PDF COMPUTATIONS FOR POWER-IN-THE-BUCKET MEASUREMENTS OF AN IR LASER BEAM PROPAGATING IN THE MARITIME ENVIRONMENT

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Sponsors: United States Naval Academy
Office of Naval Research, Counter Directed Energy Weapons Program
The Johns Hopkins Applied Physics Laboratory and
The Johns Hopkins University

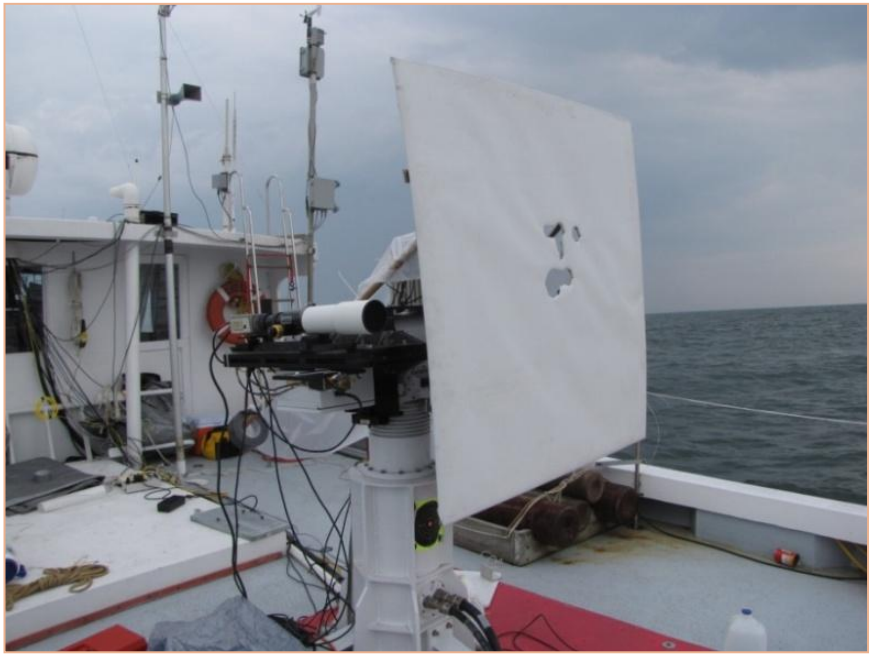
Introduction

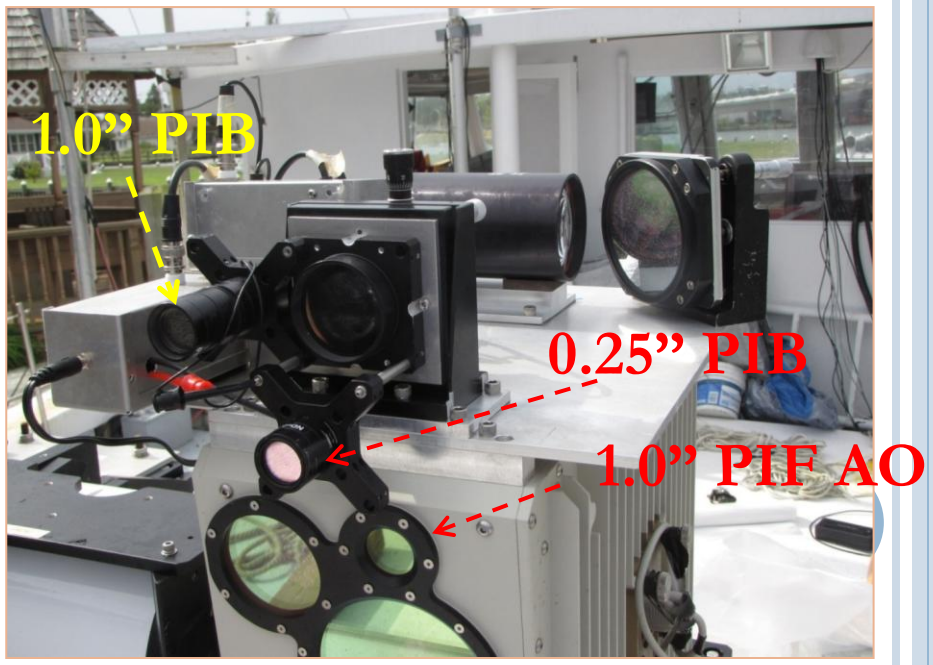
- Field Test off of Atlantic Coast
- 2 – 22 km optical horizon
- Bi-directional shore-to-ship data link between old 56' Coast Guard lookout tower and JHU Applied Physics Laboratory (APL) research vessel, "Chessie".

