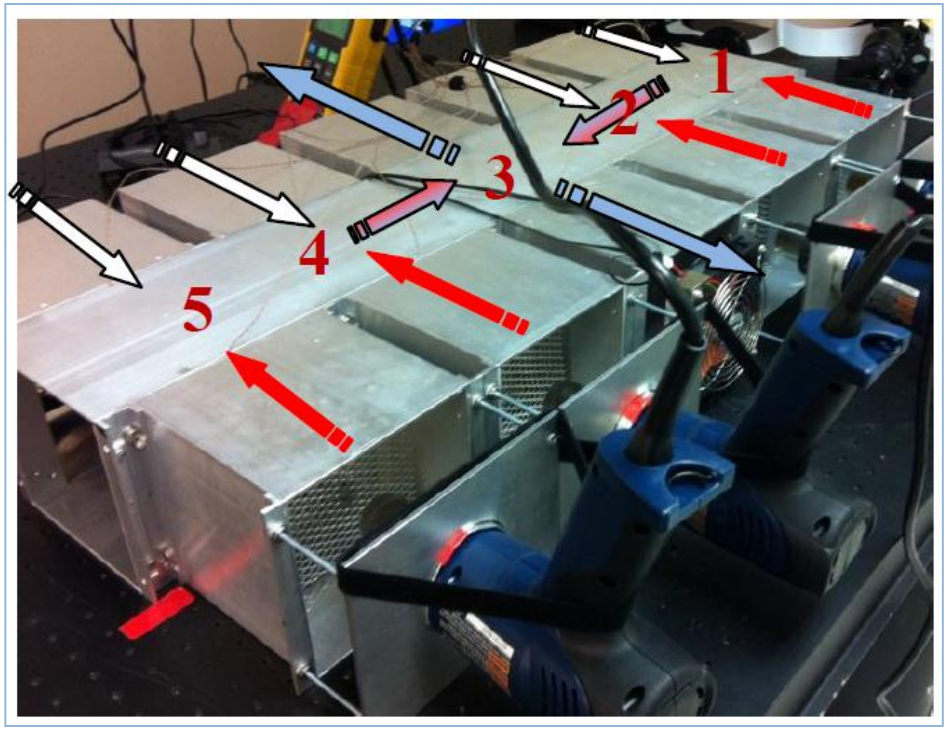
C_n^2 ~10^{-9} $m^{-2/3}$, σ_I^2 ~ 0.02 – 0.05, σ_R^2 ~0.1 - 0.7

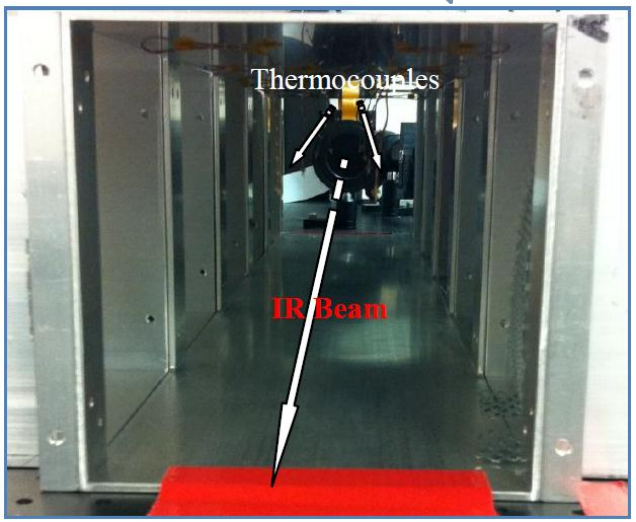
Initial design showed some positive results/proof of concept

