SPPDI® Model 1 Series Device User Manual

CLASS 1 LASER PRODUCT

March 2022

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LASER WARRANTY, CAUTION, and DISCLAIMER

The SPPDI® (Split-path Point Diffraction Interferometer) is registered with the CDRH (Center for Devices and Radiological Health), a division of the FDA (Food and Drug Administration), as a Class 1 (IEC 60825-1) or Class I (old system) laser product, CDRH Accession number 1811033-000. The SPPDI emits non-hazardous CW (continuous wave) laser radiation, at a wavelength of 650nm, in a diverging beam with an optical output power of less than 350 microwatts. If the laser fails, or fails to operate in a normal manner, the entire SPPDI unit may be returned to the factory for repairs at no cost to the original owner. No user-serviceable parts inside. All warranties stated or implied will be void if the user opens the SPPDI enclosure or removes the SPPDI laser attachment or laser module for any reason.

User Manual Contents

User Manual Terms and Conventions

Please review the terms and conventions used in this manual.

Warnings and Cautions	⚠ **WARNING:** Warnings indicate that failure to follow procedures will result in injury to the user or nearby personnel. ⚠ **Caution:** Cautions indicate that failure to follow procedures will result in damage to the device or connected devices.
Cross-References	**Examples:** **Figure** Photographs, Schematics, Instruction series **See also:** Page cross-references, More information
Notes	**Note:** Notes provide additional information about proper use of device or how to properly execute a procedure.

Getting Started

Introduction

Thank you for your purchase of the Split-path Point Diffraction Interferometer (SPPDI®). The SPPDI Model 1 Series laser interferometers are the first optical interferometers of their kind to provide high performance in a small light weight package, and at a very affordable price.

SPPDI Model 1.21 comprises a 3D printed PLA (polylactic acid) enclosure and attachments. Model 1.21 is strong yet light in weight, and is suitable for laboratory use. Model 1.21alum comprises a black anodized machined aluminum enclosure with 3D-printed attachments suitable for use in more demanding environments.

Educators will find the SPPDI to be a cost-effective tool for teaching the wave nature of light and principles of interferometry. Manufacturers will find the SPPDI to be ideal for quickly evaluating the performance of individual optical components as well as assembled optical systems. As a low-cost general-purpose interferometer, many uses for the SPPDI are possible.

This Getting Started section provides two step-by-step tutorials that illustrate some of the possible methods for setting up and operating your SPPDI. The first tutorial is the setup procedure for in-situ interferometric testing of telescopes. The second tutorial describes a technique for bench-mounted interferometric testing of telescopes or individual optical components.

Note: Review all included equipment before proceeding.

Equipment Included with Model 1.21 and Model 1.21alum:

- USB-powered laser and power cable
- USB-powered video alignment camera (NTSC -- AV2 video signal) and power cable
- Viewing Telescope Adapter
- Battery-powered laser collimator (CR2032 Li-ion battery not included)
- Foam padded carrying case
- User Manual (downloadable from Kerry Optical Systems at www.kerryos.com)

The following must be purchased separately:

- Focal Ratio Converter for calibration of the SPPDI and/or for measurement of “fast” (< f/8) optics or optical systems

The following must be supplied by the user for best performance:

- Adjustable (rotatable) linear polarizing filter for attachment to user's camera
- Adjustable (rotatable) linear polarizing filter for attachment to user's eyepiece when using the supplied Viewing Telescope Adapter

Attention: Newer models of the SPPDI require an external linear polarizing filter mounted to the user's camera lens, as a means to increase interference fringe contrast. We highly recommend Hoya brand linear polarizing camera filters (type "PL"), which are available in a variety of sizes to fit different camera lenses. These are commonly available in camera stores or online. Eyepiece polarizing filters are available from a variety of internet providers of astronomy equipment. We recommend eyepieces with a focal length between 15 and 30 mm for best visual observing of interference fringes with the Viewing Telescope Adapter.

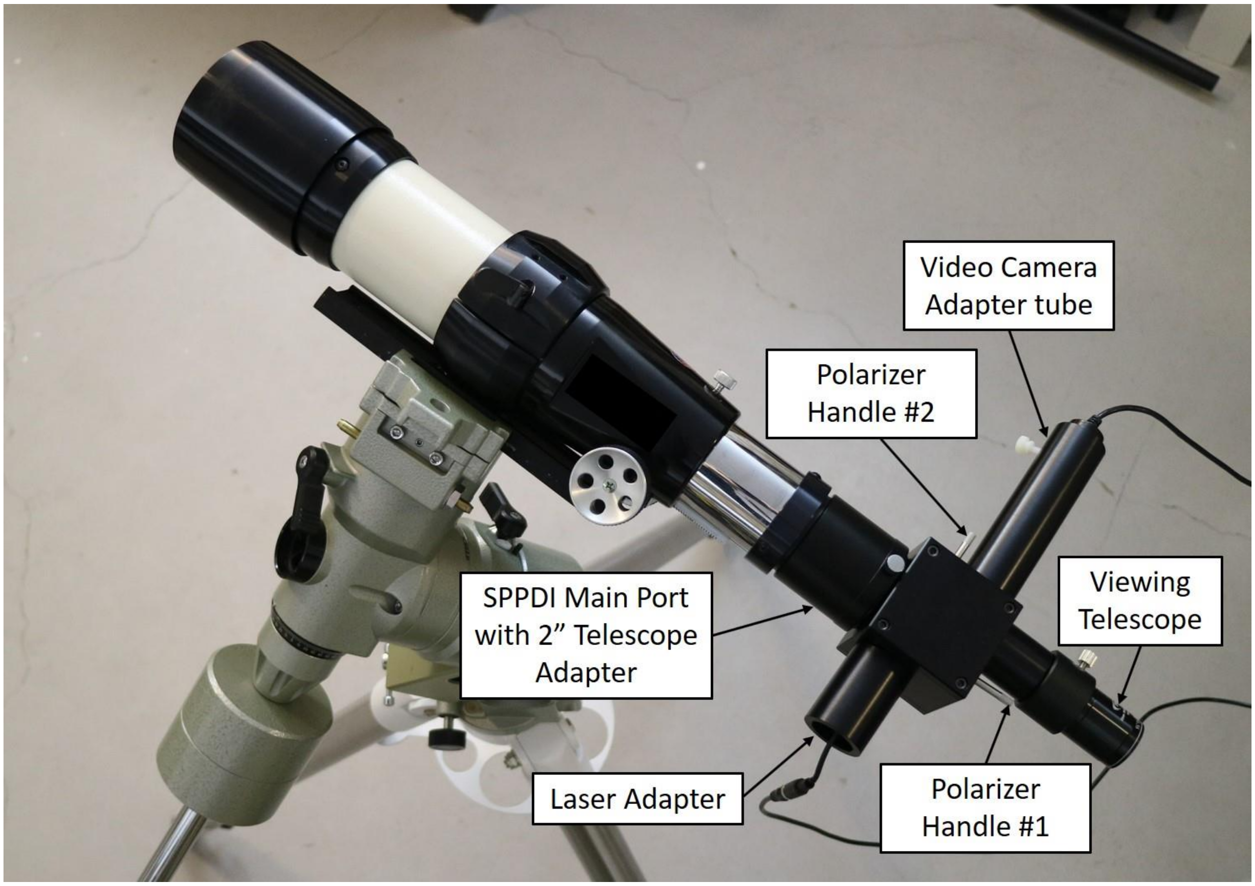
Note 1: Names of products not produced by Kerry Optical Systems, LLC, and referenced in this document, are copyrighted or trademarked by their respective companies.

Note 2: The SPPDI is generally most useful in double-pass interferometry setups where an optical flat is a typical part of the setup. Kerry Optical Systems, LLC does not provide optical flats or mounts, but will be happy to provide consultation in selection of suitable equipment.

In-situ Telescope Testing

⚠ **Caution:** Failure to carefully follow each step in this procedure may result in damage to your SPPDI and its various adapters, or the equipment that is being tested.

This test procedure describes a method for using the SPPDI® to obtain double-pass interferograms of telescopes. The availability of a large-aperture suitably mounted optical flat is assumed. The test setup (equipment) should be located in an environmentally stable (low-vibration, low-temperature variation) testing environment.

