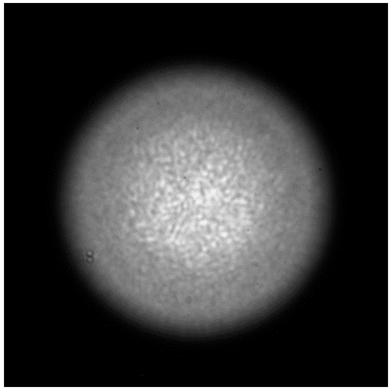
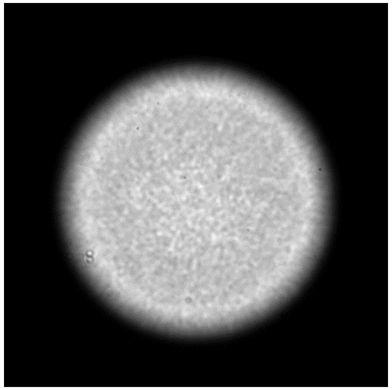
Modifying Beam Profiles with Multimode Fibers

- By increasing the launch angle of a Gaussian beam into a multimode fiber, the output beam profile can be modified.
- As the input angle was increased, the proportion of meridional rays to skew rays increased, first forming a top hat and then a donut beam profile.

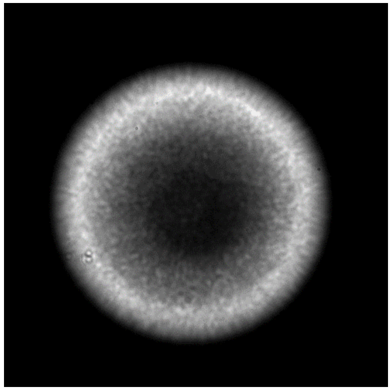
Initial Profile
(Input Angle = 0°)



Top Hat Profile
(Input Angle = 11°)



Donut Profile
(Input Angle = 15°)



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Background

- In some applications, an alternative beam distribution such as a top hat or donut are desired instead of the inherent Gaussian distribution provided by typical optics.
- For example, diffraction-limited imaging assumes a top-hat distribution in the pupil plane that creates an Airy pattern at the focus (see Figure 1).
- In other applications, a Bessel beam is desired to create an extended depth of focus (see Figure 2), which can be created by an annular distribution in the pupil plane or by utilizing an axicon lens.
- Most techniques used to modify the beam distribution lose a significant amount of the input beam power by either aperturizing smaller regions of the beam to produce the desired effect or by using special optical assemblies that can be expensive.

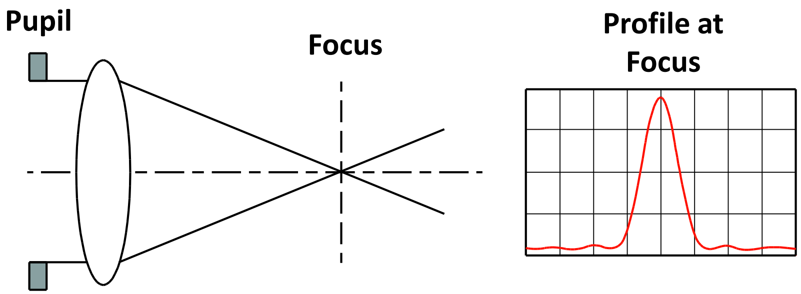

Figure 1: A circular pupil creates Airy pattern at the focus with a shallow depth of field

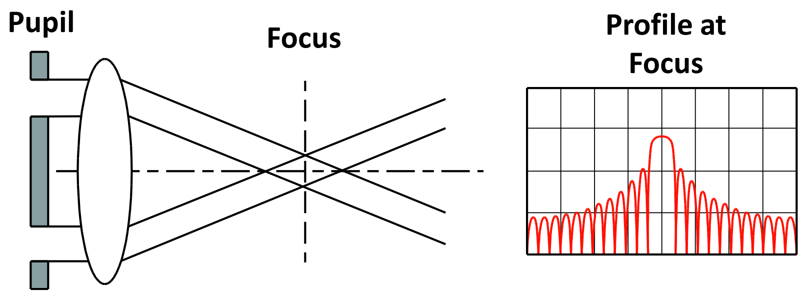

Figure 2: An annular pupil creates a Bessel beam with extended depth of field

- Here, we demonstrate the ability to use a standard multimode fiber patch cable as a relatively inexpensive method to modify the input Gaussian profile into a top hat and donut profile with minimal loss.