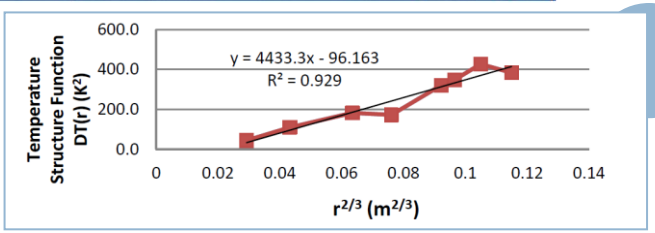
2ND TURBULENCE EMULATOR



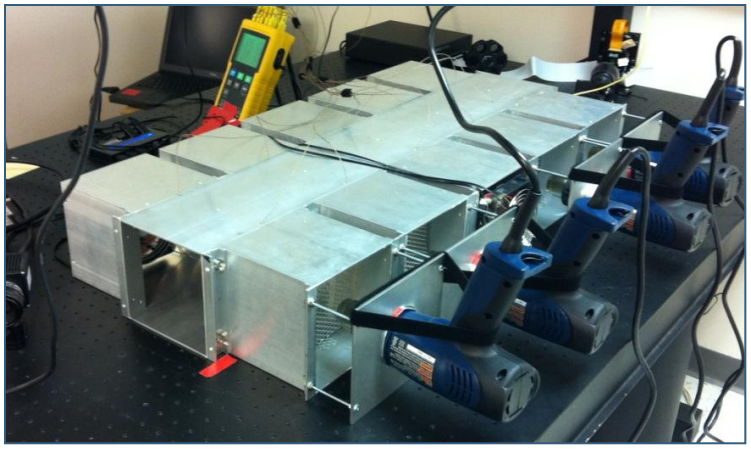
MOD 0 TO THE MOD 1

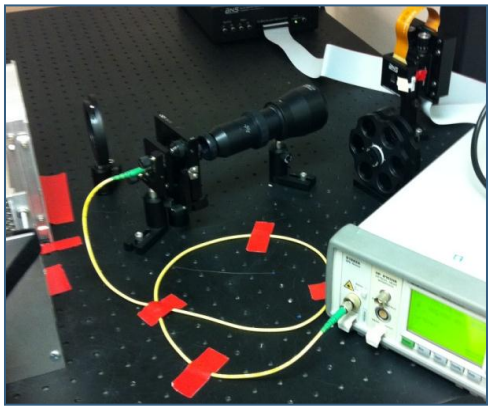






TE comparison with Field Tests





Fiber coll., 1550 nm, pol., exp., SLM, Mech. IRIS, $N_f = 0.987$

In laboratory TE set-up

THEORY

- Gamma-Laguerre (GL)
  - Medium and source independent
  - Uses first n moments
- Gamma-Gamma (GG)
  - Source, medium dependent
  - Uses first two moments
- Lognormal (LN)
  - Classical weak turbulence model
- Temporal Autocovariance

$$B_x(t_1,t_2) = \left\langle \left[x(t_1) - \langle x(t_1)\rangle\right]\left[x(t_2) - \langle x(t_2)\rangle\right]\right\rangle$$

- $B_x(\tau) = R_x(\tau) - m^2$ and $R_x(\tau) = \langle x(t_1)x(t_2)\rangle$
- $B_{(\exp fit)}(t_{data}) = Ae^{(-t_{data}/T_1)}$

$$W_{GL}(I) = W_g(I)\sum_{n=0}^{\infty} W_n L_n^{(\beta-1)}\left(\frac{\beta I}{\mu}\right), I \geq 0$$

- $W_g(I) = \frac{1}{\Gamma(\beta)}\left(\frac{\beta}{\mu}\right)^{\beta} I^{\beta-1}\exp\left(-\frac{\beta I}{\mu}\right)$
- $\mu = \langle I\rangle,\ \beta = \frac{\langle I\rangle^2}{(\langle I^2\rangle - \langle I\rangle^2)}$
- $W_n = n!\,\Gamma(\beta)\sum_{k=0}^{n}\frac{(-\beta/\mu)^k\langle I^k\rangle}{k!(n-k)!\Gamma(\beta+k)},$
- $W_0 = 1, W_1 = W_2 = 0$
- $L_n^{(\beta-1)}(x) = \sum_{k=0}^{n}\binom{n+\beta-1}{n-1}\frac{(-x)^k}{k!}$

$$W_{GG}(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right), I > 0$$

- $\alpha = \frac{1}{\exp\left(\sigma_{lnx}^2\right)-1},\ \beta = \frac{1}{\exp\left(\sigma_{lny}^2\right)-1}$
- $\sigma_{lnx}^2 = \frac{0.49\sigma_B^2}{[1+0.56(1+\vartheta)\sigma_B^{\frac{12}{5}}]^{7/6}}$ *and* $\sigma_{lny}^2 = \frac{0.51\sigma_B^2}{[1+0.69(1+\vartheta)\sigma_B^{\frac{12}{5}}]^{5/6}}$
- $\sigma_B^2 = (\langle I^2\rangle - \langle I\rangle^2)/\langle I\rangle^2,$
- $\vartheta = [1 + (\frac{2L}{kW_0^2})^2]^{-1}$

