Optimizing single mode fiber injection with CIAO SWIR

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APPLICATION NOTE

Summary

High-speed data transmission through optical laser communication is achievable by capturing the incoming light with a telescope and coupling it into a single-mode fiber (SMF). However, in long distance communication, whether between a satellite and a ground station or between two ground stations, light can encounter perturbations in the path, resulting in a distorted signal when arriving at the focus of the telescope and most of it is lost when injecting into the fiber. To counteract this effect, we use adaptive optics (AO) systems to correct in real time by achieving a near diffraction-limited image, concentrating the energy in one point so that most of the information can be received. At Imagine Optic, we combined our wavefront sensor with a deformable mirror to design an AO system ideal for this application. We tested in our bench the feasibility of injecting into a SMF with a disturbed light while correcting with AO and portrayed in this application note the results we obtained.

Introduction

Historically, space-to-ground communication has relied on Radio Frequency (RF) bands. While these longer wavelengths can penetrate clouds and rain, the RF spectrum has become extremely crowded and reached its saturation point for high-volume data needs (Rajiv Boddeda, 2023). Optical communication can transmit higher data rates than RF and were initially encoded with On-Off Keying (OOK) modulation, meaning encoding the data by switching a laser on and off at high frequency (Department, 2026). However, due to atmospheric turbulence, the spot is blurred and need to be coupled into a 200 µm diameter area free space coupled avalanche photodiode detector (APD) (Wright, 2015). To increase the data rates from 10's to 100-Gbps, one has to couple into a single mode fiber (SMF) and use coherent detection such as Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK) . The atmospheric turbulences creates then strong amplitude variations in the coupled flux. A way to overcome the effect of the atmospheric turbulence is to rely on adaptive optics (AO) correction to achieve near-diffraction limited images, even in daytime conditions (Wright, 2015). In addition, receiving data from satellite (typically at low Earth orbit (LEO)) to the ground station implies taking into account the relatively fast slew rate of the satellite that increase the transverse wind speed or rate at which the atmospheric turbulence moves (Wright, 2015). Coupling into a SMF is also challenging due to the power budget and losses: free-space loss, AO split loss, optics transmission coefficient and fading, the latter corresponds to the power fluctuations received in the fiber due to atmospheric turbulence.

How does adaptive optics work?

To correct distorted incoming light, we measure the wavefront with a Shack-Hartmann wavefront sensor to determine the local gradients of the phase. The correction is then performed by a device capable of compensating for these phase distortions in real-time, such as a deformable mirror. The link between these two components is the controller, which calculates the wavefront commands that the mirror must apply, as illustrated in **Figure 1**. This controller must calculate rapidly to maintain quasi-real-time correction, thereby optimizing both the Strehl ratio, which corresponds to the ratio of the peak observed intensity to that of a diffraction-limited image (between 0 and 1), and the coupling efficiency into a SMF. These two quantities are experimentally related (Wilson, 1994).

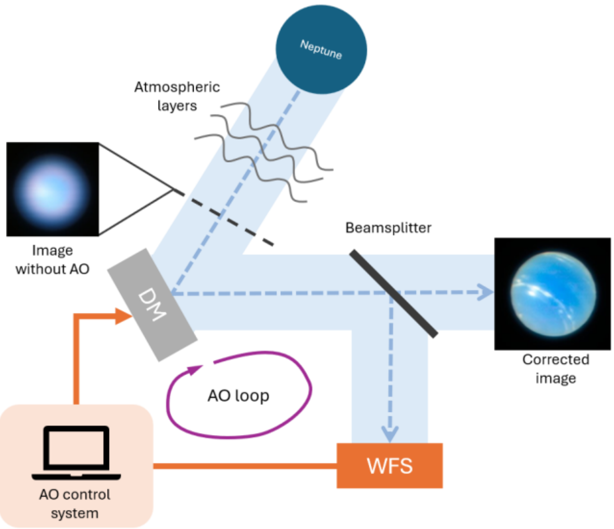


Figure 1. *Adaptive optics (AO) principle. DM is for Deformable mirror, WFS for Wavefront sensor, images of Neptune are taken from ESO*

At Imagine Optic, we offer an AO solution in this field of application, the CIAO SWIR, acronym for Compact Innovative Adaptive Optics in the SWIR range (1-1.7µm), capable of running at up to 3.5 kHz in closed-loop and ready to plug at the output of the telescope.