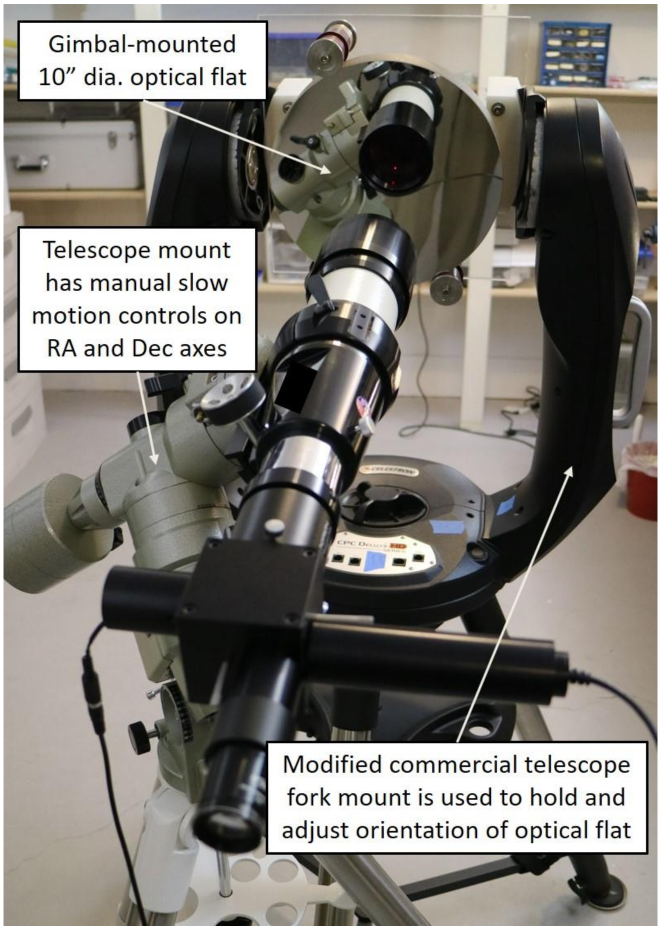


An older model of the SPPDI is shown attached to a small telescope, using the supplied 2” Telescope Adapter**.** The telescope is mounted on a two-axis mount with slow motion controls on the mount axes**.** A 10” diameter gimbal-mounted optical flat is part of this setup, but is not shown in this view.

Attach the SPPDI to a Telescope

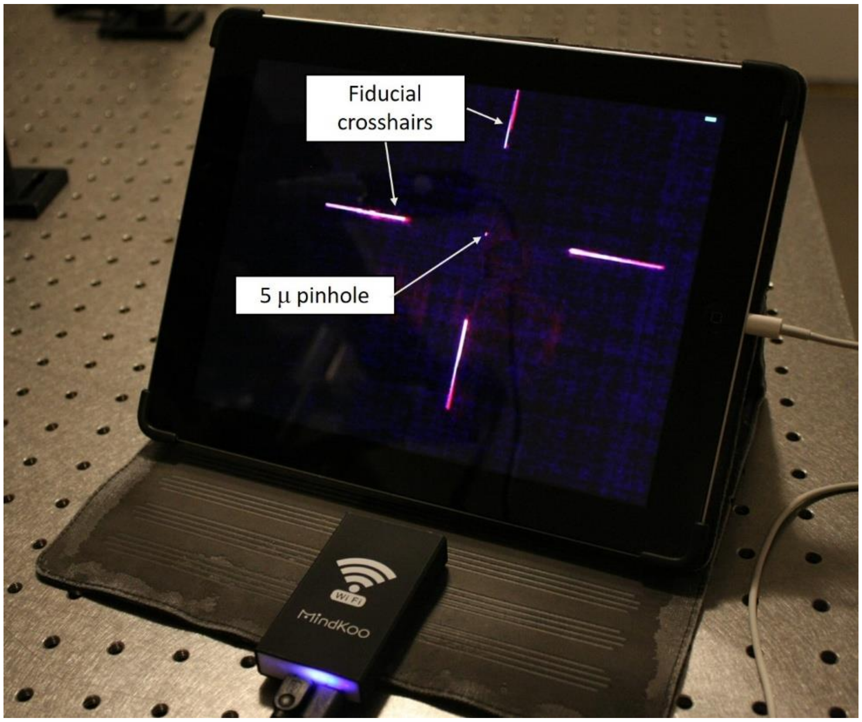
1. Attach the SPPDI to a telescope with the supplied 2" (50.8 mm) Telescope Adapter
2. Place an optical flat in front of the telescope
3. Make sure that fine angular motion controls are available on either the telescope mount and/or optical flat mount

   Note: The longer the telescope's focal length, the more critical it is that both telescope mount and optical flat mount are mechanically stable.



Connect the Supplied Video Alignment Camera

1. Connect the supplied video alignment camera to a 5-volt DC USB power supply
2. Connect the video camera BNC connector to an AV2-compatible video display
3. Verify that the video camera signal is displayed correctly on the video display



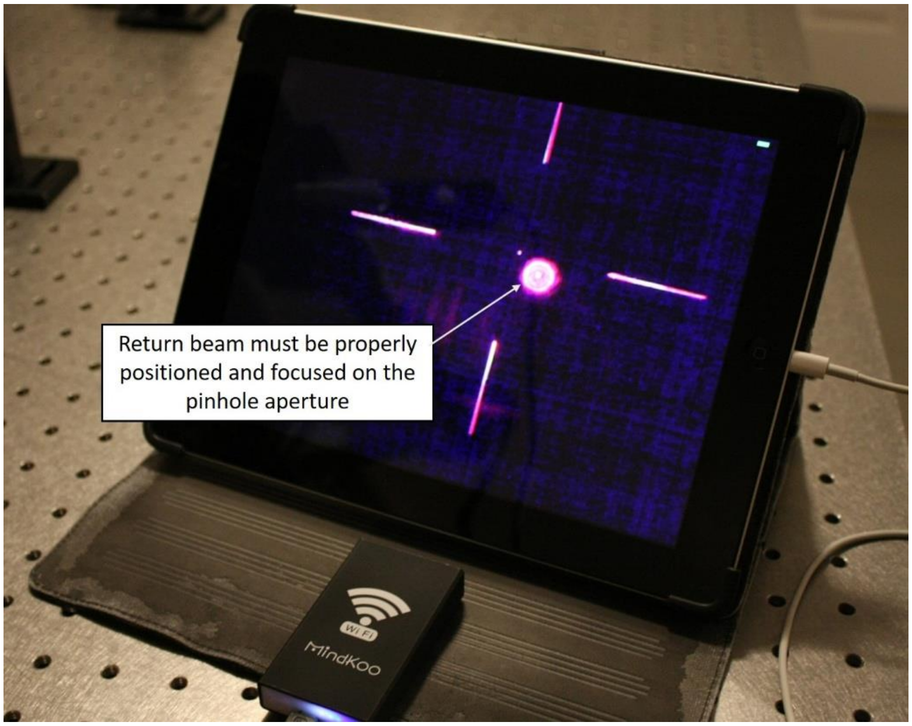
Adjust and Focus the Video Alignment Camera

1. Shine a flashlight or other illumination source into the objective lens end of the telescope
2. Loosen the thumbscrew on the side of the Video Camera Adapter tube
3. While watching the video display, rotate and slide the video alignment camera in and out until the crosshair fiducial marks and central 5-micron pinhole aperture are in best focus and oriented horizontally and vertically, then tighten the thumbscrew
4. Rotate Polarizer Handle #2 (near Video Camera Adapter tube) until the brightness of the fiducial marks is maximized, and make sure the Handle is centered in its through-hole in the SPPDI cubical enclosure

   Note: Due to small residual alignment errors in the video projection optics, the crosshairs and pinhole aperture will not be perfectly centered on the display. This residual misalignment has no impact on the performance of the SPPDI.

Turn on the Laser

1. The USB power supply must NOT be energized when plugging in the laser. Otherwise, the laser may be damaged by “in-rush” current.
2. Energize the USB power bank, and verify that laser light is emitted from the telescope



Bring the Telescope into Autocollimation

1. While observing the video display, make gradual adjustments with the angular slow-motion controls on the optical flat mount and/or telescope mount until the incoming beam is visible on the video alignment display

   Note: This process will become easier with practice. The FOV (field of view) shown on the video display is very small, so fine angular adjustments of the telescope mount or optical flat will be greatly exaggerated.

