RPC 2020

Virtual Research Presentation Conference

FIBER COUPLING TELESCOPE AND DETECTOR FOR DEEP SPACE OPTICAL COMMUNICATION DOWNLINK GROUND STATION

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Abstract

In this project we investigated the possibilities and options for using an optical fiber to couple light from a large telescope, to a fast photodetector in a way compatible with existing and future deep space optical communications projects. The problem with this is multi-faceted: the optical fiber must be large enough to collect a significant portion of the light, and it must transmit pulses to the detector without significant temporal broadening.

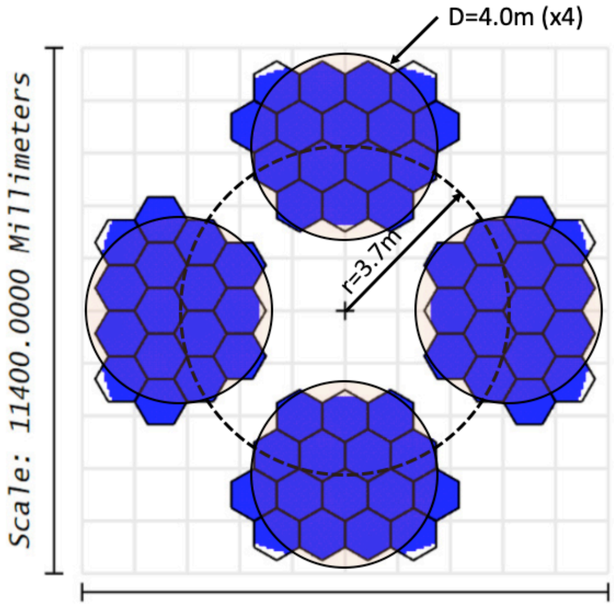
We used simulations to come up with requirements for candidate optical fibers, and a fiber was procured for testing. However, due to the COVID-related lab closure, we were not able to complete the testing of the fiber under this task. Still, the tools and requirements developed under this task should be useful for future optical communications projects.

Problem Description

- Large diameter (8-12 m) optical telescopes are needed in order to enable high bandwidth downlinks using optical communication for deep space. Light collected by these telescopes need to be coupled to a high-speed photodetector.
- The state of the art photodetector for optical communication applications is the superconducting nanowire single photon detector (SNSPD), This JPL-fabricated detector, need to be operated inside a multi-stage cryostat, with a helium fridge to reach the 1 Kelvin operating temperature.
- Continuously operating detector in a non-stationary location, such as the Prime- or Cassegrain focus of a large telescope, is not desirable.
- Coupling light from the telescope to a stationary detector assembly using an optical fiber, would significantly reduce risk and cost.
- However, coupling light from a large telescope into an optical fiber is not straightforward. The optical wavefront is distorted by the atmosphere, causing the spot at the telescope focus to be enlarged. Also, propagating in a multi-mode optical fiber is associated with temporal broadening of the pulse. These issues have to be investigated and weighed against each other in order to find out optical fibers are a viable option to enable a stationary and remote detector assembly placement.

