National Aeronautics and Space Administration

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Measurements of few-mode fiber photonic lanterns in emulated atmospheric conditions for a low earth orbit space to ground optical communication receiver application

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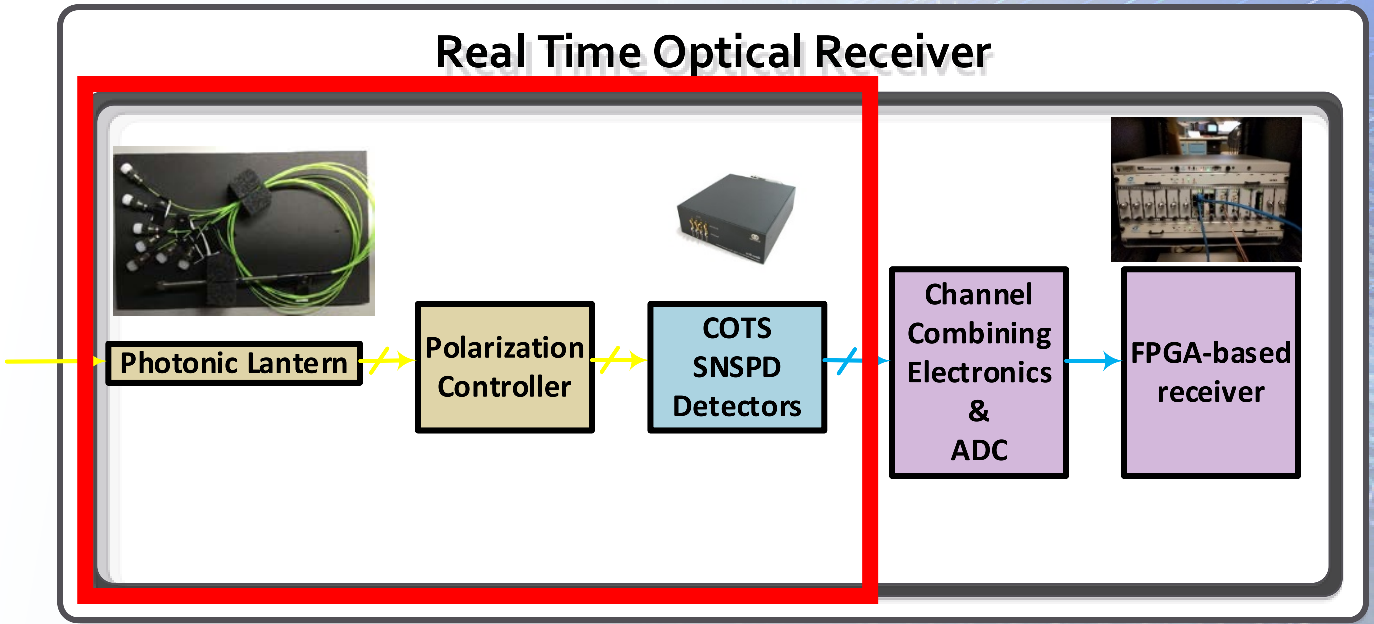
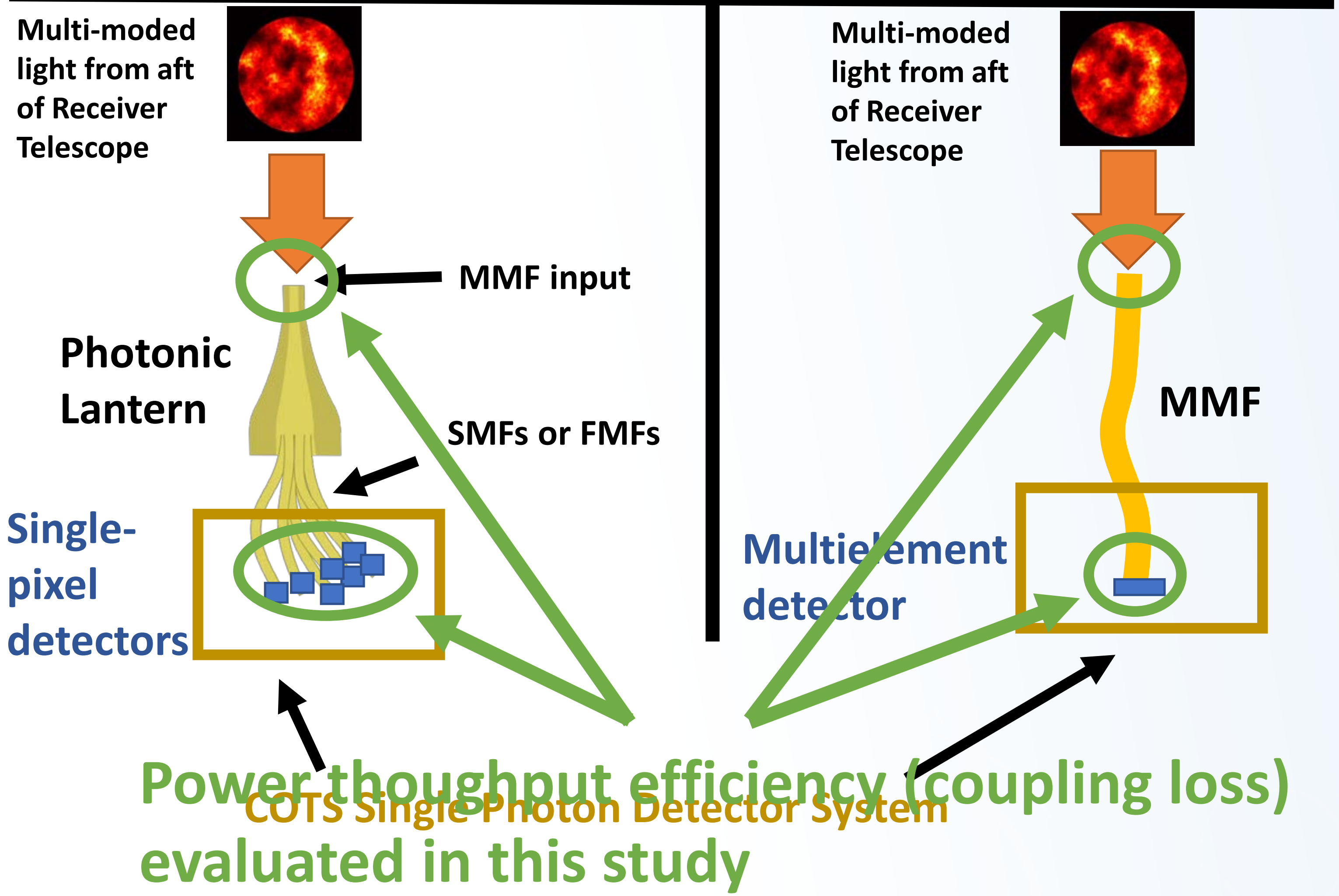
Introduction