2. When the return beam is visible on the video alignment display, use the angular slow-motion controls on the optical flat mount or telescope mount to center the incoming beam on the SPPDI pinhole aperture
3. Rotate Polarizer #1 Handle until the blanking segment obscures the incoming beam

   Note: the SPPDI Polarizer #1 (opposite the Main Port) is provided with a blanking segment. The blanking segment may be positioned in the beam by rotating Polarizer Handle #1 until the beam is blocked. The remaining light observed on the video display is the residual portion of the incoming beam that leaks through the pinhole aperture plate. This residual light leakage will become increasingly visible as the condition of best focus is approached. The residual light leakage provides visual feedback to assist fine-focusing and fine-positioning of the incoming beam on the SPPDI pinhole aperture.

4. While observing the video display, gently adjust the telescope focus until the incoming beam is in tight focus.
5. Adjust the angular slow-motion controls on the optical flat and/or telescope mount to tine-tune the lateral position of the incoming beam on the pinhole aperture until the beam passing through the pinhole aperture is maximized.

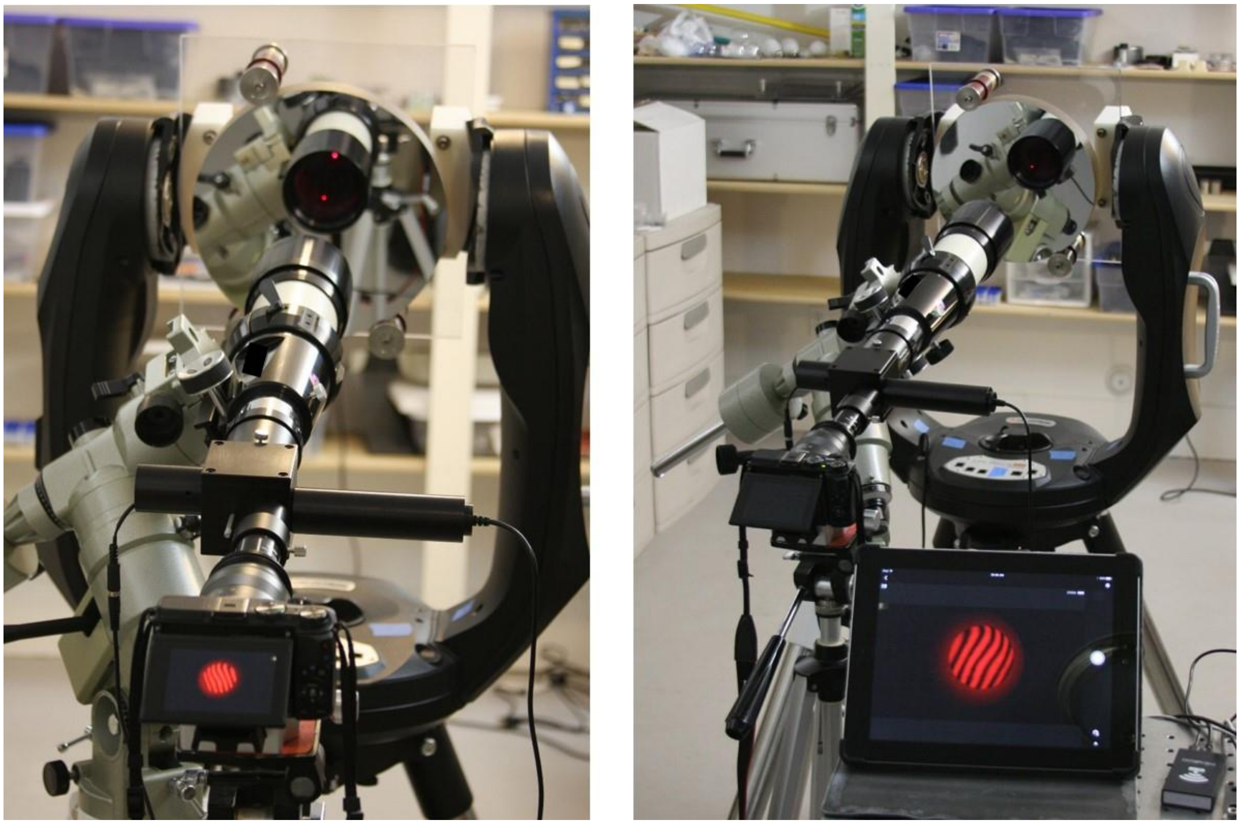
Adjust SPPDI® Polarizer Handles for Best Observation of Interference Fringes

1. View the test article through the Viewing Telescope (or digital camera "live view" screen) while carefully adjusting Polarizer Handle #1
    a. Adjust the rotational orientation of Polarizer Handle #1 to maximize the contrast of the interference fringes
    b. Adjust the tilt of Polarizer Handle #1 to change the orientation and separation of the interference fringes

       Note 1: If the Viewing Telescope is used, the user-supplied 1.25" eyepiece should include a linear polarizing filter in order to enhance the visibility of interference fringes.

       Note 2: It should not be necessary to make adjustments with Polarizer Handle #2. Due to high angular sensitivity, it may be necessary to return to the previous step and make additional small adjustments to the position of the focused beam on the pinhole aperture.

    c. Residual fringe curvature (defocus) may be removed by adjusting the focus of the test article
2. Interference fringes may be observed directly with the eye through the Viewing Telescope, or recorded with a digital camera positioned to receive light which exits the Viewing Telescope eyepiece. However, the preferred method is to remove the Viewing Telescope (objective and eyepiece) from the Eyepiece Adapter. The beam which exits the SPPDI enclosure may then be received and viewed on the live view screen of a digital camera with a suitably "fast" (large aperture) lens.



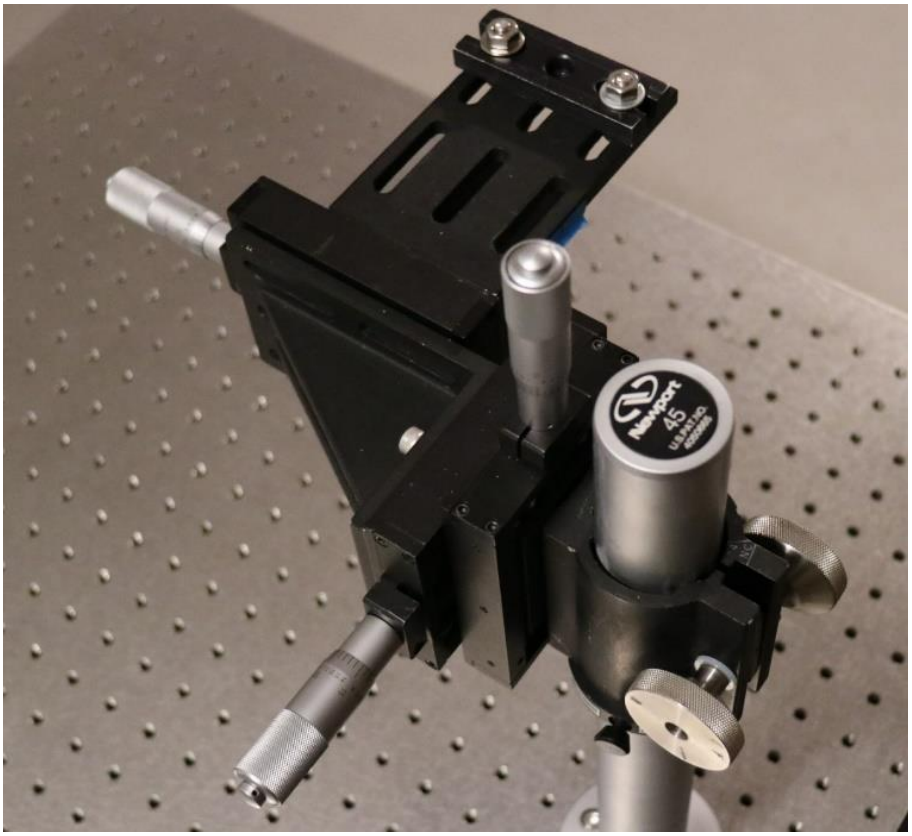
In the image on the left, interference fringes are recorded directly with a digital camera and suitable lens. In the image on the right, the interference fringes are relayed to a WiFi-connected display.