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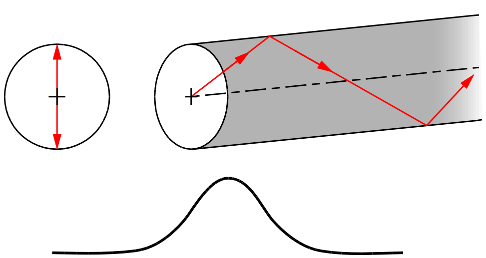
Theoretical Considerations

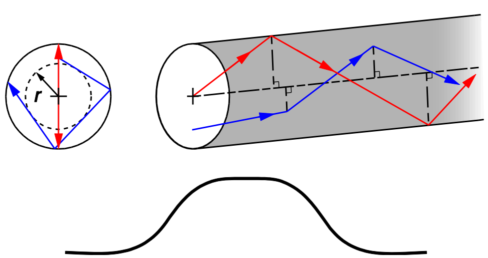
- As the name suggests, multimode fiber supports the propagation of numerous modes down the length of fiber due to the large core diameter with respect to the input wavelength.
- To a first approximation, we assume the light that remains bound within the fiber core results from rays totally internally reflecting at the core/cladding interface along the length of fiber.
- There are two general types of rays that propagate along the fiber [1]:
  - Meridional rays pass through the central axis of the fiber after each reflection.
  - Skew rays never pass through the central axis of the fiber and propagate in a helical path along the fiber that is tangent to the inner caustic of the path with radius *r*.
- By changing the input angle of the light launched into a multimode fiber, we were able to modify the proportion of light rays propagating as skew rays vs. meridional rays, and consequently, modify the output from a Gaussian distribution (all meridional rays) to a top hat (mixture of meridional and skew rays) to a donut (all skew rays).