- **NASA GRC is developing a low cost scalable photon counting optical ground receiver that includes:**
  - **Fiber optic devices to deliver light to detectors**
  - **Commercial of the shelf single photon counting detectors**
  - **Real time FPGA-based receiver compliant with CCSDS HPE Standard**



Fiber/Detector architectures under evaluation

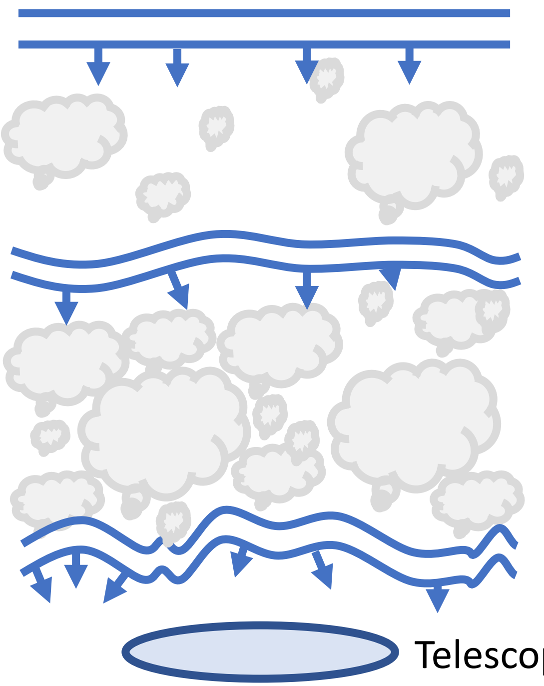
Photonic Lantern to multiple single-pixel detectors	MMF to a multi-element detector