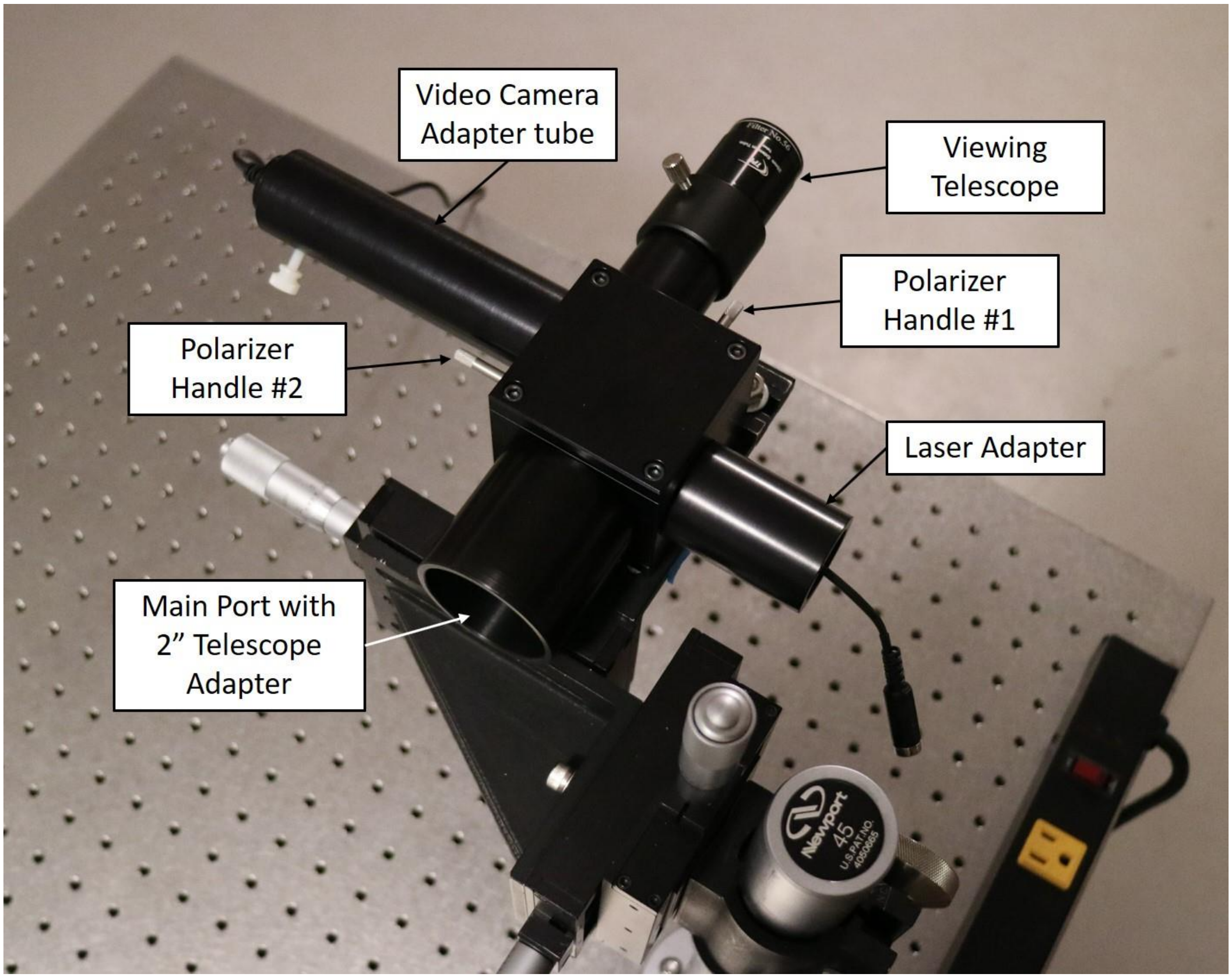
Bench-mounted Interferometry Setup

This test procedure describes a method for using the SPPDI® to obtain double-pass interferograms of telescopes, lenses, mirrors, optical windows, etc. A suitably mounted optical flat will be required for testing transmissive optics under autocollimation. An optical bench or other stable surface upon which to mount the SPPDI and other articles comprising the test setup is required. The test setup (equipment) should be located in an environmentally stable (low-vibration, low-temperature variation) testing environment.

Mount the SPPDI to an Optical Bench

1. Provide a stable mounting platform (*e.g.*, optical bench)
2. Arrange three micrometer-driven linear stages in an x-y-z configuration on an optical post attached to the bench
3. If required, attach an L-bracket type mounting platform to the three-axis linear stages
4. Attach the SPPDI to the L-bracket mounting platform with ¼-20 screws

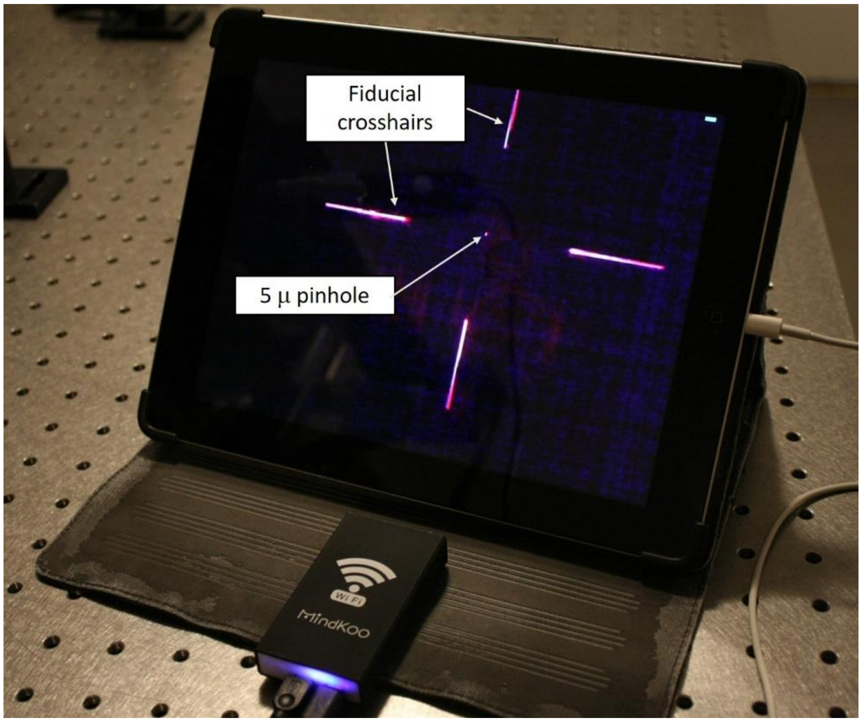




An older model of the SPPDI is shown attached to three micrometer-driven linear stages in an x-y-z arrangement. An optical flat (not shown here) may be a component of a setup for testing transmissive optics.

Connect the Video Alignment Camera

1. Connect the supplied video alignment camera USB power cord to a suitable 5-volt USB power source
2. Connect the video camera BNC connector to a display with an AV2 compatible input
3. Verify that the video camera signal is displayed correctly on the display



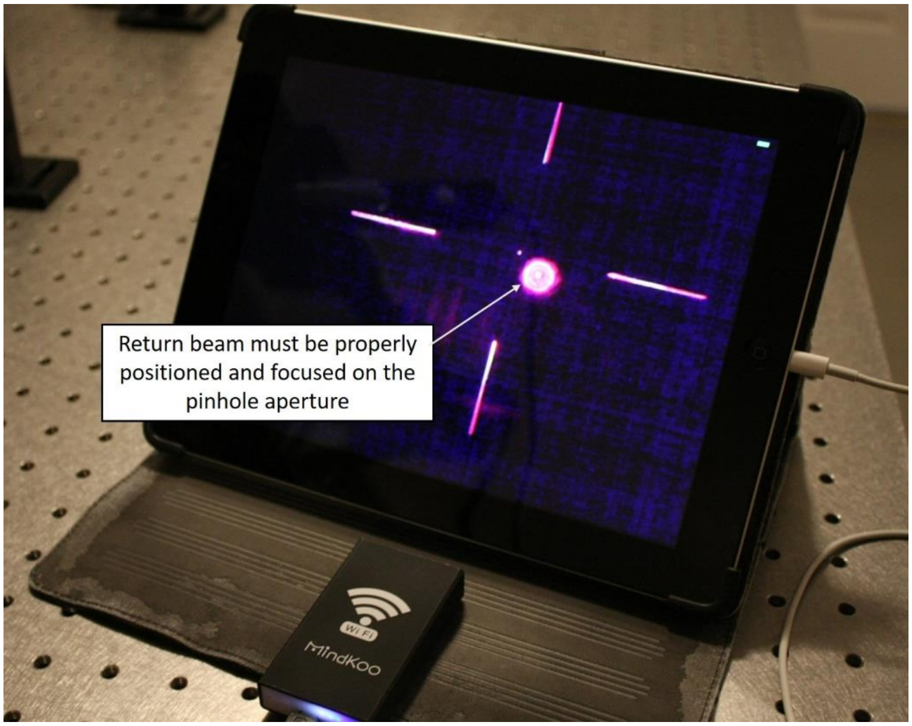
Adjust and Focus the Video Alignment Camera