Figure 2. *Picture of CIAO SWIR*

The output of CIAO SWIR can be connected to a SMF, and we will demonstrate in this application note how to optimize its coupling efficiency.

We begin by describing the optical test bench and experimental setup. Subsequently, we provide a power budget estimation to determine the coupling efficiency. Finally, we detail the methodology employed and present the results.

Experimental setup

An optical test bench was developed in our laboratory to evaluate the coupling efficiency into a SMF. We used a divergent laser diode source at 1550 nm with adjustable power, followed by a collimating lens. An iris was used to set the system aperture to F/10, matching that of the CIAO SWIR system. To simulate a reflector telescope, we included a central obstruction (approximately 40% in diameter) supported by a 4-arm spider. Atmospheric turbulence was emulated using a heating element capable of reaching 200°C, which induces local refractive index fluctuations to perturb the incoming beam's phase. Finally, the focusing lens converges the beam at the entrance of CIAO SWIR, as illustrated in **Figure 3**.

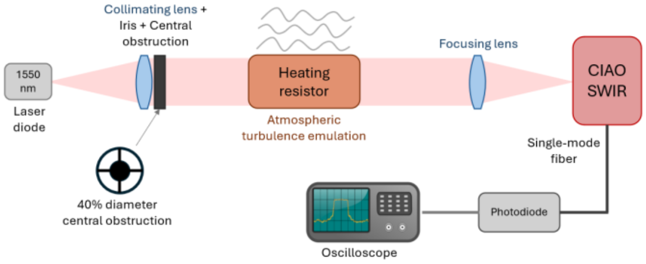


Figure 3. *Optical test bench in the lab to test the CIAO SWIR system*

A mount is positioned at the CIAO system output to connect the FC/APC SMF, which has a numerical aperture (NA) of 0.14 and a mode field diameter (MFD) of 9 µm. To monitor the injected photon flux, a photodiode and an oscilloscope are installed at the fiber output.

Power budget estimation

Theoretically, it's impossible to couple 100% of the light into a SMF. In this section, we estimate the power budget, how many incident photons we can inject into the fiber with CIAO SWIR.

What is the coupling efficiency?

The coupling efficiency relies on the overlap integral between the incident beam and the fundamental mode of the SMF. Thus, on the one hand, we need to analyze the amount of incident photons that reach the output of CIAO SWIR, which depends on the transmission of our system. On the other hand, we also need to determine how many of these photons can actually be injected into a SMF.