Movie Clip

Experimental Set-up

- 1.0” Adaptive Optics (AO) Power-in-Fiber (PIF) as will as 0.25” and 1.0” Power-in-Bucket (PIB).
- IR images were collected on screen attached to “Chessie” tracking mount





Goals:

Can we best determine the PDF in the maritime environment as a:

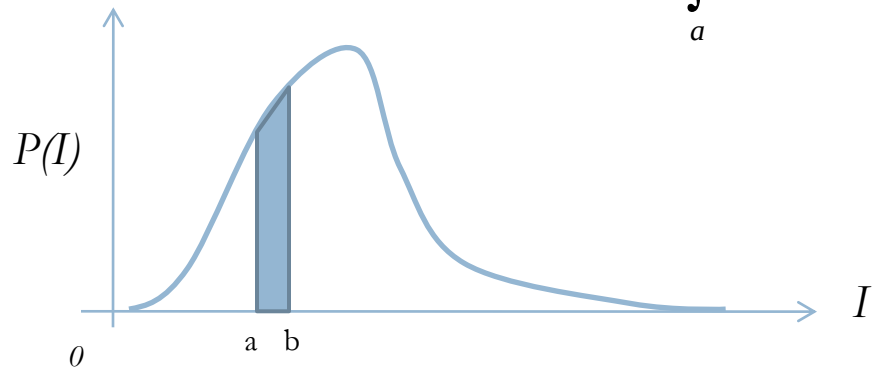
- 1) Function of propagation distance
- 2) Function of three optical detectors – 0.25”, 1.0”, as well as for a 1.0” Adaptive Optics (AO) Terminal
- 3) Function of varying levels of optical turbulence.

Theory and Experiment

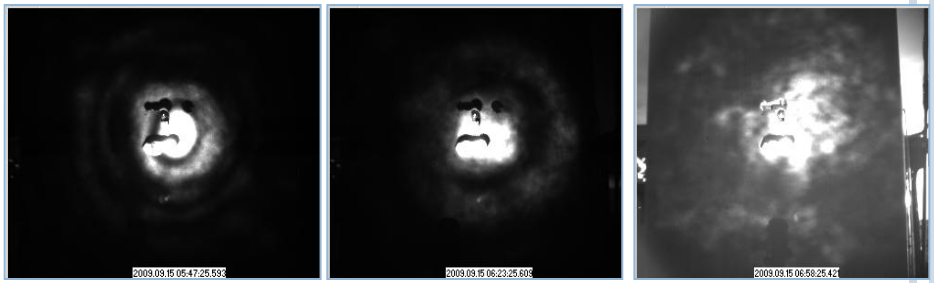
- Understanding the PDF is a critical link for Free Space Optical Communications (FSO) through the bit-error rate (BER)
- The IR profiles highlight the rapidly varying nature of the intensity profile of a propagating laser beam in the maritime environment.