1. Shine a flashlight or other illumination source into the objective lens end of the telescope
2. Loosen the thumbscrew on the side of the Video Camera Adapter tube
3. While watching the video display, rotate and slide the video alignment camera in and out until the crosshair fiducial marks and central 5-micron pinhole aperture are in best focus and oriented horizontally and vertically, then tighten the thumbscrew
4. Rotate Polarizer Handle #2 (near Video Camera Adapter tube) until the brightness of the fiducial marks is maximized, and make sure the Handle is centered in its through-hole in the SPPDI cubical enclosure

   Note: Due to small residual alignment errors in the video projection optics, the crosshairs and pinhole aperture will not be perfectly centered on the display. This residual misalignment has no impact on the performance of the SPPDI.

Turn on the Laser

1. The USB power supply must NOT be energized when plugging in the laser. Otherwise, the laser may be damaged by “in-rush” current.
2. Energize the USB power bank, and verify that laser light is emitted from the SPPDI.



Bring the Test Article into Alignment

1. Position a test article (including optical flat, if required) within the output beam from the SPPDI

   Note: for lens testing, make sure that the infinite conjugates side (generally the most curved side) of the lens faces away from the SPPDI. If the test article focal ratio is “faster” than f/8, a Kerry Optical Systems Focal Ratio Converter and appropriate microscope objective should be installed in the supplied 2” Telescope Adapter. The SPPDI should be mounted on a platform with micrometer-driven linear stages arranged in a 3-axis configuration to achieve both cross-range (X, Y) and down-range (Z, or focus) adjustments. Tip/tilt (elevation/azimuth) adjustability should also be provided either on the SPPDI mounting platform and/or the optical flat. If sufficient adjustability is provided for both the SPPDI and the optical flat, it should not be necessary to adjust the position or angular orientation of the test article itself.

2. Center the SPPDI output beam on the test article with the supplied laser alignment tool.

   Note: Turn the alignment tool on, and insert it into the 1.25” inside diameter of the 2” Telescope Adapter. The beam from the alignment tool represents the optical axis of the SPPDI. For reflective optics, make sure the laser spot is centered on the test article. For transmissive optics, make sure the beam is co-aligned with the optical axis of the test article.

2. While observing the video display, make gradual adjustments with the angular slow-motion controls until the incoming beam is visible on the video display.

   Note: The FOV (field of view) shown on the video display is very small, so fine angular adjustments will be greatly exaggerated.

3. When the return beam is visible on the video display, use the down-range (focus) controls on the SPPDI mount, and angular slow-motion controls on the optical flat mount and/or SPPDI mount to center and focus the incoming beam on the SPPDI pinhole aperture.

   Note: For testing a refractive test article (*e.g.*, telescope), make sure that the co-alignment between the SPPDI and the optical axis of the telescope is preserved.

4. Rotate Polarizer Handle #1 until the blanking segment obscures the incoming beam

   Note: the SPPDI Polarizer #1 (opposite the Main Port) is provided with a blanking segment. The blanking segment may be positioned in the beam by rotating Polarizer Handle #1 until the beam is blocked. The remaining light observed on the video display is the residual portion of the incoming beam that leaks through the pinhole aperture plate. This residual light leakage will become increasingly visible as the condition of best focus is approached. The residual light leakage provides visual feedback to assist fine-focusing and fine-positioning of the incoming beam on the SPPDI pinhole aperture.

5. While watching the video display, use the micrometer-driven linear stages on the SPPDI mount to fine-tune the focus and position of the PSF (point spread function) of the incoming beam on the pinhole aperture until the beam passing through the pinhole aperture is maximized

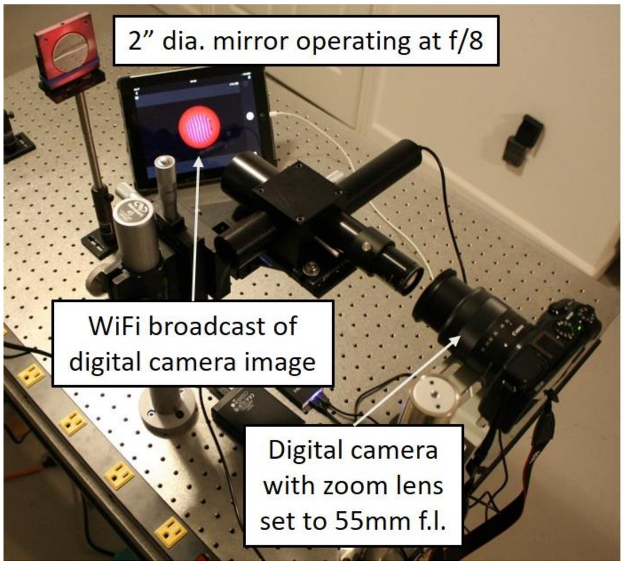
Adjust SPPDI Polarizer Handles for Best Observation of Interference Fringes

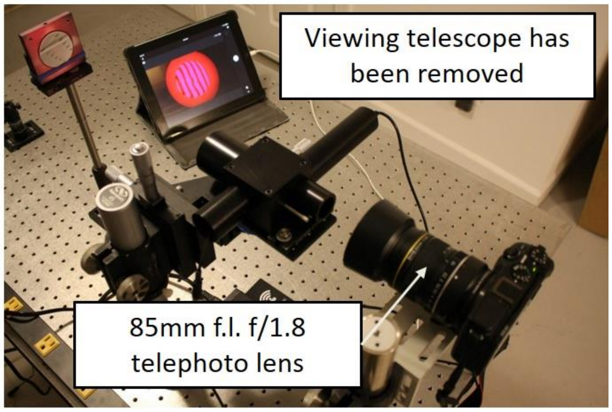
1. View the test article through the Viewing Telescope (or digital camera “live view” screen) while carefully adjusting Polarizer Handle #1
   a. Adjust the rotational orientation of Polarizer Handle #1 to maximize the contrast of the interference fringes
   b. Adjust the tilt of Polarizer Handle #1 to change the orientation and separation of the interference fringes

      Note 1: If the Viewing Telescope is used, the user-supplied 1.25” eyepiece should include a linear polarizing filter in order to enhance the visibility of interference fringes.

      Note 2: It should not be necessary to make adjustments with Polarizer Handle #2. Due to high angular sensitivity, it may be necessary to return to the previous step and make additional small adjustments to the position of the focused beam on the pinhole aperture.

   c. Residual fringe curvature (defocus) may be removed by adjusting the down-range position of the SPPDI
2. Interference fringes may be observed directly with the eye through the Viewing Telescope, or recorded with a digital camera positioned to receive light which exits the Viewing Telescope eyepiece. However, the preferred method is to remove the Viewing Telescope (objective and eyepiece) from the Eyepiece Adapter. The beam which exits the SPPDI enclosure may then be received and viewed on the live view screen of a digital camera with a suitably “fast” (wide aperture) lens.





In the image on the left, the viewing telescope is installed and the camera records the image projected by the viewing telescope eyepiece (eyepiece projection method). In the image on the right, the viewing telescope has been removed, and an image of the test article and interference fringes are recorded directly with the digital camera and camera lens.