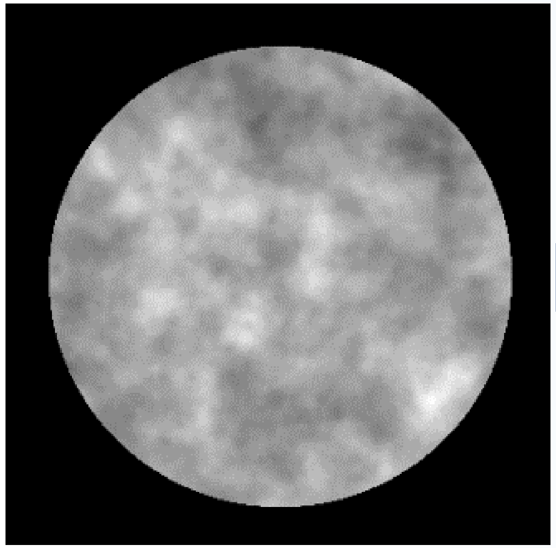


- **Focus of this study**
  - **Fiber devices**
  - **Evaluate main purpose: efficiently deliver light to detectors**
    - > Measured power throughput efficiency
    - > Coupling loss to detector NOT included
  - **Case study of emulated atmospheric conditions:**
    - > Low earth orbit
    - > 60 cm receiver telescope aperture
    - > Range of turbulence levels:
      - (r_0=7-50 cm → D/r0 = 1.2-8.6)

Creation of emulated atmospheric conditions

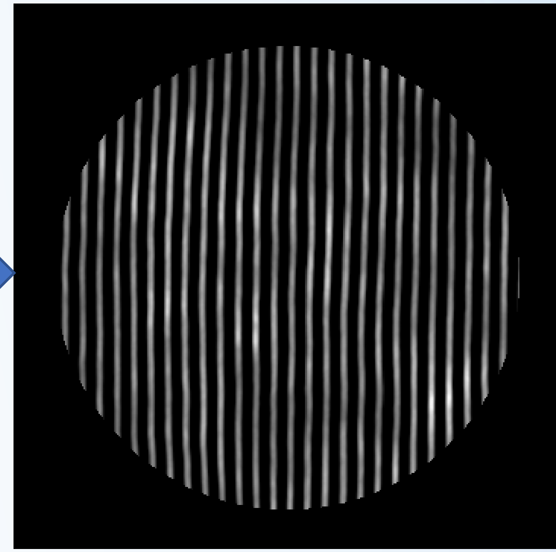
Simulation

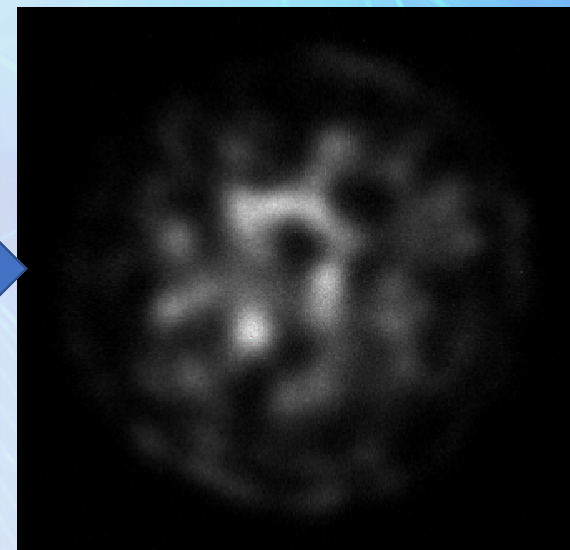



Simulated Intensity

- **Optical turbulence is modeled with phase screens distributed based on the Hufnagel-Valley turbulence strength profile.**
- **Simulation model verified.**
- **Details in: Chahine et al,** "Beam propagation through atmospheric turbulence using an altitude-dependent structure profile with non-uniformly distributed phase screens", **Tuesday poster session.**

Emulation


Phase Hologram


Emulated intensity

- **Complex amplitude phase hologram created from simulated wavefront.**
- **Hologram applied to beam with spatial light modulator generates emulated wavefront.**
- **Emulation accuracy not fully verified**
- **Results preliminary**