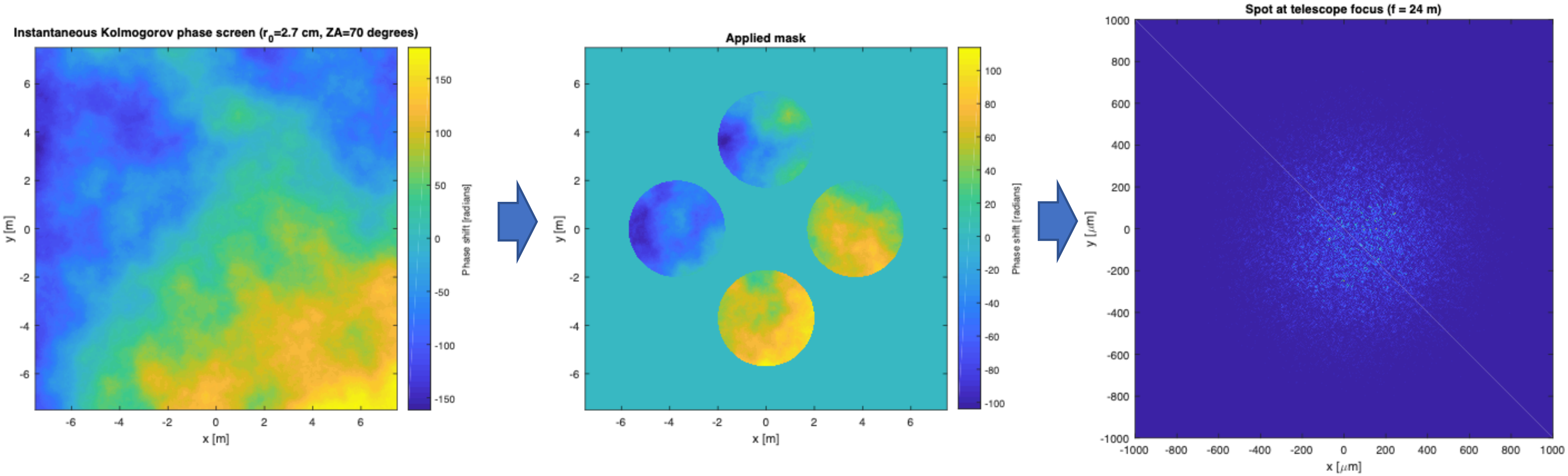
Methodology – Fiber coupling

- A custom Matlab code was developed to study the fiber coupling portion of the problem.
- The future RF-optical hybrid telescope was selected as the test case for the problem. The 90th percentile worst case atmospheric seeing at Goldstone was used to represent adverse conditions (r=2.7cm, ZA=70deg).
- The fiber NA was set to 0.21 (common for large core GRIN fibers), which resulted in a telescope EFL = 24 m.



RF-optical hybrid telescope. The 4 groups of hexagonal elements were approximated with four D=4.0 m circular sub-apertures.

Fiber coupling simulations



Instantaneous Kolmogorov phase screen (r_0=2.7 cm, ZA=70 degrees)

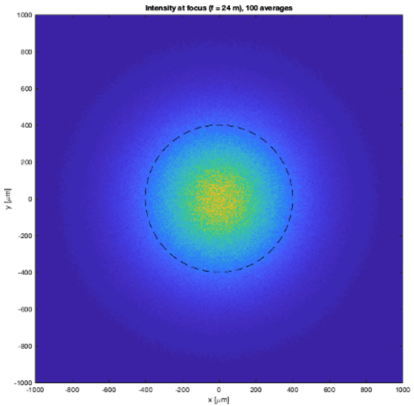
Applied mask

Spot at telescope focus (f = 24 m)

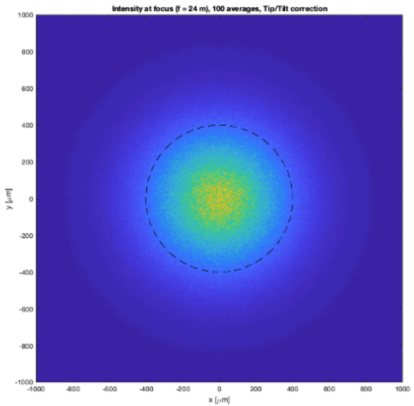
- The code generates a random static Kolmogorov phase screen, applies a mask corresponding to the telescope aperture, and propagates the optical wave through an ideal telescope. The simulation was repeated 100 times per case to generate long term average spots.
  - The instantaneous spots were averaged with and without tip/tilt correction in order to understand the benefit of implementing a tip-tilt correction system.