Movie Clip
July data

$$\text{Probability}(a < I < b) = \int_a^b P(I)\,dI$$



5.1 km — Relatively benign — 17.8 km



The challenge of the Maritime Environment

Theory and Analysis

- Gamma-Laguerre (GL)
  - Medium and source independent, no free parameters
  - Uses first n moments
- Gamma-Gamma (GG)
  - Free parameters related to medium
  - Source, medium dependent
  - Uses first two moments
- Lognormal (LN)
  - Classical weak turbulence model

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

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

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

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

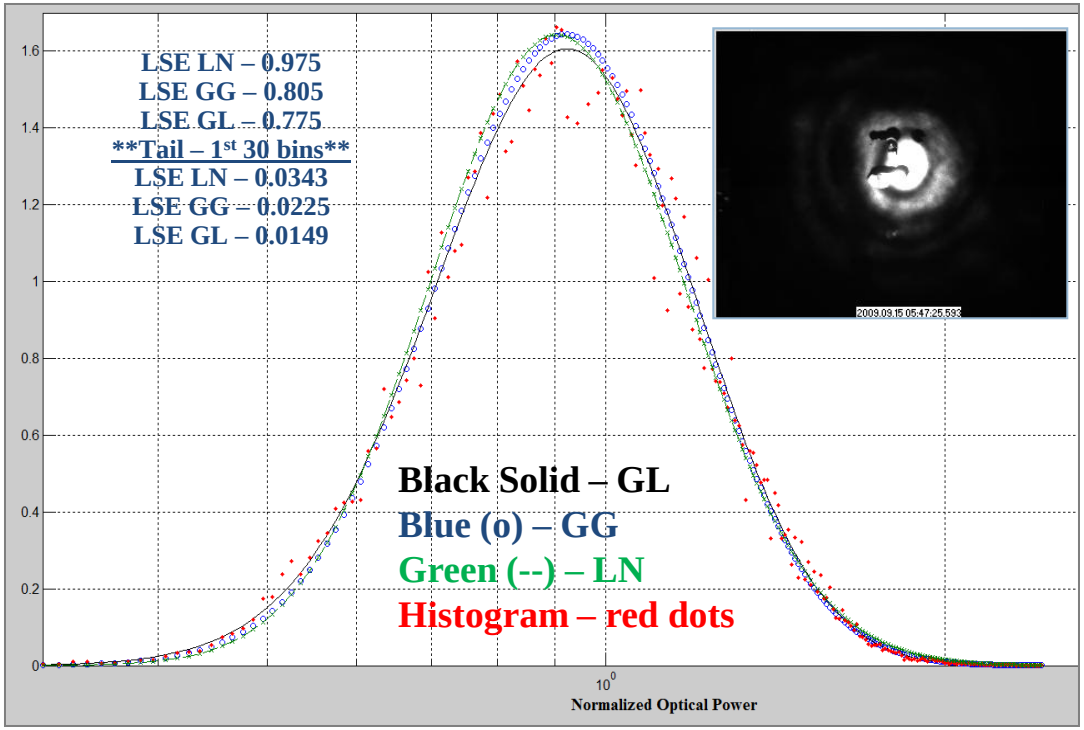
$$W_{LN}(I) = \frac{1}{I\sigma\sqrt{2\pi}} exp\left[-\frac{[\ln(I)-\mu]^2}{2\sigma^2}\right], I > 0$$