1. Overview and Description of the SPPDI®

1.0. Overview of the SPPDI

The Split-path Point Diffraction Interferometer (SPPDI) is a patented extension of the Point Diffraction Interferometer (PDI) as described in 1972 by Dr. Raymond N. Smartt of the University of Massachusetts. (Reference R. N. Smartt and J. Strong, JOSA, 62, 737, 1972.). In the Smartt PDI, interference fringe spacing and fringe visibility (contrast) are coupled, which reduces operational practicality. The SPPDI separates this coupling, greatly improving the available range for fringe spacing and fringe visibility (*i.e.*, fringe contrast or dynamic range). For a full description of the SPPDI, refer to the SPPDI patent document (United States Patent # US005457533d, now expired), which can be found at the United States Patent Office website: www.uspto.gov.

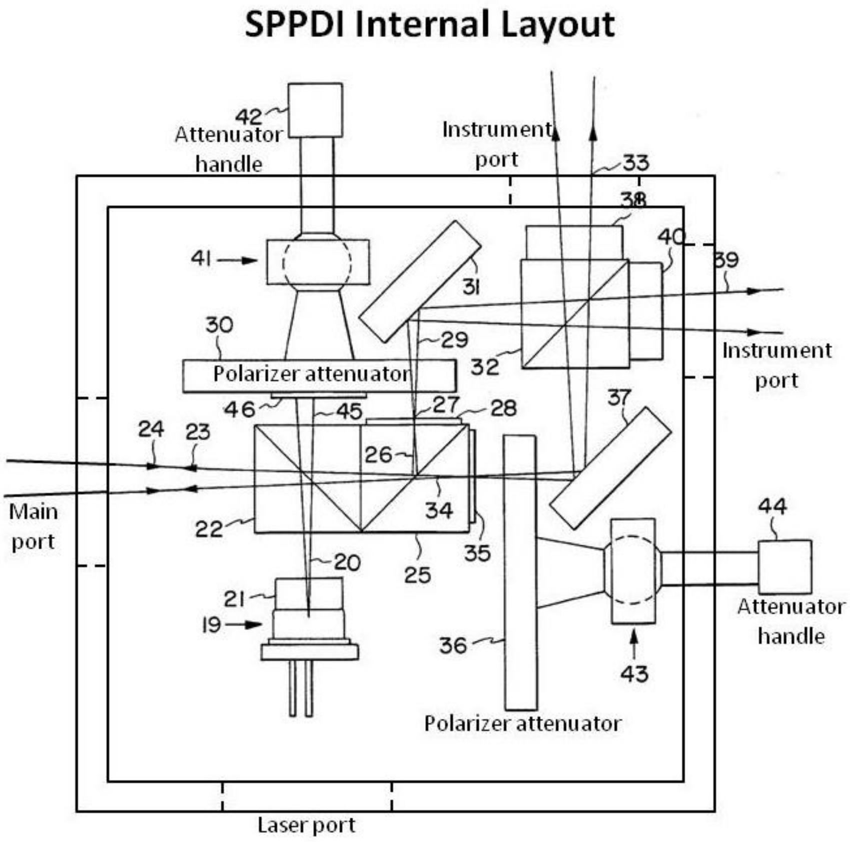
The compact optical design of the SPPDI and small internal beam footprint reduces the impact of optical figure errors that may be present in the internal optical components. Residual figure errors are easily measured by a Focal Ratio Converter available from Kerry Optical Systems. The compact size and sturdiness of the SPPDI enclosure helps ensure that the critical alignment of the internal signal and reference beam paths are maintained when exposed to the ambient environment. We are confident that the operational benefits and simplicity of operation of the SPPDI outweigh the added complexity, while retaining the core elegance and simplicity of a PDI.

Some types of interferometers (*e.g.*, Bath interferometer) require a physical displacement between the optical axis of the test article and/or the optical axis of the interferometer in order to generate interference fringes. The SPPDI, on the other hand, is used completely on-axis. A single diffraction-limited probe beam is emitted from the SPPDI. The aberrated signal beam is returned precisely along the same axis. The reference beam is generated internally within the SPPDI by splitting off and spatially filtering a portion of the aberrated signal beam. Because the outgoing probe beam and incoming signal beam are completely co-axial, it is possible to measure small mirrors or very small lenses with short focal lengths. There is never any astigmatism introduced by the need to separate external reference and signal beams. Those skilled in the art will be able to quickly and easily interpret "live" interferograms.

1.1. Physical Layout of the SPPDI

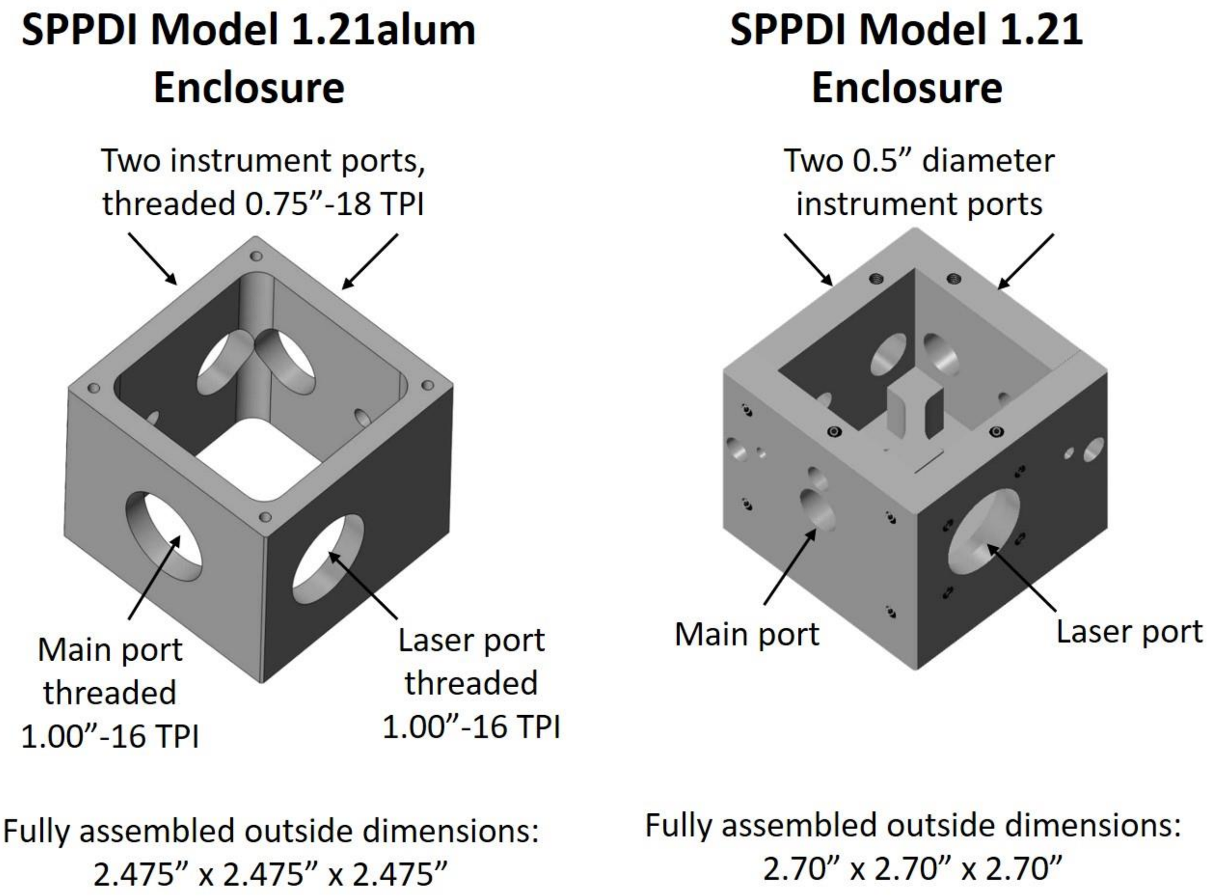
The SPPDI is comprised of a cube-shaped enclosure with four ports and a variety of internal optical and mechanical components. The following four figures **1.1.1.**, **1.1.2.**, **1.1.3.**, and **1.1.4.** provide internal and external schematic, graphical, and assembled views of the SPPDI.

See also: For more schematic diagrams, see Figure 3 of the patent.