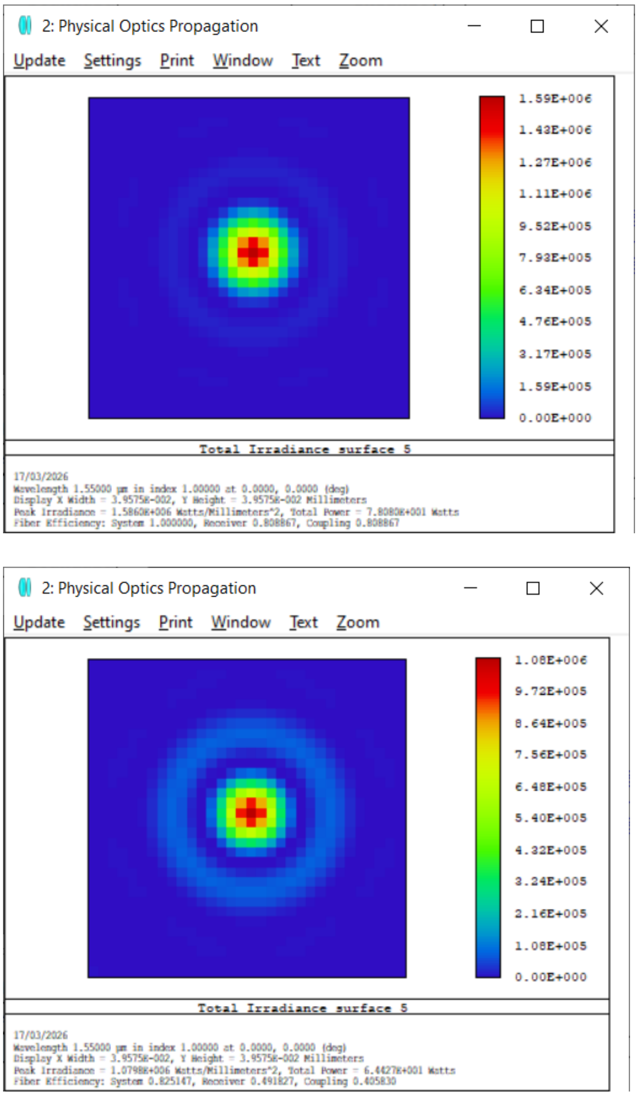
Transmission inside CIAO SWIR

Without the presence of a beamsplitter, the transmission inside CIAO SWIR is 90.8%. By default, a 50/50 beamsplitter is included, dropping the overall transmission to 45.3%. The choice of the beamsplitter can be customized, which impacts the final transmission of the system. For example, using a 90/10 beamsplitter would result in an 81.7% transmission.

Coupling efficiency at the fiber

If the beam is perfectly gaussian and adapted to the MFD of the fiber, 100% of the transmitted photons could be injected. In reality, if the beam is not perfectly gaussian, or adapted to the MFD of the fiber, there's a mismatch between the beam's fundamental mode and the fiber's MFD, resulting in a decrease in the maximum coupling efficiency.

We simulated the expected coupling efficiency of CIAO using Zemax, and obtained up to 77%. In addition, for a reflector-type telescope with a central obstruction, the incident beam is no longer gaussian but a pattern that redistributes intensity into the secondary lobes. We illustrate this in the **Figure 4** below with the Physical Optics Propagation simulation on Zemax with and without a 40% diameter central obstruction.



```
17/03/2026
Wavelength 1.55000 µm in index 1.00000 at 0.0000, 0.0000 (deg)
Display X Width = 3.9575E-002, Y Height = 3.9575E-002 Millimeters
Peak Irradiance = 1.5860E+006 Watts/Millimeters^2, Total Power = 7.8080E+001 Watts
Fiber Efficiency: System 1.000000, Receiver 0.808867, Coupling 0.808867
```

```
17/03/2026
Wavelength 1.55000 µm in index 1.00000 at 0.0000, 0.0000 (deg)
Display X Width = 3.9575E-002, Y Height = 3.9575E-002 Millimeters
Peak Irradiance = 1.0798E+006 Watts/Millimeters^2, Total Power = 6.4427E+001 Watts
Fiber Efficiency: System 0.825147, Receiver 0.491827, Coupling 0.405830
```