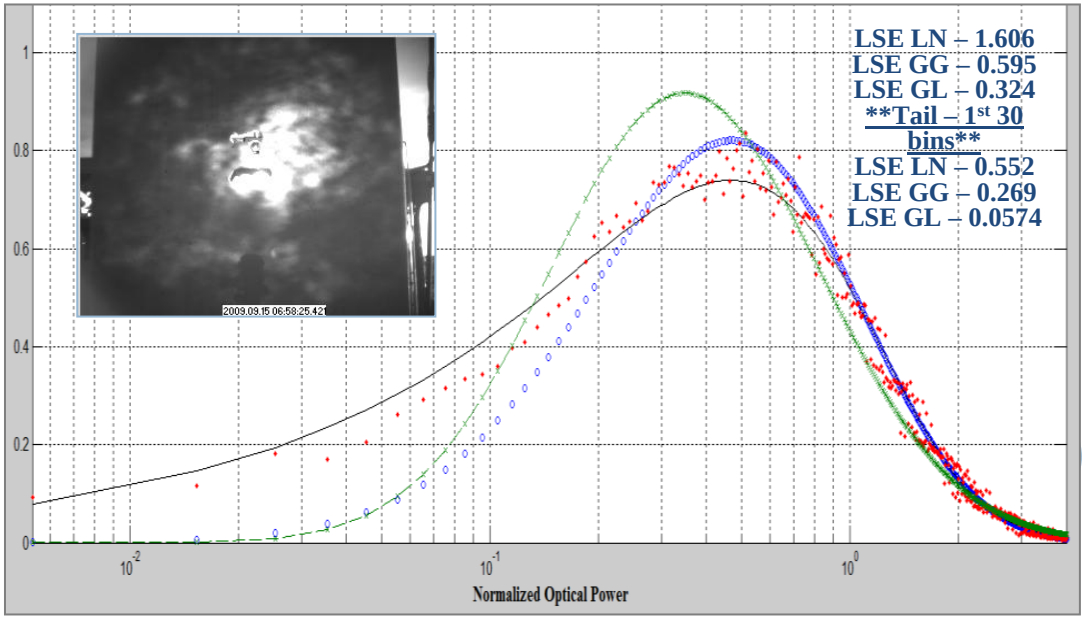
- $\mu = \langle \ln(I)\rangle$
- $\sigma^2 = var(\ln(I))$

Experimental Data/Results

- Low Turbulence – ($C_n^2 \sim 1.5*10^{-14}\ m^{-2/3}$)
- 1.0" PIF AO
- 5.1 km to 17.8 km
- Good data fits in low turbulence across all of the distributions
- Note – this is aperture averaged data