Meridional Ray



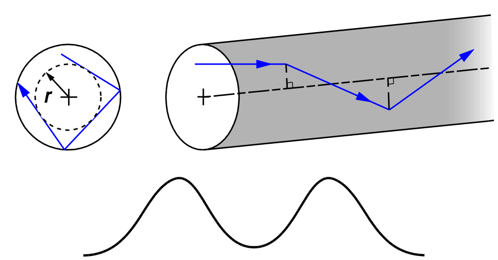
Gaussian Distribution

Meridional and Skew Rays



Flat Top Distribution

Skew Ray

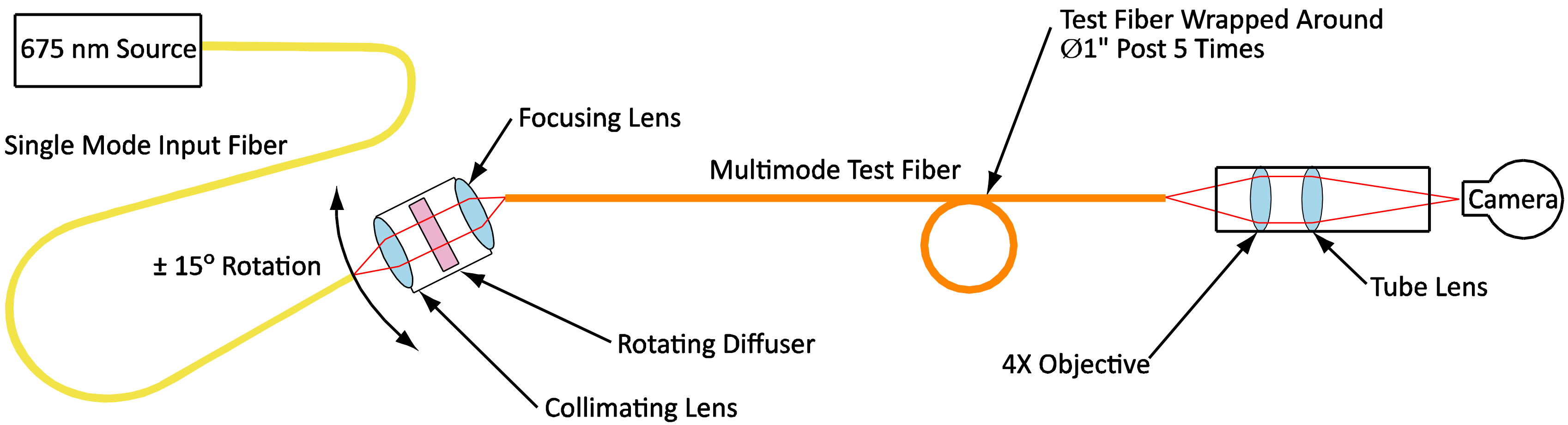


Donut Distribution

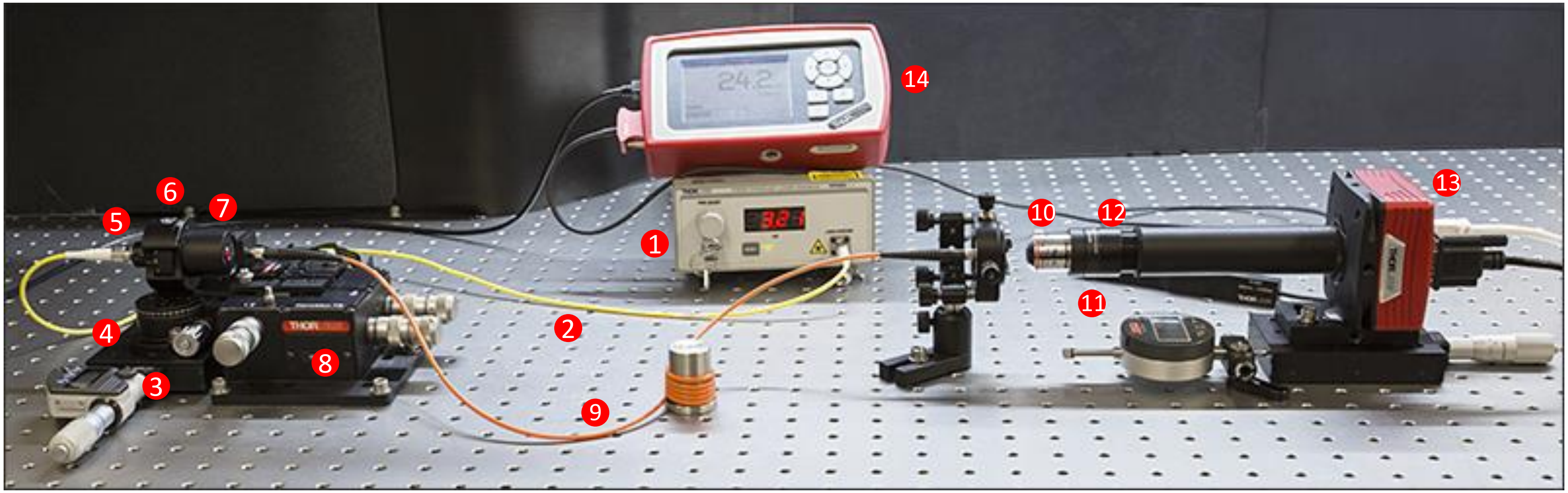
[1] Snyder, A. W., & Love, J.D. (1983). *Optical Waveguide Theory* (pp. 27-31). Chapman & Hall.