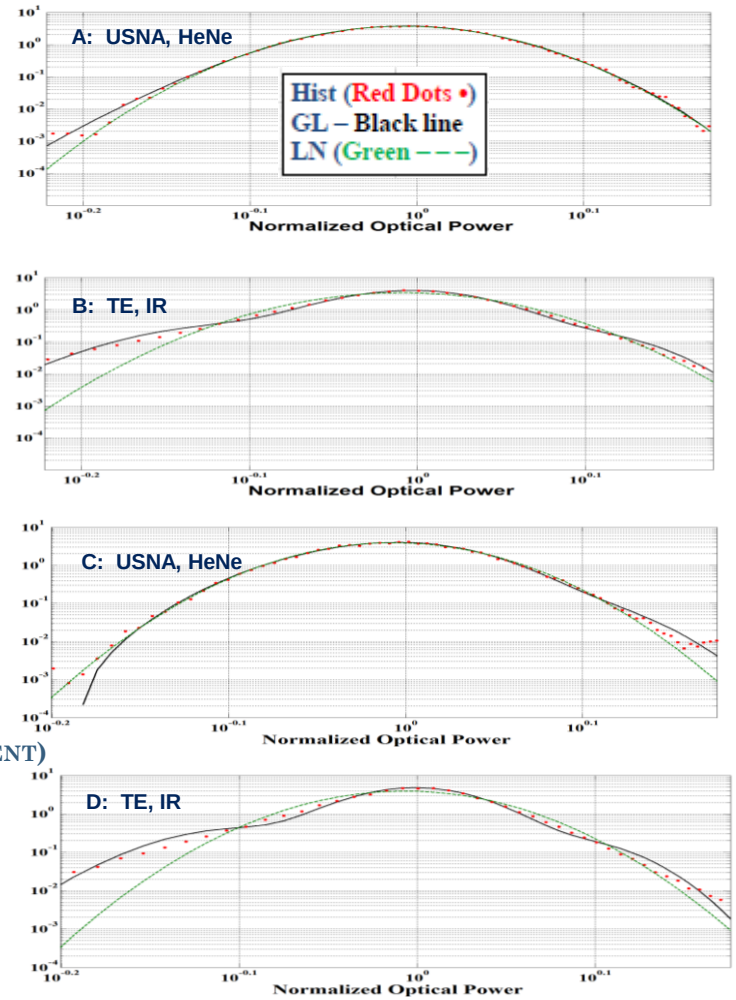
$$W_{LN}(I) = \frac{1}{I\sigma\sqrt{2\pi}} exp\left[-\frac{[\ln(I)-\mu]^2}{2\sigma^2}\right], I > 0$$

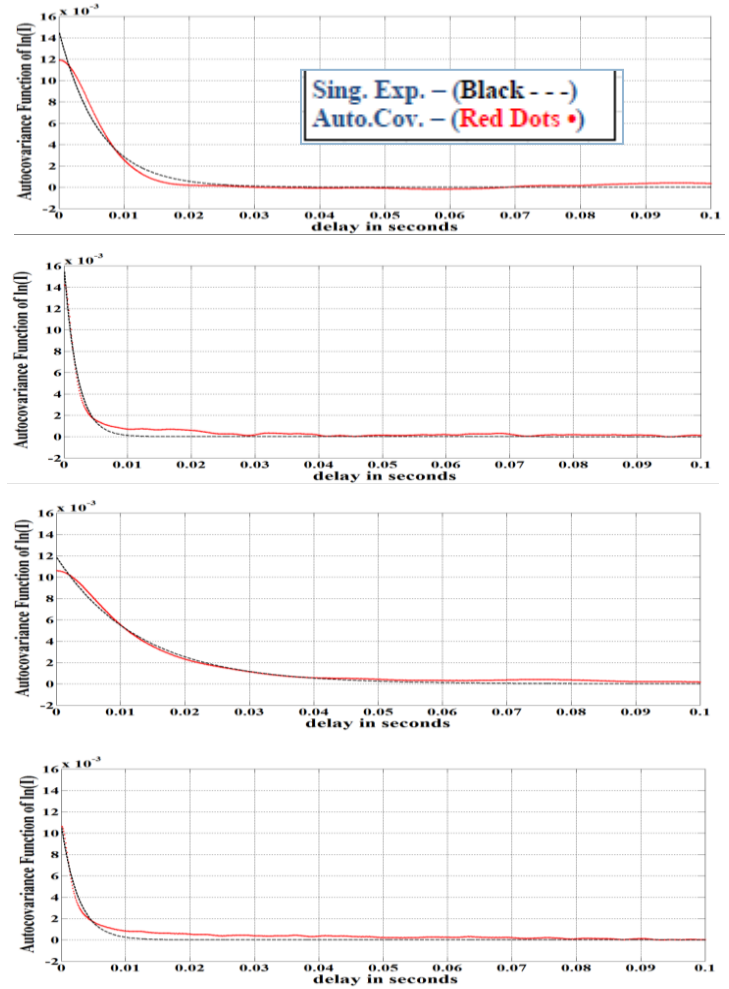
- $\mu = \langle \ln(I)\rangle$
- $\sigma^2 = var(\ln(I))$