GL had best LSE fit

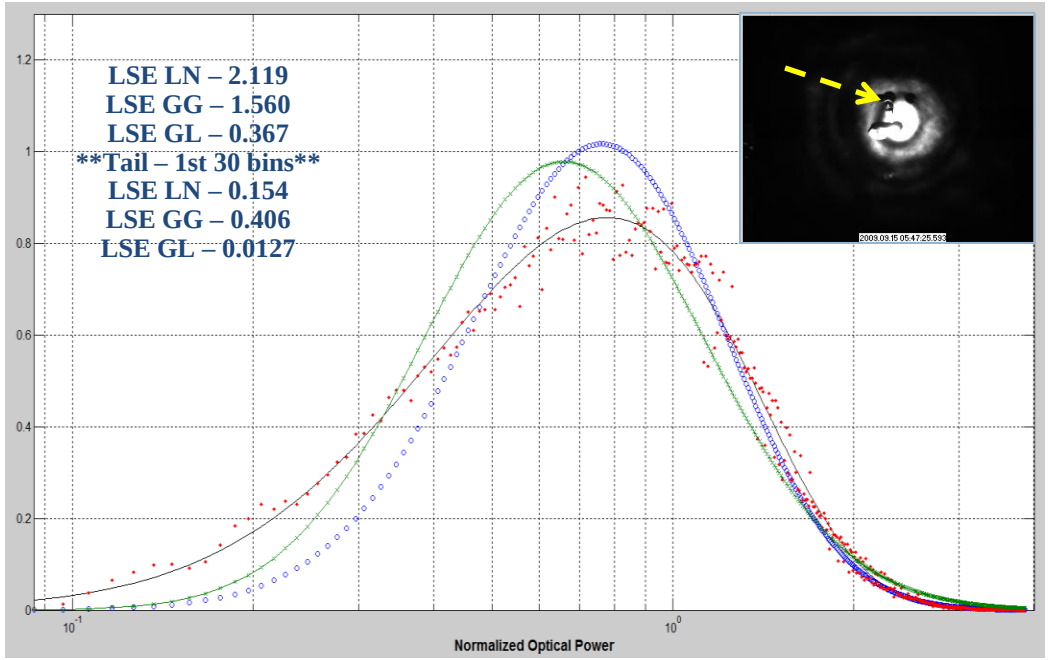


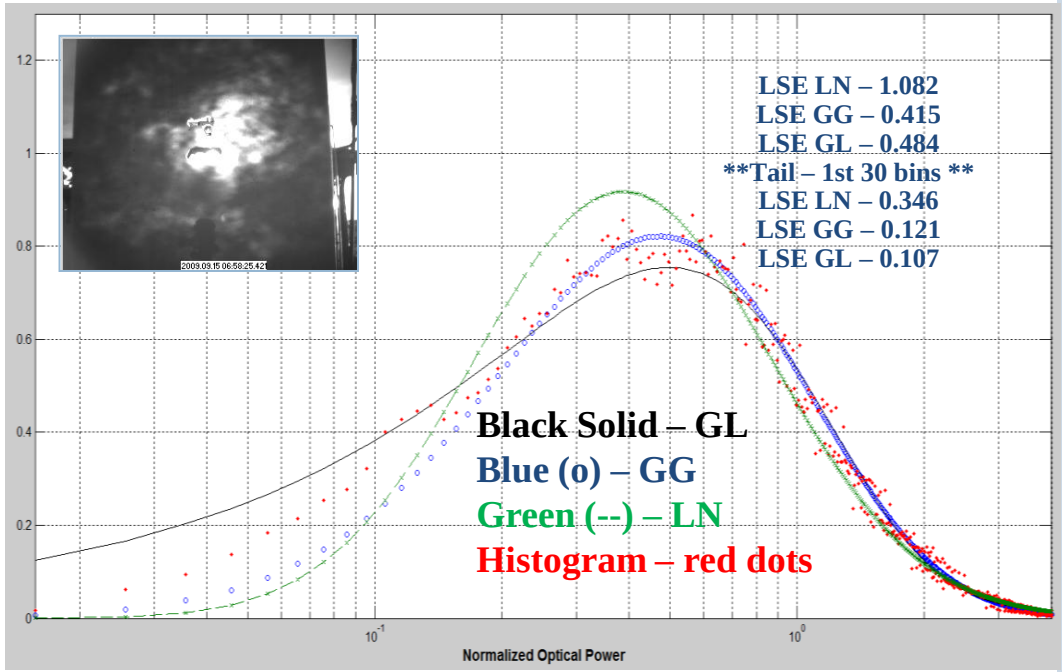


Experimental Data/Results

- Low Turbulence
- 0.25” PIB
- 5.1km to 17.8 km
- At short range, 0.25” PIB detector is on the fringes of beam (yellow arrow) – GL still did well
- Long range GL underestimates peak
- Similar results were seen for the 1.0” PIB

GG - best overall fit (17.8 km)
GL – best tail fit (17.8 km)