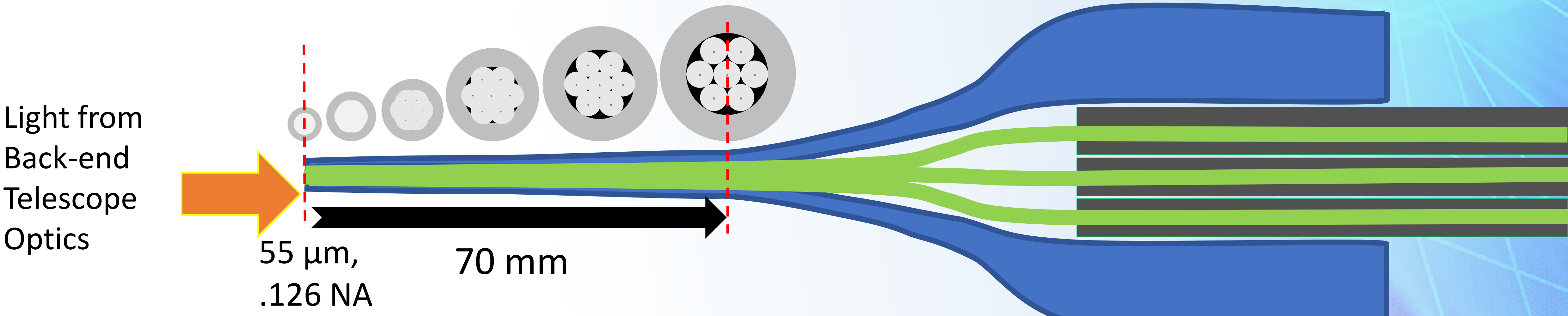
Fiber devices tested

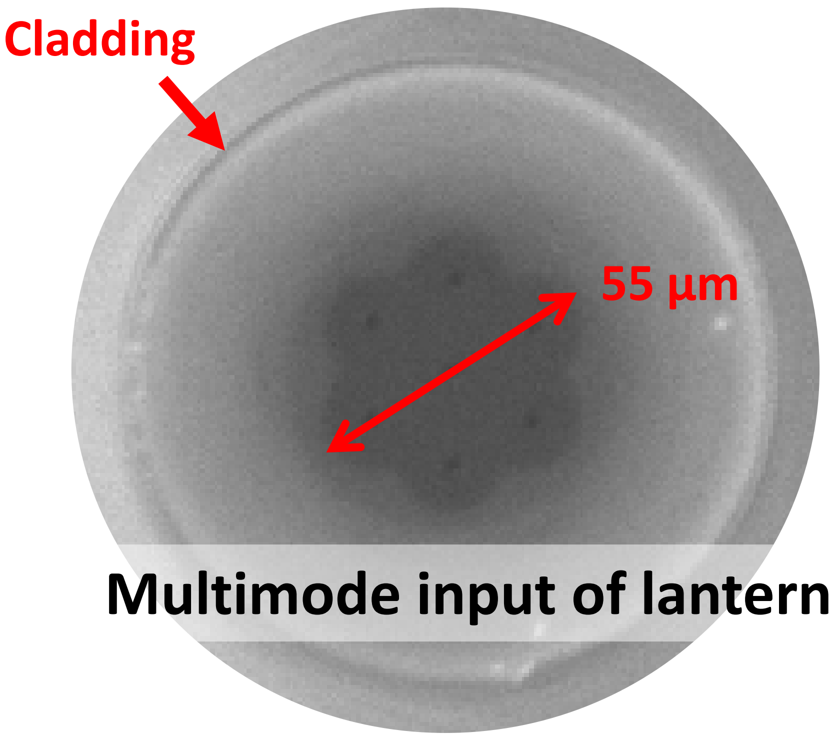
Fiber Device	Core Size, µm	# of modes supported
Graded Index Multi-Mode Fiber	30	15
7:1 Single-mode fiber lantern	30	7
7:1 Few-mode fiber lantern	55	41

- **Power throughput efficiency of fiber devices depends on number of supported modes**
  - Light arriving to the telescope is multi-moded
  - Energy scattered into higher-order modes
- **Standard photonic lanterns (single-mode fiber)**
  - 1:1 output leg to mode ratio. Ex: 7 legs → 7 modes
- **New few-mode fiber lanterns:**
  - Increase modes supported by each output leg
  - Enables higher number of modes with same number of detectors. Ex: 7 legs → 42 modes