Experimental Design

- Light from a benchtop 675 nm laser diode source was coupled into a single-mode patch cable, collimated with an 11 mm focal length lens, and then focused with an identical lens into an 1-meter-long, step-index, multimode fiber with a Ø200 µm core.
- The multimode patch cable was wrapped around a Ø1″ post 5 times in order to remove cladding modes.
- A 4X objective lens and 150 mm focal length achromat (tube lens) were used to image the output beam profile onto a CCD camera that was located 5 mm beyond the output tip of the fiber.
- The input light was set incident at 0˚, 11˚, and 15˚ to the input face of the multimode fiber to create the initial, top hat, and donut profiles, respectively.
- Each time the angle was changed, the alignment of the input fiber was optimized while the output power was monitored with a power meter to ensure maximum coupling was achieved.
- Images were acquired with a 9 second exposure while manually rotating a 1500 grit diffuser placed between the collimating and focusing lenses to reduce the spatial coherence and create a clean output beam profile.



Experiment Setup

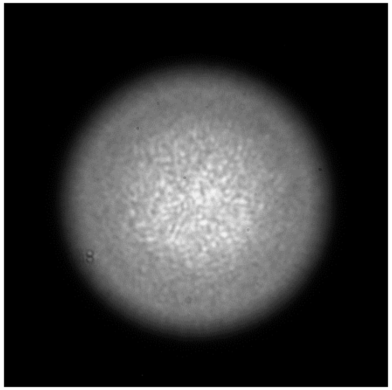


1. Laser Source: S1FC675
2. Input Fiber: P1-630A-FC-2
3. Translation Stages: PT1
4. Rotation Stage: CR1
5. Fiber Collimator: F220FC-B
6. 1500 Grit Diffuser: DG10-1500
7. Focusing Lens: C220TMD-B
8. 3-Axis Stage: MAX313D
9. Test Fiber: Ø200 µm Core, 0.39 NA: M38L01
10. Microscope Objective: RMS4X
11. Neutral Density Filter: NE30A
12. Tube Lens: AC254-150-A
13. 1.4 MP Scientific CCD Camera: 1500M-GE
14. Power Sensor Head: S130C with
    Power Meter: PM100D

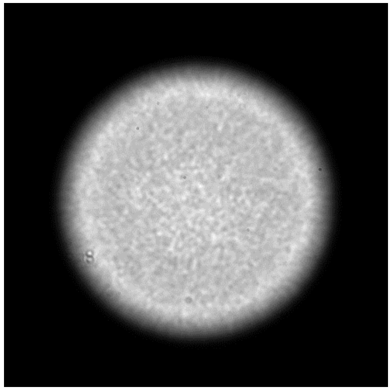
Results: Output Profiles

- Output profiles are shown below for input angles of 0°, 11°, and 15°. The camera imaged the output beam profile 5 mm from the output of the fiber. All images were acquired with a spinning diffuser to reduce the spatial coherence and demonstrate the underlying profile from each configuration.
    - Initial Profile: Baseline profile from a 0° input angle.
    - Top Hat Profile: As we rotated the input angle, the proportion of light output from the perimeter of the core increased with respect to the light output from the center. We assume this change corresponds to an increased amount of skew rays with respect to the meridional rays. Output power at 11° input angle was 91% of the initial profile.
    - Donut Profile: Further increasing the input angle increased the proportion of skew rays until minimal light was observed within the center of the beam profile. Output power at 15° input angle was 64% of the initial profile.
- Plots through the center of each profile to support our assumption are provided on the following slide.

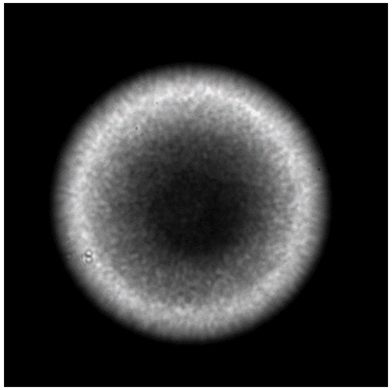
Initial Profile
(Input Angle = 0°)



Top Hat Profile
(Input Angle = 11°)



Donut Profile
(Input Angle = 15°)