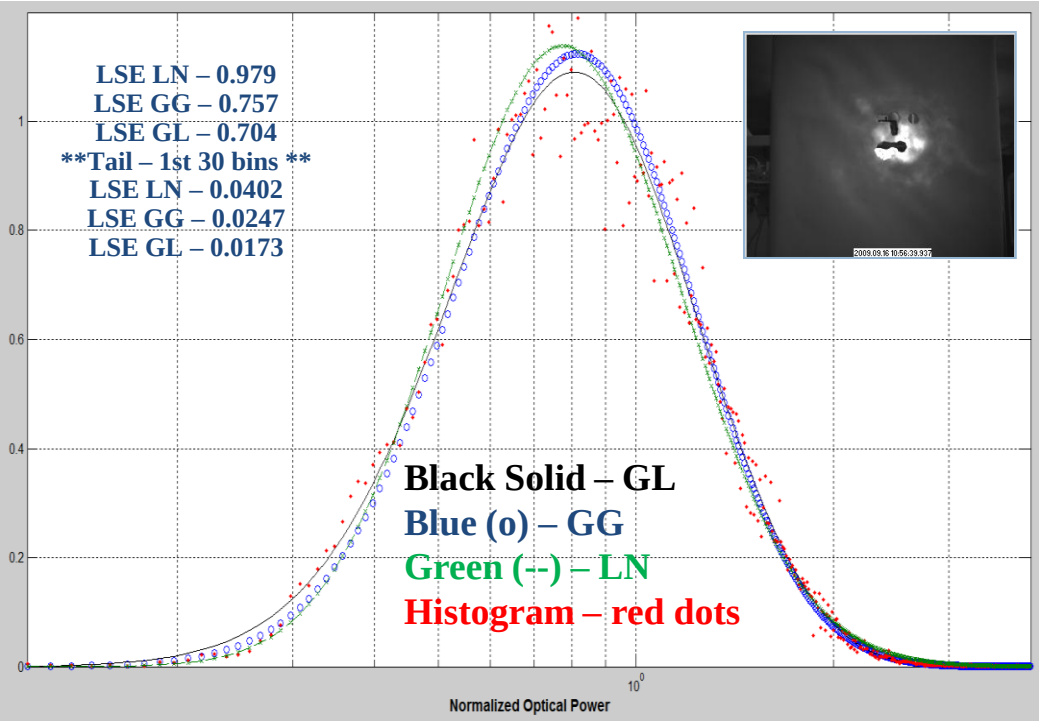
Experimental Data/Results

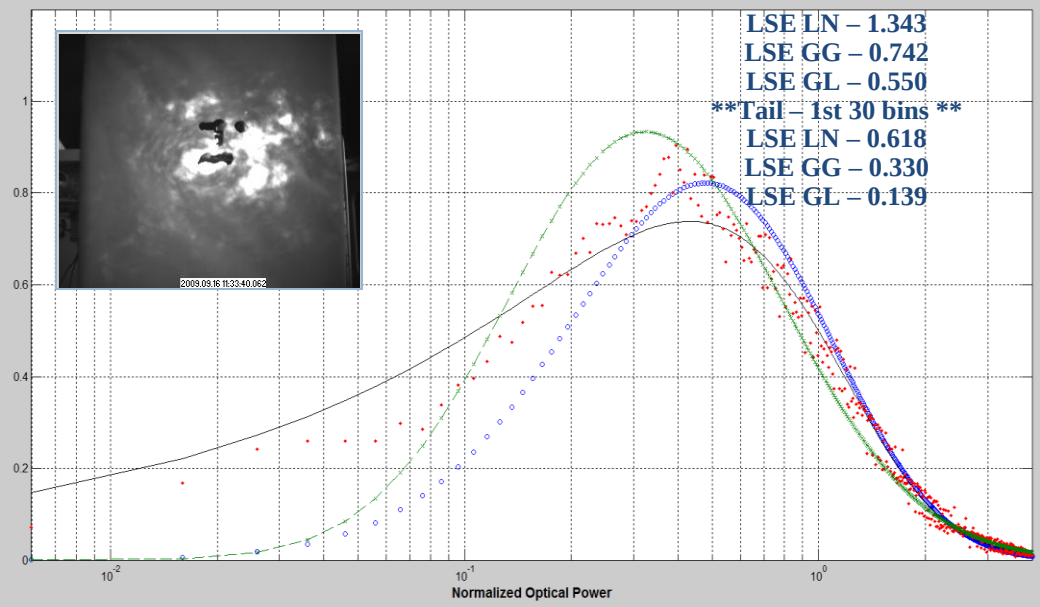
- Low to moderate turbulence,

($C_n^2 \sim 8*10^{-15}\ m^{-2/3}$ and $\sim 4*10^{-14}\ m^{-2/3}$

- 1.0" PIF AO
- 6.9 km to 10.5 km
- Good fits by all modeled distributions at short range with noticeable spread at longer range