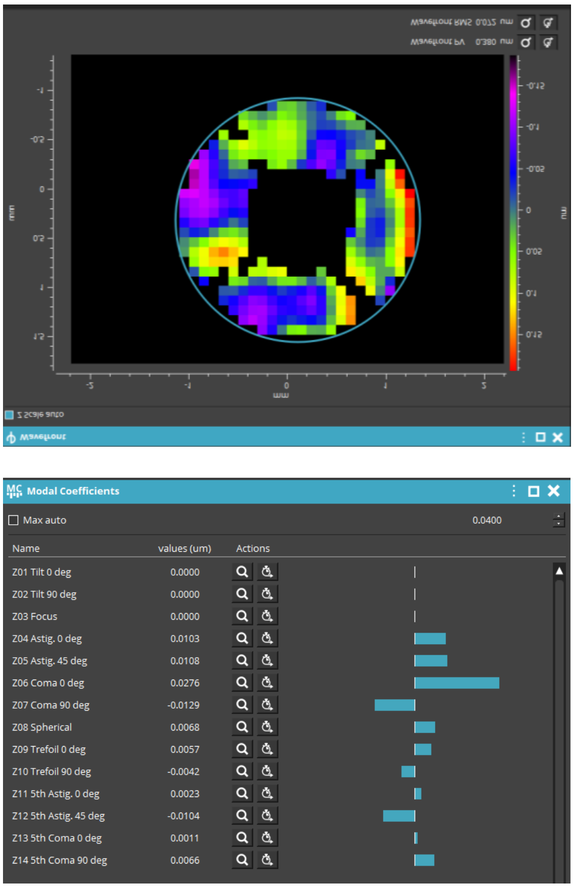
Figure 4. *Physical Optics Propagation on ZEMAX without (top) and with a 40% diameter central obstruction (bottom)*

A 40% central obstruction reduces the coupling efficiency by 30%, falling from 77% to 54%. Finally, if we consider a residual wavefront correction at $\lambda/10$, we induce additional 35% losses in the coupling, which results in 35.1% maximum coupling efficiency.

Adding the overall transmission inside CIAO SWIR, we can inject at most 28.7% of incident photons into the fiber, in a 90/10 beamsplitter configuration.

Methodology

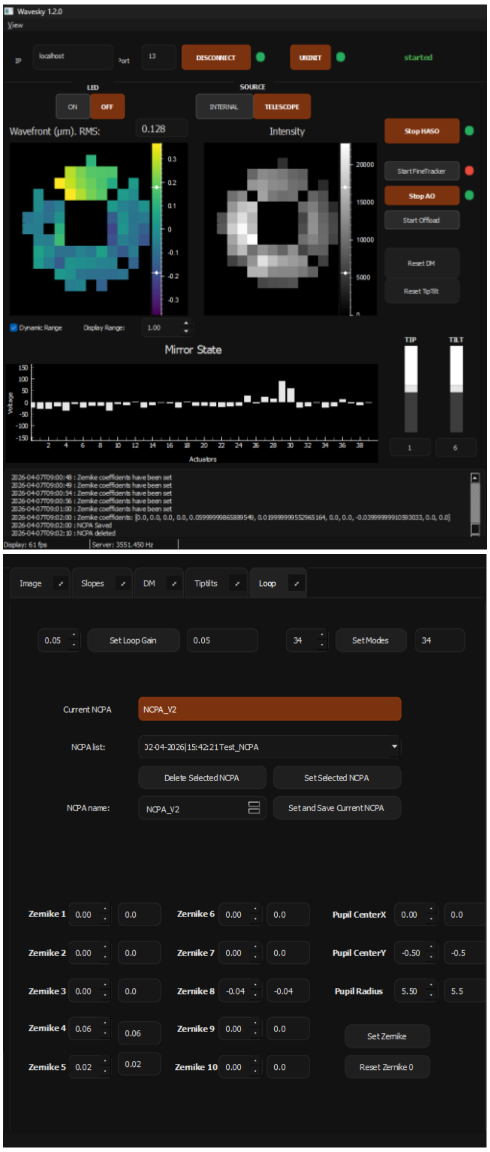
Before trying to couple into a SMF, we first need to characterize the residual wavefront when the AO loop is closed. To perform this, we mount a HASO at the output of CIAO SWIR to characterize the wavefront, which we can see in **Figure 5**, and using the Non Common Path Aberration (NCPA) parameters on the WaveSky software, we apply Zernike coefficients to minimize the residual wavefront error, as shown in **Figure 6**. This ensures that the injection losses induced by the residual wavefront error are minimized.