21	Polarization "cleaner"
22	Non-polarizing beamsplitter cube
25	Non-polarizing beamsplitter cube
27	5-micron pinhole aperture
28	Pinhole aperture plate
30	Polarizer attenuator
31	Beam turning mirror
32	Non-polarizing beamsplitter cube
35	Optical thickness compensation plate
36	Polarizer attenuator
37	Beam turning mirror
38	Polarizer resolver
40	Polarizer resolver
41	Polarizer attenuator mount
42	Polarizer attenuator handle
43	Polarizer attenuator mount
44	Polarizer attenuator handle

Figure 1.1.1. Internal schematic view of the SPPDI®. The SPPDI comprises a variety of optical and mechanical components as shown in this figure. Note that in the commercial version of the SPPDI, the polarization "cleaner" (#21) is optically bonded to beamsplitter cube #22, instead of laser #19 as shown in the patent figure. Also note that the SPPDI polarizer attenuator mounts #41 and #43 comprise spherical bearings which provide for tip, tilt, and rotation adjustments of the polarizer attenuators. The polarizer resolvers (analyzers) #38 and #40 are no longer used in the commercial version of the SPPDI. Instead, the users is expected to attach a rotatable linear polarizing filter to the external viewing or recording instrumentation.



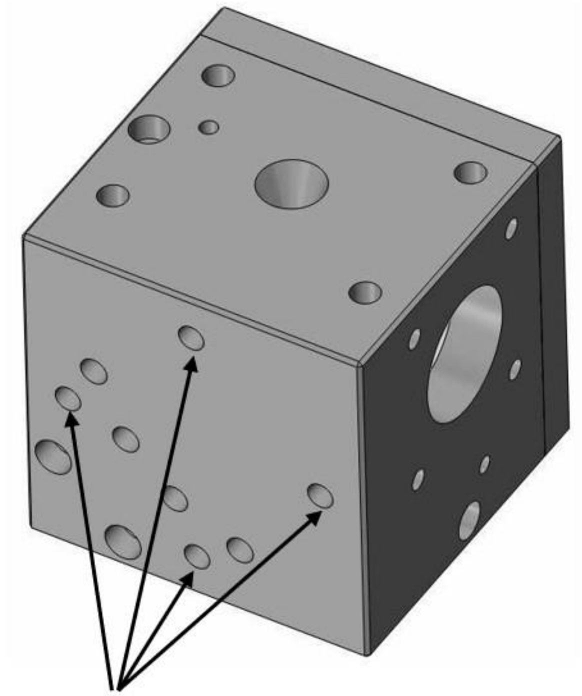
SPPDI Model 1.21alum Enclosure

Fully assembled outside dimensions: 2.475” x 2.475” x 2.475”

SPPDI Model 1.21 Enclosure

Fully assembled outside dimensions: 2.70” x 2.70” x 2.70”

Figure 1.1.2. Both SPPDI model enclosures are cube-shaped with four ports: 1) the main port centered on one face of the SPPDI; 2) a laser attachment port; and 3) two viewing or instrument ports. Both models use the same 3D printed attachments.



SPPDI Mounting Holes

Models 1.21 and 1.21alum

Four ¼”x20 TPI threaded holes on 2” centers

Figure 1.1.3. The bottom surface of the baseplate is provided with four 1/4"x20 TPI threaded holes on 2" (50.8 mm) centers for convenience in mounting to user assemblies.

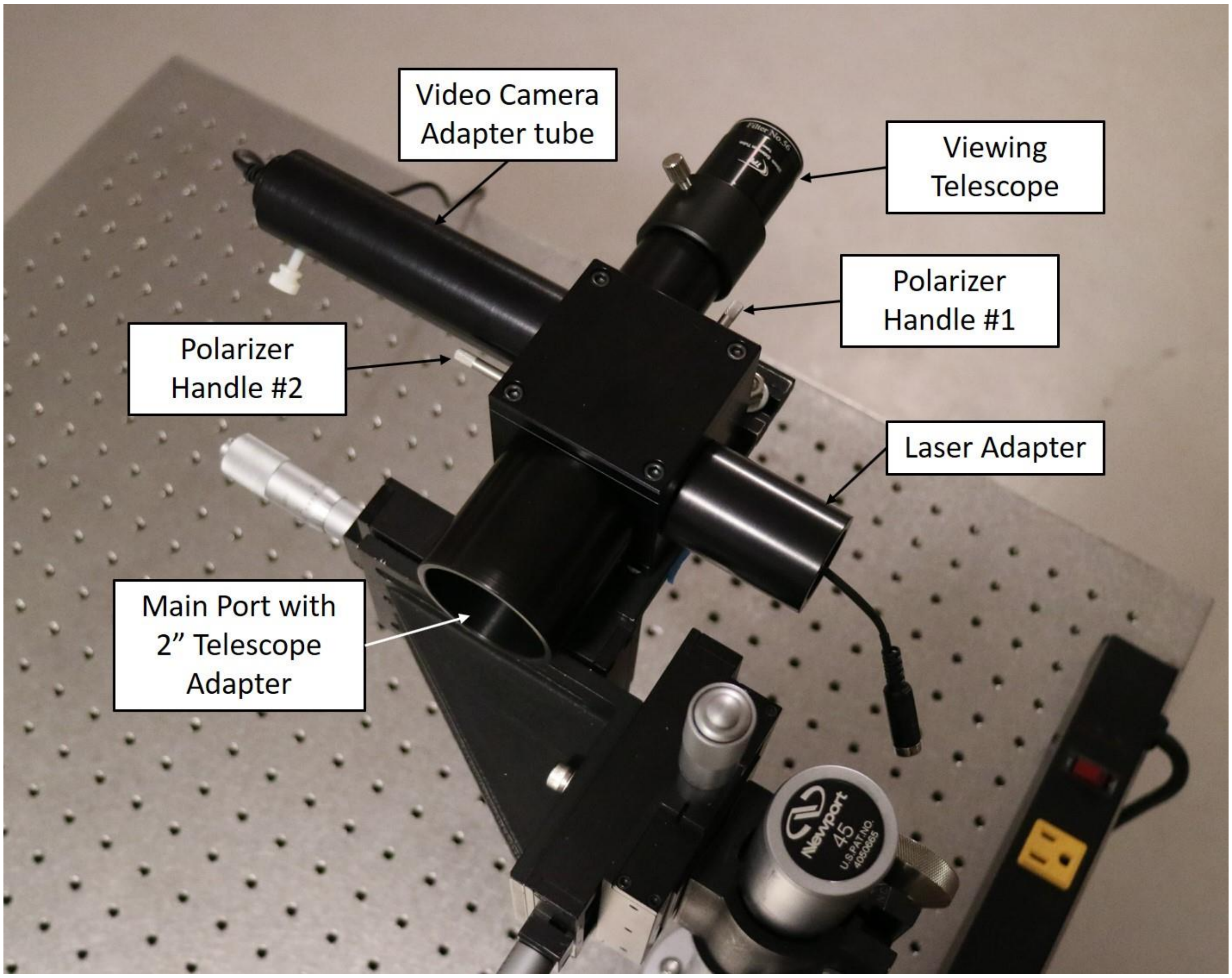


Figure 1.1.4. This is a fully assembled view of an older SPPDI® model, in a configuration suitable for testing a variety of optical components. The SPPDI includes a Video Camera Adapter with an included video camera, a 2" Telescope Adapter, a Laser Adapter, an Eyepiece Adapter, and a Viewing Telescope.

1.2. SPPDI® Attachments

The following sections describe the various attachments supplied with the SPPDI.

1.2.1. SPPDI Laser Adapter

⚠ **WARNING:** Removal of the Laser Adapter from the SPPDI will void its FDA/CDRH registration as a Class 1 (IEC 60825-1) or Class I (old system) laser product, CDRH Accession Number 1811033-000. The laser point source provided with the SPPDI is comprised of a commercial Class IIIa laser diode module (LDM) with the collimating lens removed. The NOHD (Nominal Ocular Hazard Distance) for the diverging beam produced by the lens-less LDM is about 6 inches. Viewing the diverging laser beam emitted by the lens-less LDM outside the SPPDI at a range closer than 6 inches without proper eye protection may result in ocular injury.

⚠ **Caution:** if the user chooses to remove the Laser Adapter and/or replace the laser module supplied with the SPPDI with their own laser source, the Laser Class designation and associated warning label supplied with the SPPDI will no longer apply. Furthermore, the SPPDI warranty will be voided.