7:1 Few-Mode Fiber Photonic Lantern

Leon-Saval et al, Opt.Exp. 18, 8430 (2010); Noordegraaf et al, Opt.Exp 17, 1988 (2009)

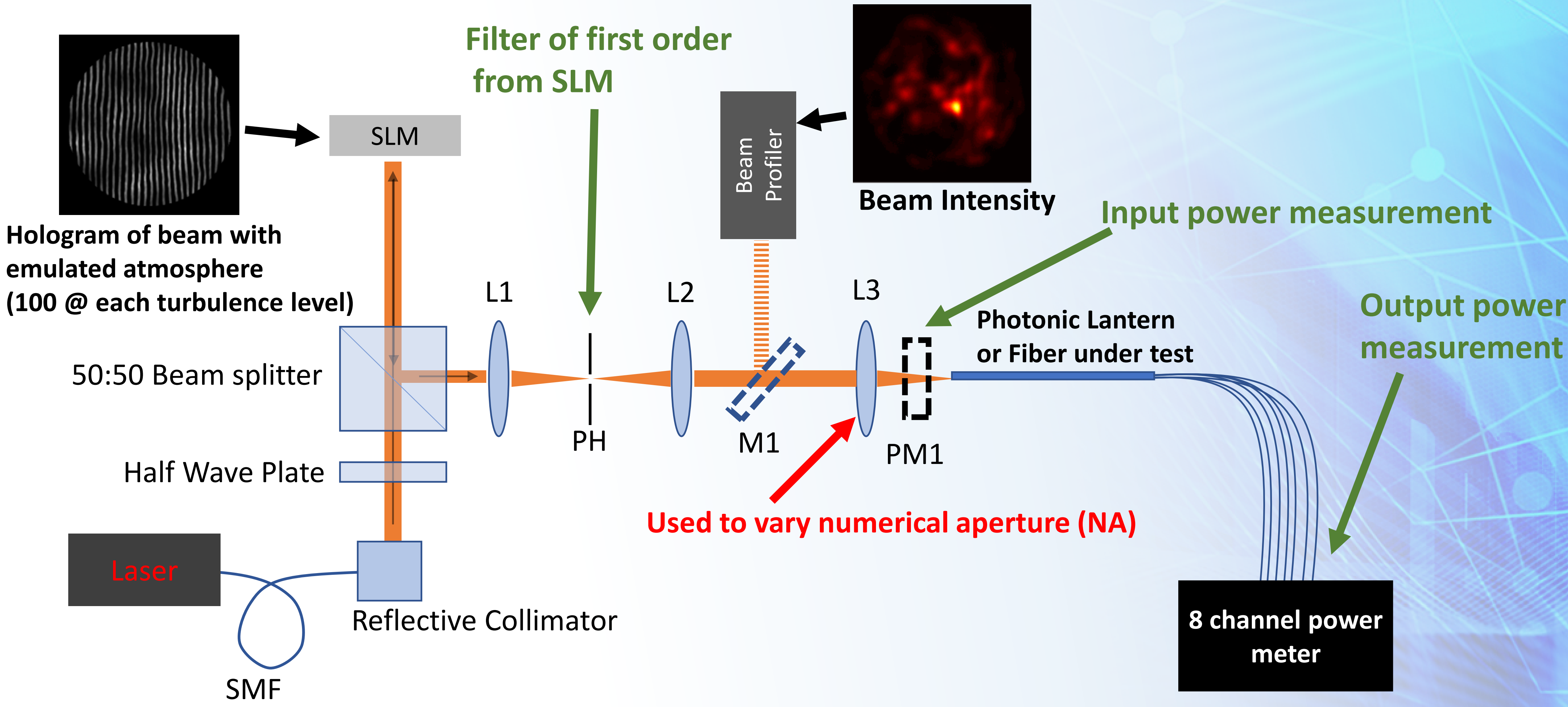