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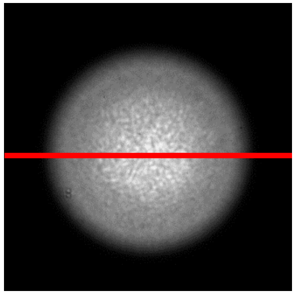
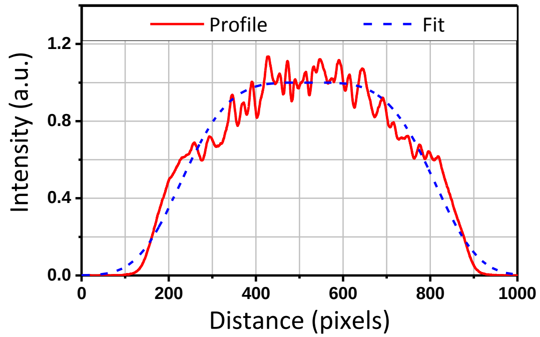
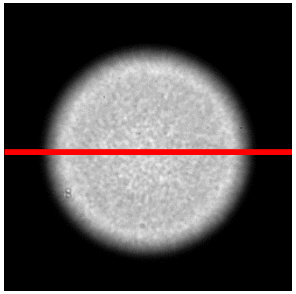
Results: Profile Fits

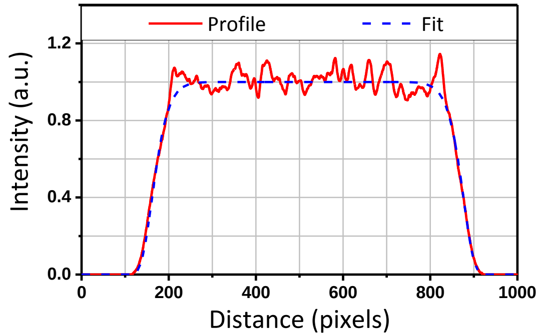
Initial Profile (Input Angle = 0°)



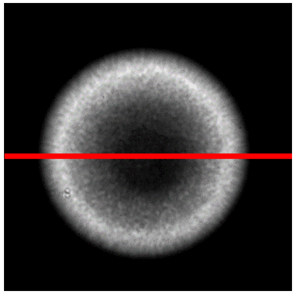


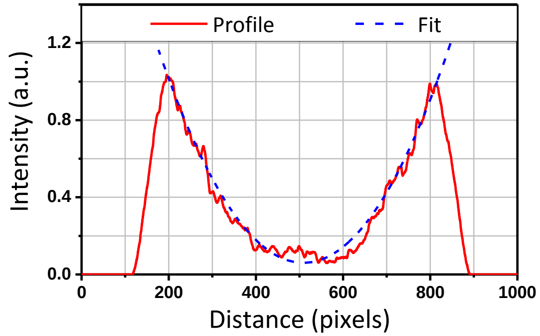
Top Hat Profile (Input Angle = 11°)





Donut Profile (Input Angle = 15°)





- Here we plot the average intensity at each point along the 10 pixel tall line through the center of each profile (red) and fit the data (blue) as described below.
- Initial Profile fit with a super Gaussian:

$$y = Ae^{-2\left(\frac{(x-x_0)}{w}\right)^{\beta}},$$

where A = 1, x_0 = 519, w = 375, and β = 4 [1]. The departure from a pure Gaussian output suggests an initial combination of meridional rays and skew rays.

- Top Hat Profile fit with a super Gaussian:

$$y = Ae^{-2\left(\frac{(x-x_0)}{w}\right)^{\beta}},$$

where A = 1, x_0 = 519, w = 375, and β = 16 [1].

- Donut Profile internal void fit with a parabola:

$$y = A(x - x_0)^2 + \beta,$$

where A = 10^{-5}, x_0 = 509, and β = 0.06 [2].