☐ Max auto 0.0400

Name	values (um)
Z01 Tilt 0 deg	0.0000
Z02 Tilt 90 deg	0.0000
Z03 Focus	0.0000
Z04 Astig. 0 deg	0.0103
Z05 Astig. 45 deg	0.0108
Z06 Coma 0 deg	0.0276
Z07 Coma 90 deg	-0.0129
Z08 Spherical	0.0068
Z09 Trefoil 0 deg	0.0057
Z10 Trefoil 90 deg	-0.0042
Z11 5th Astig. 0 deg	0.0023
Z12 5th Astig. 45 deg	-0.0104
Z13 5th Coma 0 deg	0.0011
Z14 5th Coma 90 deg	0.0066

Figure 5. *Wavefront characterization with WaveView software (top) and the Zernike coefficient in µm (bottom)*



IP: localhost
Port: 13

Wavefront (µm). RMS: 0.128

Display Range: 1.00

```
2026-04-07T09:00:48 : Zernike coefficients have been set
2026-04-07T09:00:49 : Zernike coefficients have been set
2026-04-07T09:00:54 : Zernike coefficients have been set
2026-04-07T09:00:56 : Zernike coefficients have been set
2026-04-07T09:01:00 : Zernike coefficients have been set
2026-04-07T09:02:00 : Zernike coefficients: [0.0, 0.0, 0.0, 0.0, 0.05999999865889549, 0.019999999552965164, 0.0, 0.0, -0.03999999910593033, 0.0, 0.0]
2026-04-07T09:02:00 : NCPA Saved
2026-04-07T09:02:10 : NCPA deleted
```

Display: 61 fps | Server: 3551.450 Hz

Loop gain: 0.05 — Set Loop Gain — 0.05
Modes: 34 — Set Modes — 34

Current NCPA: NCPA_V2
NCPA list: 02-04-2026|15:42:21 Test_NCPA
NCPA name: NCPA_V2

Zernike 1: 0.00 / 0.0
Zernike 2: 0.00 / 0.0
Zernike 3: 0.00 / 0.0
Zernike 4: 0.06 / 0.06
Zernike 5: 0.02 / 0.02
Zernike 6: 0.00 / 0.0
Zernike 7: 0.00 / 0.0
Zernike 8: -0.04 / -0.04
Zernike 9: 0.00 / 0.0
Zernike 10: 0.00 / 0.0
Pupil CenterX: 0.00 / 0.0
Pupil CenterY: -0.50 / -0.5
Pupil Radius: 5.50 / 5.5

Figure 6. *Wavefront map in the WaveSky software (top) and NCPA correction (bottom)*

Then, to inject into the SMF, a fiber mount with xyz translations screws is placed at the output of CIAO SWIR. To quantify the coupling efficiency, we first measure the input power of the AO system using a photodiode, with the resulting voltage displayed on an oscilloscope.

With the AO correction, we inject into the SMF using the translation of the mounting and the NCPAs, by mainly using the *x*- and *y*-tilt and the defocus parameters, and observing the change in voltage on the oscilloscope.

Results

The results of the measurements obtained on the oscilloscope are summarized in the following figures where we display the coupling efficiency in a 90/10 beamsplitter configuration.

Figure 7 represents the probability density in function of the coupling efficiency in dB with and without AO, blue and red histogram respectively, and the theoretical coupling efficiency in dashed line, assuming a $\lambda/10$ RMS wavefront. **Figure 8** represents the coupling efficiency in dB and in %. The theoretical coupling efficiency is 28.7% corresponding to -5.41 dB, represented in dashed line.