Multimode input of lantern

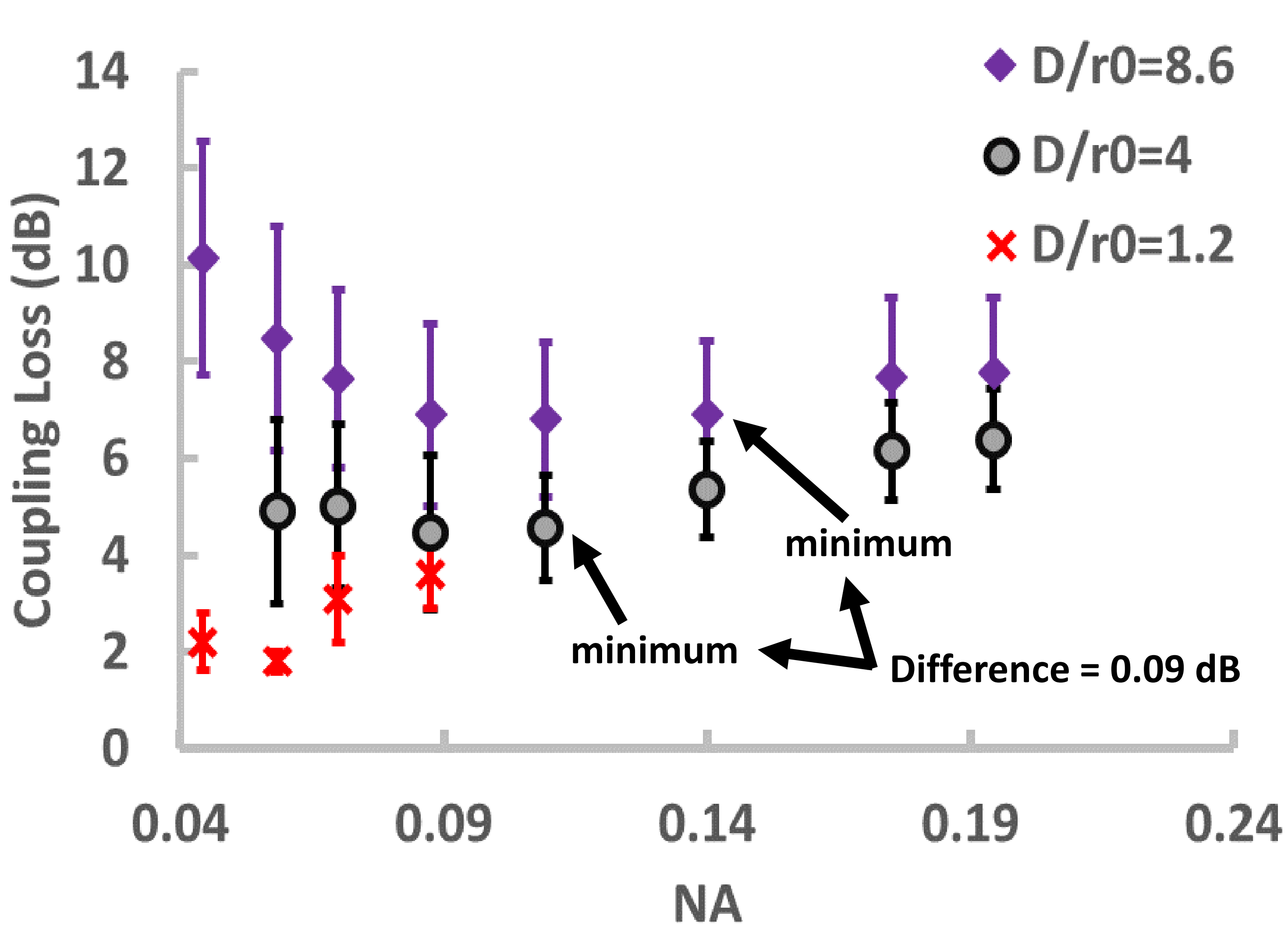
- **Made at NASA GRC**
- **Made with graded index few-mode fibers**
- **Each couples 1^{st} 6 fiber spatial modes**