TE comparison with Over the Creek

Black (coherent)

16 (Less Coherent)

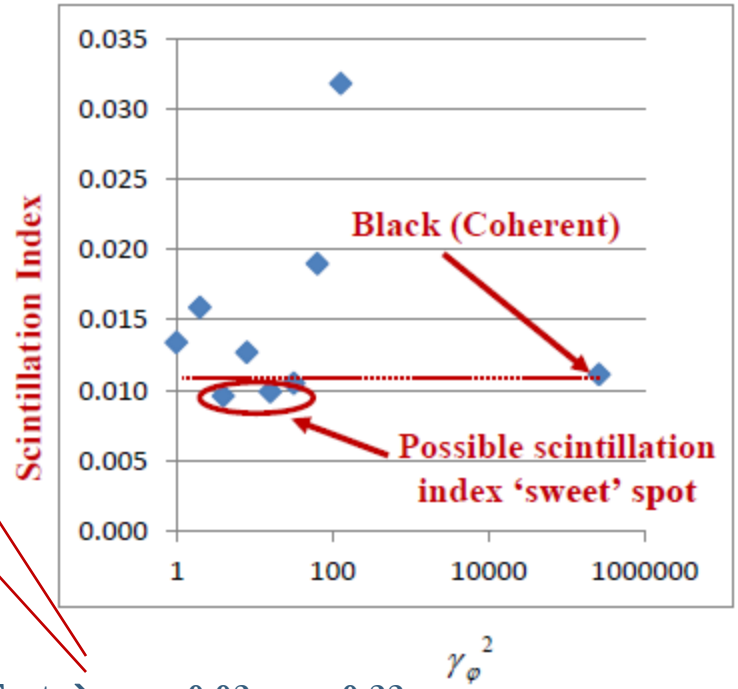




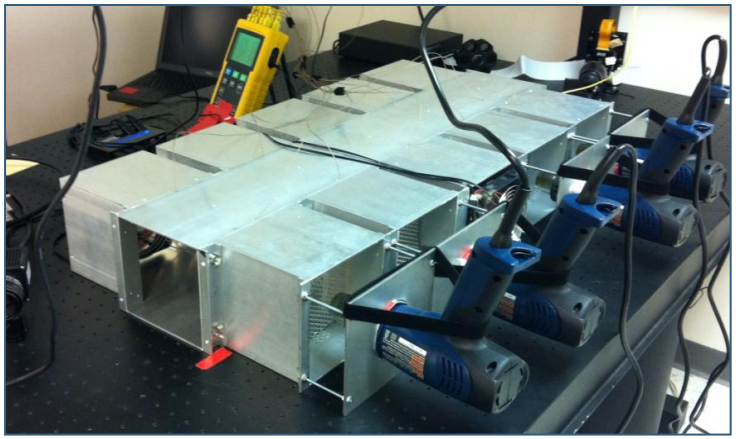
Case	N_f	D_S/ρ_0	σ_I^2	T_1	# Fades	80/100	Avail.
A	0.1	0.2	0.012	6	294	7 to 22 ms	98.1%
B	1.0	0.3	0.014	2	1622	2 to 9 ms	96.7%
C	0.1	0.2	0.011	12.9	416	4 to 30 ms	98.7%
D	1.0	0.3	0.010	2.6	1281	2 to 12 ms	97.5%

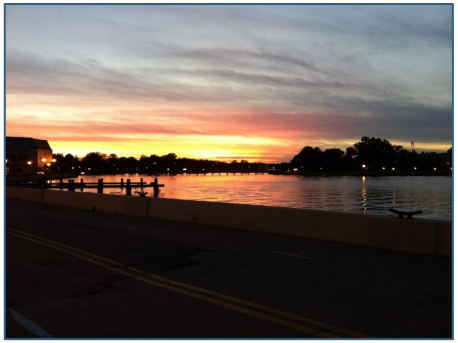
TE Comparison with over the creek

γ_φ^2 (pixels^2)	σ_I^2	% Diff.
Black (Coherent, ~512^2)	0.0111	N/A
1 (Strong diffuser)	0.0134	20.4
2	0.0159	42.9
4	0.0096	-13.7
8	0.0127	14.2
16	0.0099	-11.0
32	0.0105	-5.6
64	0.0190	70.8
128 (more weakly diffusing)	0.0318	185.8



T-Test → $p_{16} = 0.02$, $p_4 = 0.22$





Conclusions/Discussion

- Possible scintillation index ‘sweet’ spot, that depends on range and atmospheric characteristics
- PDF and 2nd order temporal Autocovariance in combination can possibly provide important information about fade statistics – notably, that a shorter correlation time leads to a higher number, but shorter duration fades

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