GL – overall best LSE fit

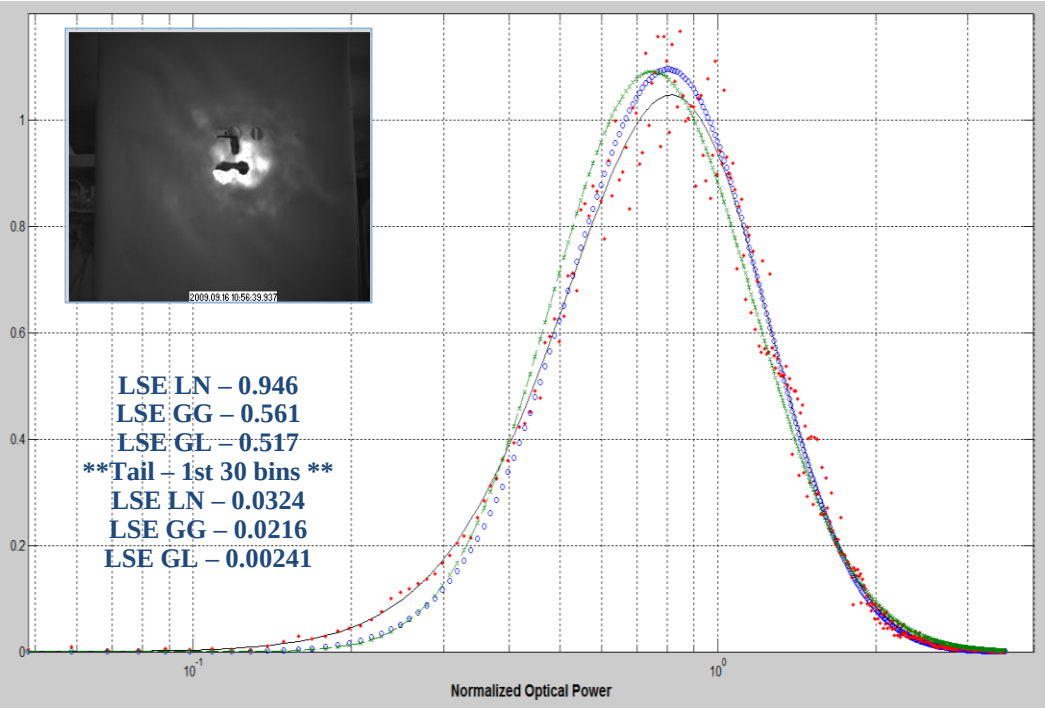


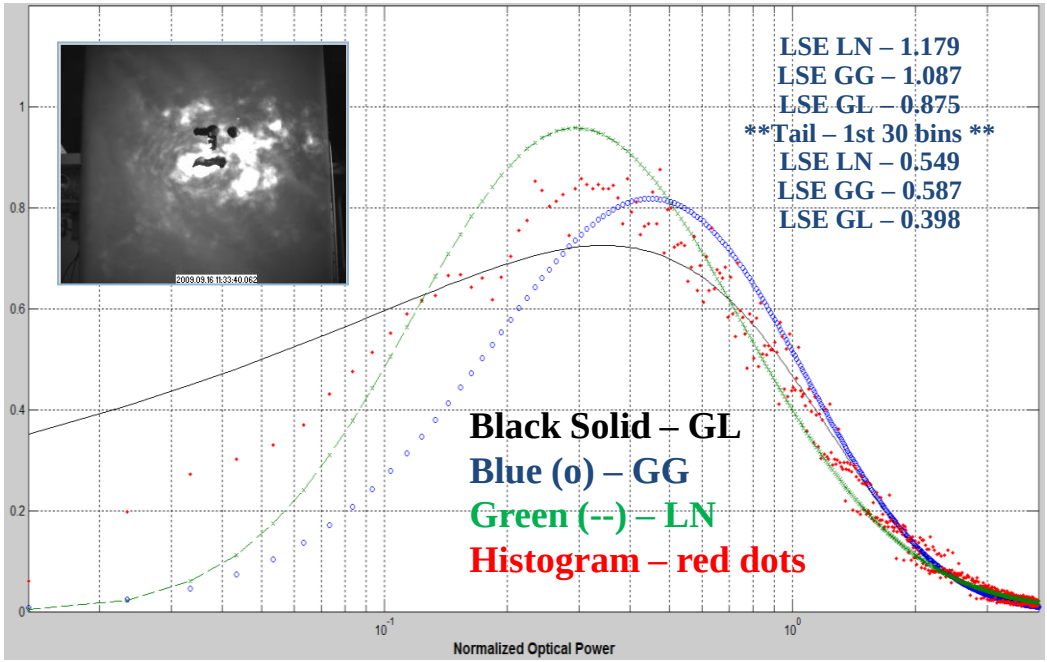


Experimental Data/Results

- Low to moderate turbulence
- 0.25” PIB
- 6.9 km to 10.5 km
- Good fit at short range with larger spread at longer range
- GL understimates the peak (this is mentioned in paper by Barakat)