Results – Fiber coupling

- The results from the simulations are shown to the right.
- We learn three things from these results:
    - The long term average spot size is marginally improved by a tip-tilt correction scheme
    - The theoretically predicted spot size (676 µm) is very close to the simulated 679 µm
    - A 800 µm core diameter fiber encircles only 60% of the energy (this serves as an upper bound for the coupling efficiency)

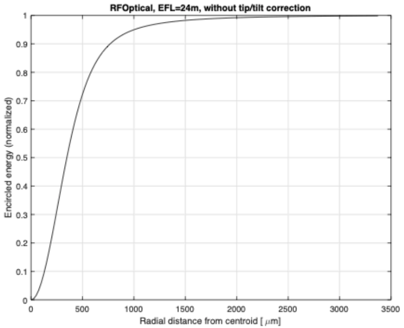


No tip/tilt correction
FWHM = 679 µm

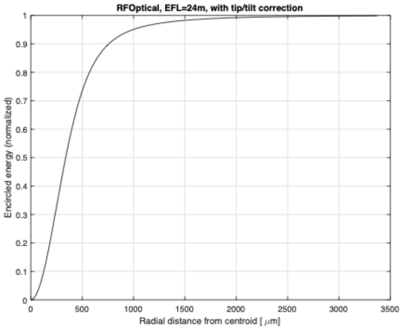


With tip/tilt correction
FWHM = 661 µm

Dashed circle = 800 µm diameter

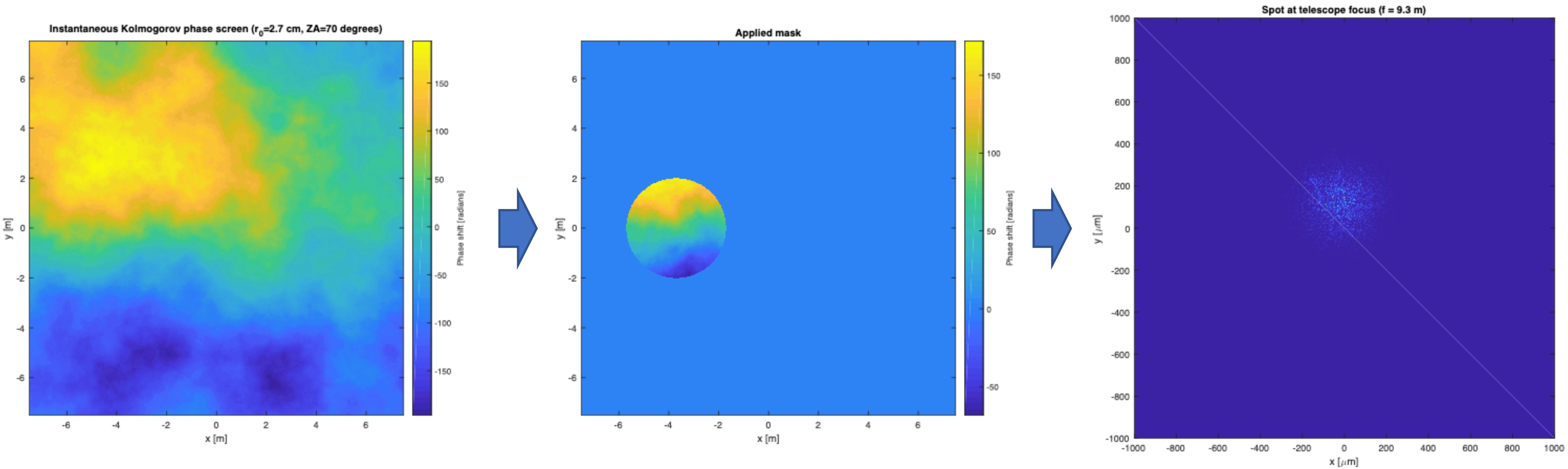


No tip/tilt correction
Energy encircled by 400 µm circle: 22%
Energy encircled by 800 µm circle: 59%



With tip/tilt correction
Energy encircled by 400 µm circle: 23%
Energy encircled by 800 µm circle: 60%