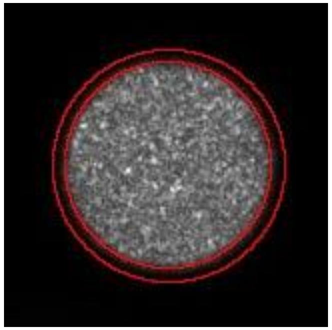
[1] Shealy, D. L., & Hoffnagle, J.A. (2006). Laser beam shaping profiles and propagation. *Appl. Optics*, **45** (21), 5118-5131. doi:10.1364/AO.45.005118

[2] Neupane, B., Chen, F., Sun, W., Chiu, D.T., & Wang, G. (2013). Tuning donut profile for spatial resolution in stimulated emission depletion microscopy. *Rev. Sci. Instr.* **84** (4), 043701. doi:10.1063/1.4799665

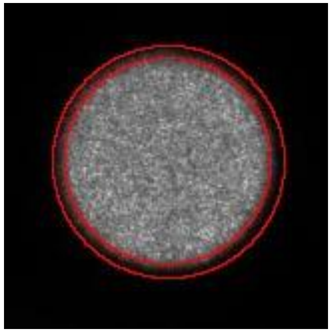
Results: Image at Fiber Face

- The multimode fiber under test was wrapped five times around a Ø1″ post in order to reduce the amount of cladding modes, which is light propagating in the cladding from the initial launch or after leaking from the core.
- Images were also acquired at the fiber face to confirm that the results presented on the previous slides were not caused by cladding modes.
- Circles were drawn on the images below to signify the location of the core and cladding. We can see that all of the light was output from the core, suggesting that our profiles result from light propagating through the core and not the cladding.
- Note that the beam profiles at the fiber face differ from those obtained at a 5 mm distance from the fiber output.

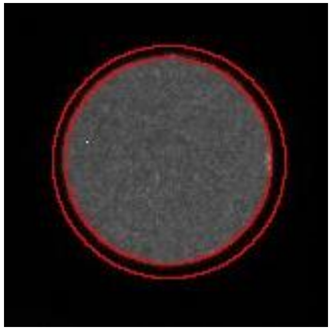
Initial Profile
(Input Angle = 0°)



Top Hat Profile
(Input Angle = 11°)

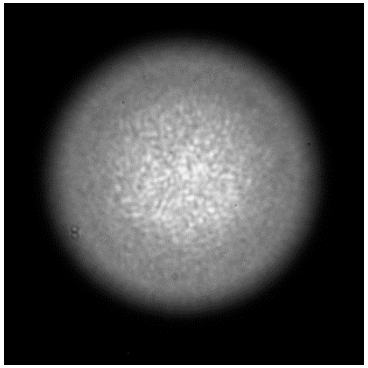


Donut Profile
(Input Angle = 15°)

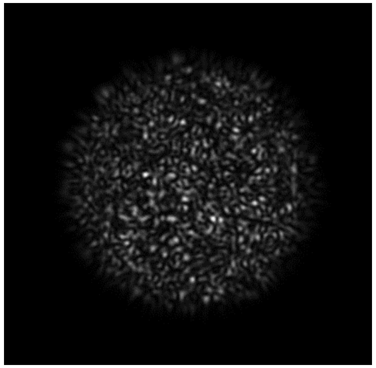


Experimental Limitations

- Only a single multimode core size, fill factor (ratio of input spot size to multimode core), and input numerical aperture and wavelength were shown to demonstrate that the output profile from a multimode fiber could be modified. These results are for demonstration purposes and are far from exhaustive.
- Input angles were chosen to provide the optimal output profile with minimal power loss with the chosen components.
- It is important to emphasize that a spinning diffuser was used to reduce the spatial coherence to demonstrate the overall profile. Without the diffuser, or when the diffuser was held stationary, a speckle pattern was observed within the overall profile due to the inference between modes (see below).



Output Profile with Spinning Diffuser



Output Profile Without Diffuser

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Summary

- Here we demonstrated the ability to use a standard multimode fiber patch cable as a relatively inexpensive method to modify an input Gaussian profile into a top hat and donut profile with minimal loss.
- Output profiles were imaged 5 mm from the end of the fiber.
- When the input angle was 0°, the beam profile was a low-order super-Gaussian profile indicating a high proportion of meridional rays to skew rays.
- As the input angle increased to 11°, the number of skew rays increased until the output beam transformed into a high-order super-Gaussian profile, often called a top hat.
- As the input angle increased to 15°, the proportion of meridional rays to skew rays increased until a donut profile was achieved.