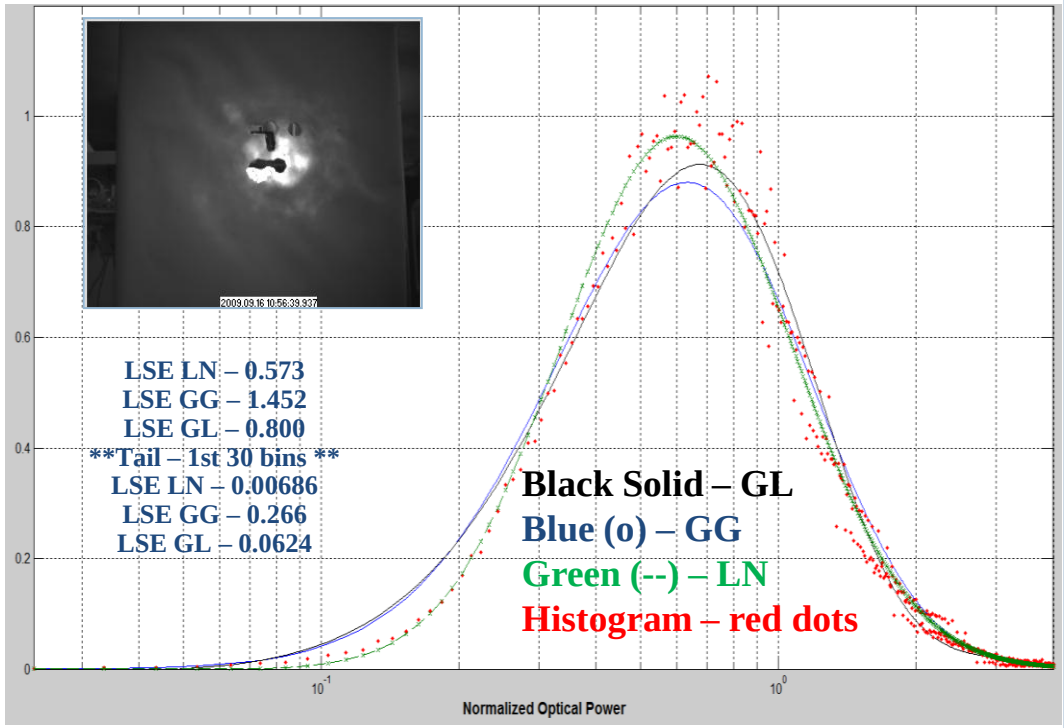
GL – overall best LSE fit





Experimental Data/Results

- Low to moderate turbulence
- 1.0” PIB
- 6.9 km
- The 1.0” PIB in this region had a very good Lognormal fit – this can be reasonably expected from additional aperture averaging where the small scale fluctuations are averaged out, leaving the large scale distribution



LN – overall best LSE fit

Conclusions/Discussion

- Three PDF models (LN, GG, GL) and their fits to data collected in the maritime environment
- Low turbulence
  - Excellent fits by all models at short range for 1.0” PIF
  - Good LN fit supports historical for distribution in regions of weak irradiance fluctuation
  - Off axis robustness shown by GL for the 0.25” PIB
- Low-moderate turbulence
  - Similar distributions in 0.25” PIB vs. 1.0” PIF (possible sm fiber acting as a spatial frequency filter)
  - GL showed overall best fit – exception 1.0” PIB (LN)
- Detector size
  - Aperture averaging in 1.0” PIB → LN (large scale PDF)

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