Fiber coupling simulations, pt.2

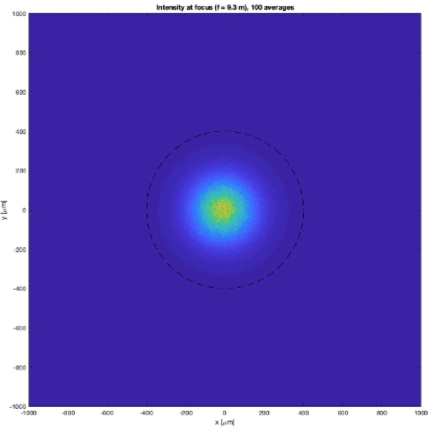


- We repeat the simulation, but instead of coupling all four sub apertures into a single fiber, we couple each sub aperture into its own individual fiber. This way we can reduce the telescope EFL to 9.3 m.

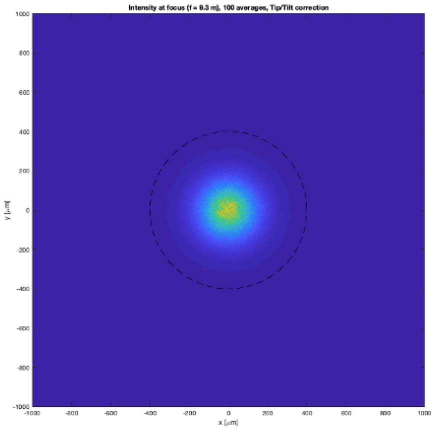
Results – Fiber coupling

- The results from the simulations with a single subaperture are shown to the right.
- Like the previous case, we see that the tip-tilt correction offers marginal improvement.
- The spot size matches the theoretically predicted size (261 µm).
- 75% of the energy is encircled by a 400 µm diameter circle.
    - This is important since 400 µm is a more common fiber core size.
    - Remember that is for an adverse seeing case.

- We conclude that coupling light from sub apertures offer a significant advantage for large diameter telescopes and that a 400 µm core fiber could offer acceptable coupling efficiency.