Experimental setup for coupling efficiency



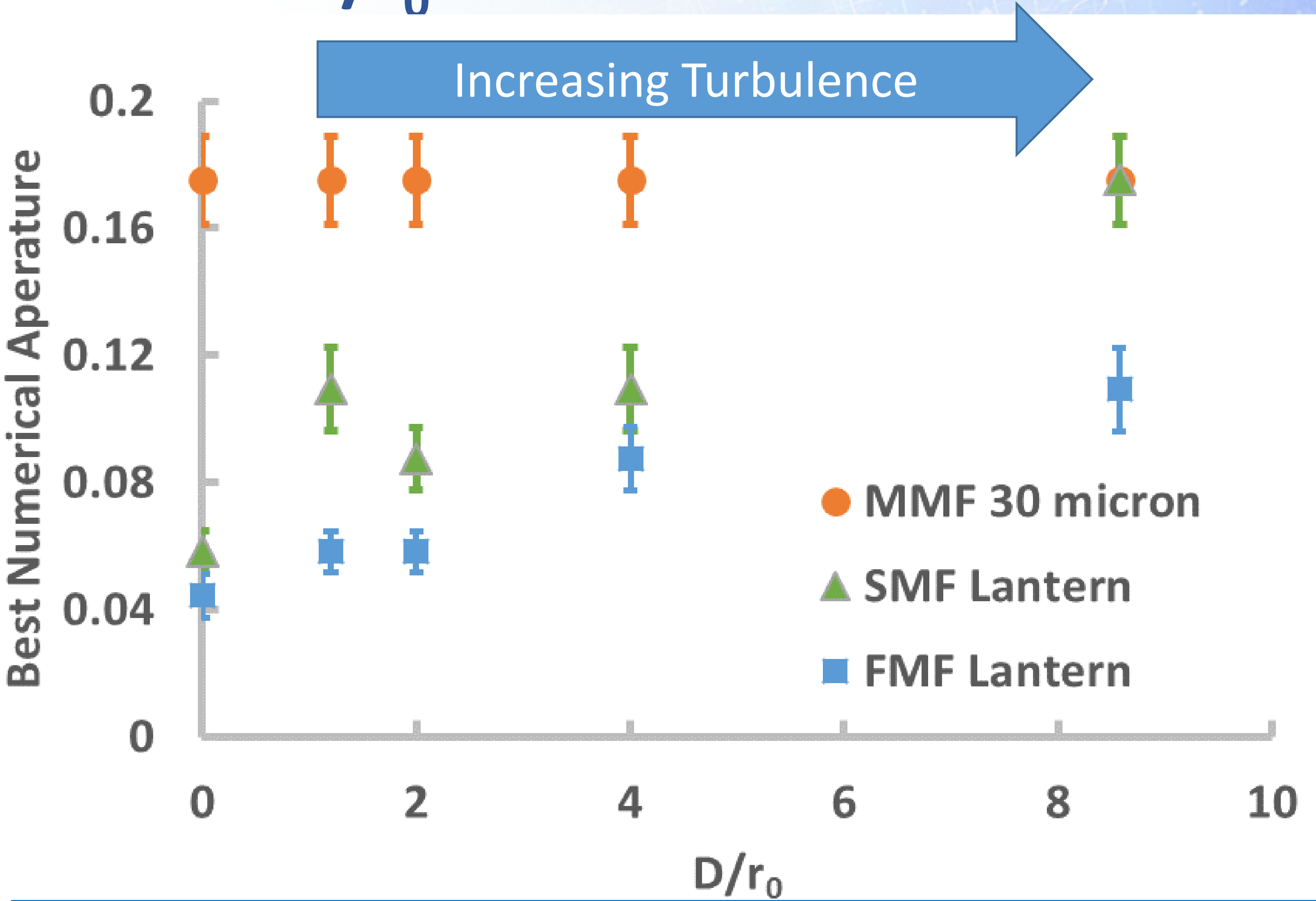
Test setup measures efficiency of lanterns and fibers over a range of input numerical apertures and emulated turbulences levels.

FMF Lantern coupling loss over a range of input numerical apertures at a few emulated D/r_0's