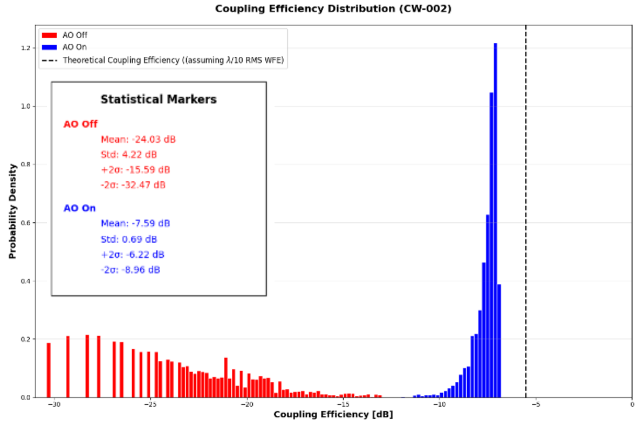
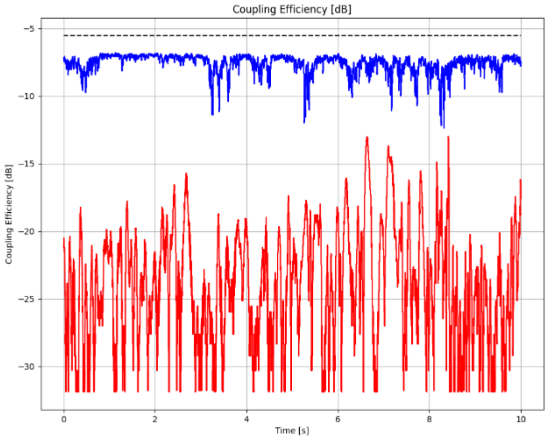


Figure 7. *Probability density in function of the coupling efficiency in dB, with AO (in blue) and without AO (in red) compared to the theoretical coupling efficiency represented in dashed line*



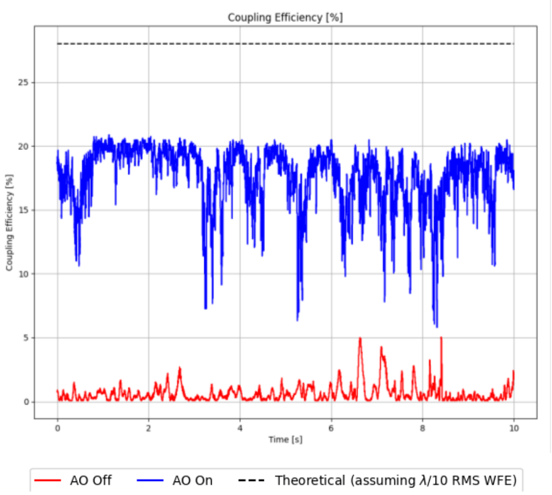


Figure 8. *Coupling efficiency in dB (top) and in % (bottom) in function of time with a 20 µs sampling period, with AO (in blue) and without AO (in red), compared to the theoretical coupling efficiency*

The gain provided by the CIAO system is clearly visible in **Figure 7**. The narrow distribution represents the stability achieved with the correction when coupling into the SMF, compared to the wider, fluctuating distribution without AO. With AO, we can almost reach the theoretical maximum coupling efficiency proving its performance.

The summary of the different values of maximum coupling efficiency depending on the configuration assuming a correction at $\lambda/10$ wavefront RMS, is represented in the **Table 1** below.

40% central obstruction	50/50 BS	90/10 BS	Coupling efficiency in dB	Coupling efficiency in %
			-3.43	45.4
		x	-3.89	40.9
x		x	-5.42	28.7
	x		-6.45	22.7
x	x		-7.99	15.9

Table 1. *Summary of the different values of maximum coupling efficiency depending on the configuration, BS for beamsplitter*

Conclusion

In this application note, we demonstrated how we can optimize the coupling efficiency into a SMF with AO loop correction enabled by CIAO SWIR. Depending on the configuration of the beamsplitter and the entrance pupil of the telescope, losses during the SMF coupling can reach at most -8 dB.

References

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