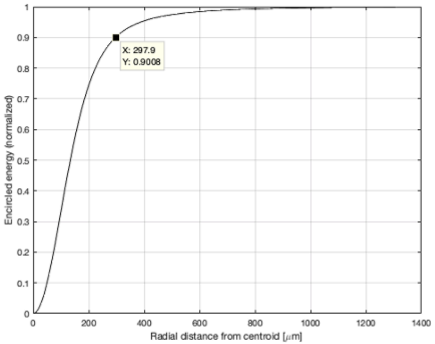


No tip/tilt correction
FWHM = 261 µm

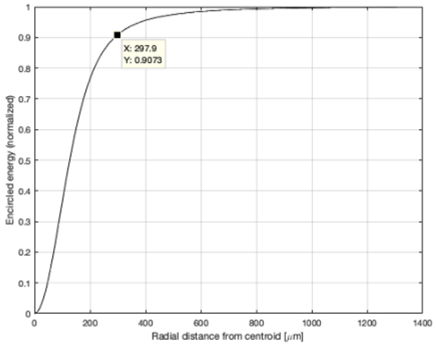


With tip/tilt correction
FWHM = 247 µm

Dashed circle = 800 µm diameter



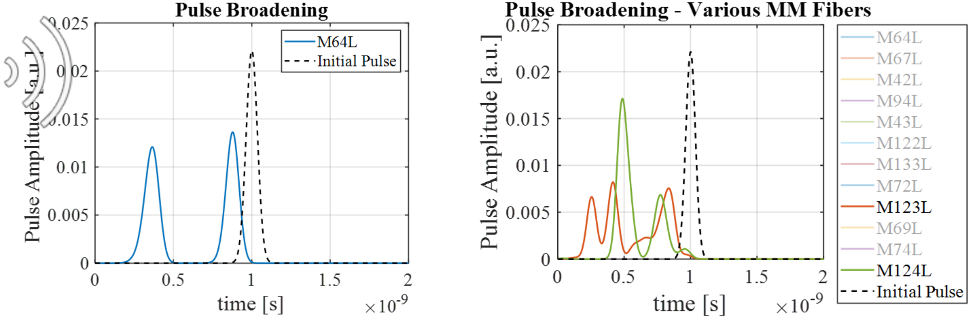
No tip/tilt correction
Energy encircled by 400 µm circle: 75%
Energy encircled by 600 µm circle: 90%
Energy encircled by 800 µm circle: 95%



With tip/tilt correction
Energy encircled by 400 µm circle: 77%
Energy encircled by 600 µm circle: 91%
Energy encircled by 800 µm circle: 96%

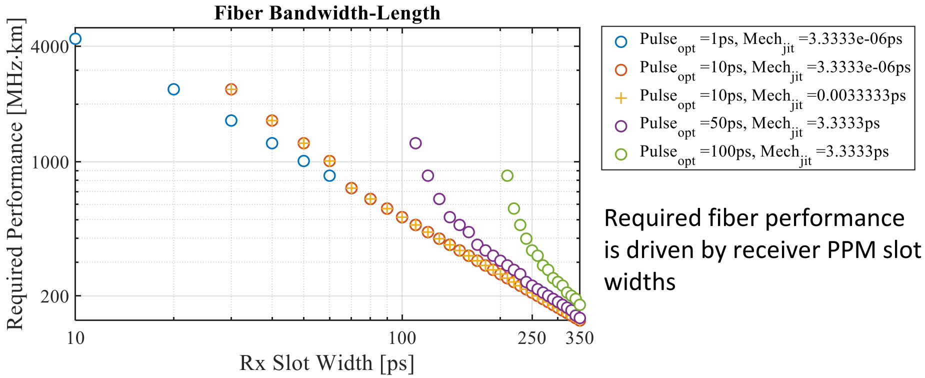
Temporal broadening simulations

- Custom Matlab code was developed to simulate the temporal pulse broadening in step-index MM fibers.
- The results show that the temporal broadening in step-index fibers exceeds realistic slot width for optical communication (<=250 ps)



(Left) For smaller diameter MM fibers, TE & TM modes are broadened and distinguishable. (Right) For larger diameter MM fibers, TE & TM modes are broadened and mixed.

- A second Matlab code was developed to plot the required fiber bandwidth-length product as a function of slot width, optical pulse duration and telescope mechanical jitter.
- For a 75 m long optical fiber, and 250 ps slot width, the minimum required bandwidth is 350 MHz*km (at 1550 nm).
- We conclude that GRIN fibers are the only viable option to meet the bandwidth and core diameter requirements.



Required fiber performance is driven by receiver PPM slot widths

Fiber selection and procurement

- Based on the simulation results, we conclude that Gradient Index (GRIN) optical fibers represents the only existing option to meet the bandwidth and core diameter requirements.
- 400 μm core GRIN fibers are commercially available, but no specifications are available at 1550 nm (these fibers are typically optimized/specified for 800 or 1300 nm operation)
- We reached out to several vendors with requests to make custom draws of fiber, but the inquiry was put on hold due to COVID-19.
- Eventually we decided to buy, and test, a commercially available fiber from Fibercore.
- Unfortunately, due to the fiber lead time, and the shutdown of the lab due to COVID, we were never able to complete the fiber testing before the end of the FY.

Conclusions

- We developed tools to understand and specify the requirements imposed on optical fibers for this application
    - We learned that it is advantageous to divide the aperture of large telescopes into sub apertures and that tip-tilt correction systems offers marginal advantage .
- Using these tools we specified the requirements for a test case
- We procured a candidate optical fiber for testing
- We developed a test setup for filling the modes of the fiber, and enable realistic test conditions