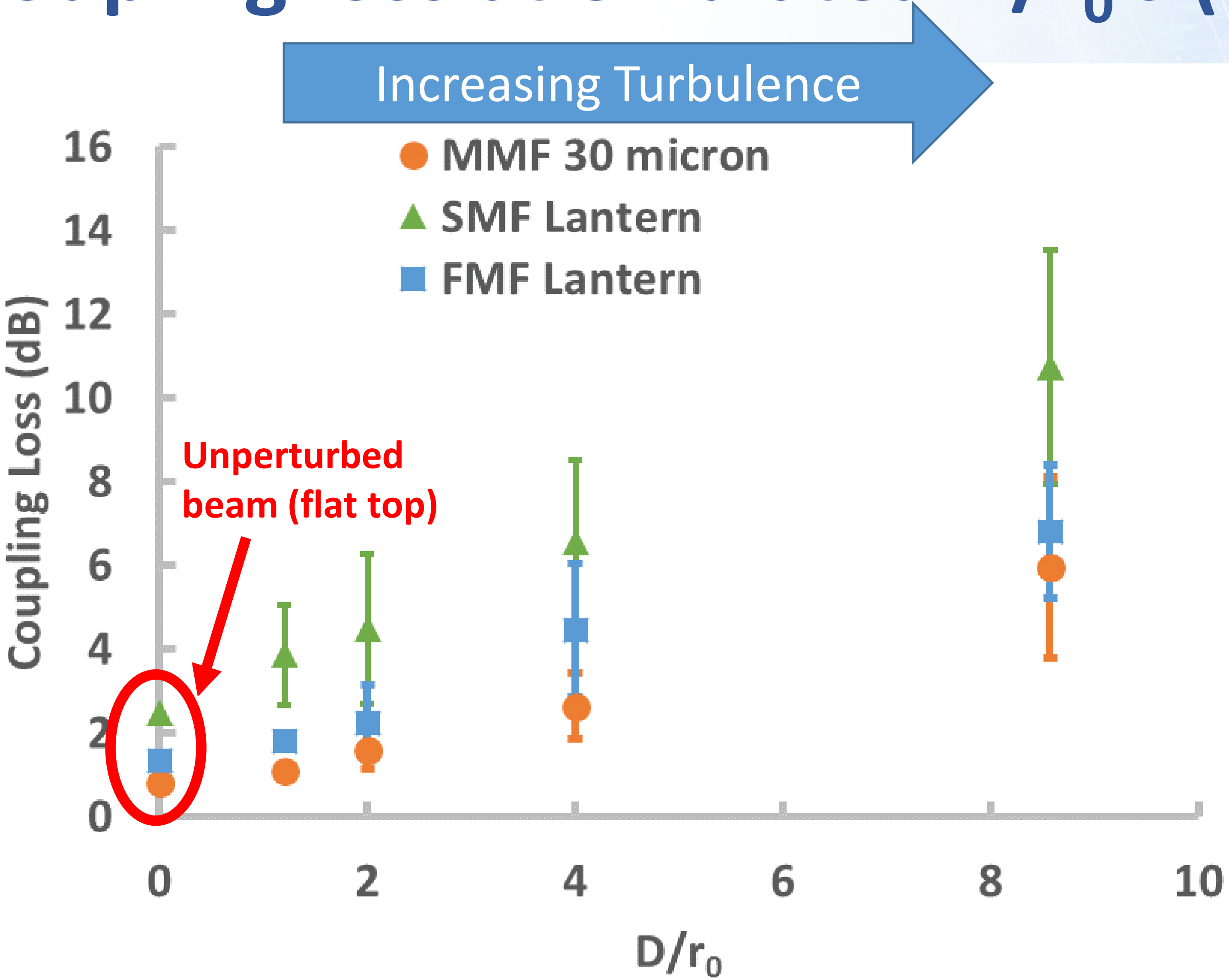
The input NA at which the FMF lantern minimum coupling loss occurs depends on the emulated D/r_0. This indicates a fixed optical design wouldn't be ideal for a FMF Lantern.

Best input numerical aperture for minimum coupling loss versus D/r_0



The GI-MMF's best coupling NA is independent of D/r_0.
The lanterns' best NA is dependent on D/r_0.

Coupling loss at emulated D/r_0's (at best input NAs)



D/r_0	Gain Relative to the SMF Lantern (dB)	Loss Relative to the GI-MMF (dB)
8.6	3.92	0.86
4.0	2.10	1.83
2.0	2.25	0.66
1.2	2.07	0.69
0	1.17	0.53

Results shown at each devices' NA with minimum coupling loss.
FMF lantern coupling losses: between SMF lantern and GI-MMF.

Conclusion

- A preliminary case study of a 60 cm diameter telescope receiving light from low earth orbit was performed for two types of lanterns and a GI-MMF.

- Best input NA→ Lanterns are dependent on the atmospheric condition.

- Emulated turbulence →
  - FMF lantern had increased coupling efficiency over SMF lantern
  - FMF lantern have slightly less coupling efficiency than a 30 micron GI-MMF.

- Future Work on FMF lanterns
  - Study dependence on input NA
  - Refine design and fabrication process to reduce losses.
  - Perform system-level comparison to GI-MMF with corresponding detectors

Acknowledgements

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