The SPPDI can operate either in single-pass or double-pass mode. For double-pass interferometry, the SPPDI utilizes an internal laser point source (emission from a diode laser chip) supplied with the instrument. The laser point source is mounted in the Laser Adapter shown in Figure 1.2.1.1. The Laser Adapter is then installed in the SPPDI Laser Port. The laser point source is powered by connecting to a 5-volt USB power supply.

The laser point source provided with the SPPDI is comprised of a commercial Class IIIa laser diode module (LDM) with the collimating lens removed. After removal of the collimating lens, the LDM is inserted into the Laser Adapter. The Laser Adapter is retained, and slidably adjustable, against the external surface of the SPPDI by means of four screws. At assembly time, the position of the Laser Adapter is slidably adjusted until the virtual images of the diode laser chip and the pinhole aperture are in focus and overlap. The four screws are then tightened. Set screws in the barrel of the Laser Adapter allow the LDM to be: (1) adjusted along its axis until the diode laser chip is in coincident focus with the pinhole aperture; (2) tilted to bring the narrow axis of the beam into alignment with the SPPDI optical axis; and (3) rotated about its axis to set the SPPDI output beam power to the maximum allowed for a Class 1 laser device.

Although the Laser Adapter may be easily removed from the SPPDI enclosure, removal of the Laser Adapter for any reason (unless performed at the factory in case of warranty repair) will void the warranty and will void the CDRH registration of the SPPDI as a Class 1 (Class I) laser product.

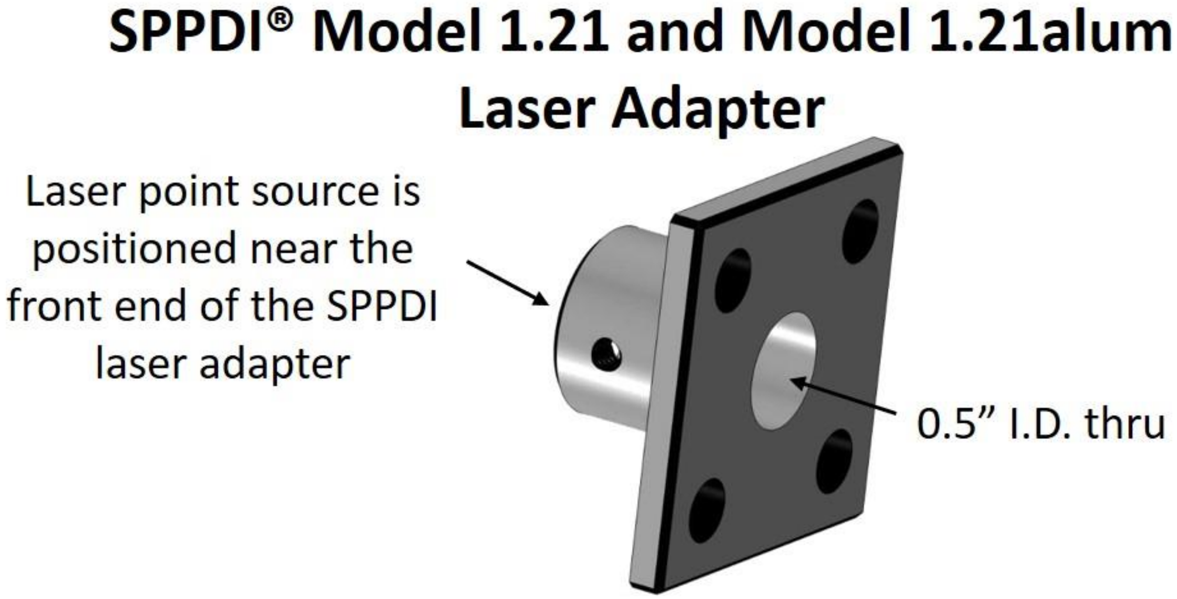


Figure 1.2.1.1. The Laser Adapter supplied with the Model 1.21 series SPPDI will accept cylindrical laser modules with diameters up to 0.5”. A commercial laser diode module, with collimating lens removed, is inserted into the SPPDI Laser Adapter. The tangential (x-y) position of the Laser Adapter and the longitudinal (z) position of the LDM within the Adapter are adjusted until the laser diode “chip” appears to be coincident and in focus with the SPPDI pinhole aperture. The rotational orientation of the LDM is adjusted until the laser power emitted from the Main Port of the SPPDI is less than the maximum laser power allowed for a Class 1 laser device. The set screws are then tightened.

The diverging beam emitted from the Main Port of the SPPDI is strongly elliptical in shape. Only the central f/8 or slower portion of the beam has a uniformity that is acceptable for interferometry. The user of the SPPDI will need to purchase a Focal Ratio Converter (“transmission sphere”) which will enable the measurement of optical systems that are faster than f/8. The Focal Ratio Converter is also required in order to calibrate the SPPDI using a “random ball test” or suitably accurate concave reference mirror.

After exiting the SPPDI, the beam intercepts the user's test article (lens, mirror, or optical system that is being tested). The signal beam returned by the user's test article (along the same beam path) re-enters the interferometer through the Main Port, where it is then divided into several paths. One path brings the incoming signal beam to a focus at or near the laser point source where it originated. Another path brings the incoming signal beam to a focus on the pinhole aperture, where the signal beam is spatially filtered by the pinhole aperture. The spatially filtered beam re-emerges from the pinhole aperture as an expanding spherical reference beam. A third path, which carries the wavefront information (signal) produced by the test article, comes to a focus inside the SPPDI at the virtual position of the pinhole aperture, and then diverges again without modification. The reference and signal beams pass through respective polarizing filters and are re-directed by beam turning mirrors to the final beam combining beamsplitter cube, where the reference and signal beams are combined. The diverging combined beams exit the interferometer through the two instrument ports, and into the interferogram viewing or recording devices. The recording or viewing device must include a linear polarizer resolver (analyzer) to achieve high contrast interference fringes.

The signal and reference beam paths within the SPPDI are very nearly identical. This enables the use of low-cost diode lasers with short coherence lengths. Although the SPPDI is a type of common-path interferometer, it should be noted that the signal beam encounters about 32 mm of physical path length through internal glass beamsplitters, which will add a small amount of spherical aberration to the signal beam. This spherical aberration is negligible for signal beams with a focal ratio “slower” than f/8. “Faster” beams require the use of a Kerry Optical Systems Focal Ratio Converter, which also facilitates removal of residual instrumental errors.

1.2.1.1. An Important Word about Laser Safety

The laser supplied with each standard SPPDI model is based on a modified commercial Class 3R (IEC 60825-1) or Class IIIa (old system) collimated laser diode module (LDM), operating at a wavelength of 650 nm, with a CW (continuous wave) optical output power of about 5 mW (milliwatts). The collimating lens is removed before the LDM is installed in the Laser Adapter. The lens-less LDM emits a strongly diverging laser beam, with an NOHD (Nominal Ocular Hazard Distance) of about 6 inches. After the collimating lens is removed, the lens-less LDM is installed in the Laser Adapter, and the Laser Adapter is attached to the SPPDI enclosure. Internal losses associated with the SPPDI internal apertures and optical components limit the optical output power of the diverging laser beam emitted by the SPPDI at the Main Port to less than 0.35 mW. Every SPPDI unit is tested at the factory with a calibrated laser power meter to assure that the exit beam power is less than 0.35 mW.

The 0.35 mW diverging beam exits the SPPDI Main Port with a beam diameter of 0.68 cm and with a focal ratio of f/5.5 (10.4 angular degrees full angle). If this beam were collimated with a diameter of 0.7 cm and allowed to enter the pupil of the eye, it would be below the AEL (Accessible Emission Limit, or Accessible Exposure Limit) value of 0.39 mW for a Class 1 laser device. A 0.7 cm diameter collimated laser beam with a beam power of 0.35 mW would produce an exposure (irradiance) of 0.0009 W/cm^2 at the cornea, which is less than the MPE (Maximum Permissible Exposure) of 0.001 W/cm^2 (per IEC 60825) for continuous exposure to a 650 nm collimated laser beam. These values for the AEL and MPE are considered safe levels for long-term viewing or exposure by the CDRH (Center for Devices and Radiological Health), a division of the FDA (Food and Drug Administration).

When the total 0.00035 W exit beam power is averaged over the 0.0258 steradian (0.0258 sr) solid angle of the f/5.5 light cone which passes through the 0.68 cm diameter (0.363 cm^2) SPPDI exit aperture, the beam radiance is 0.037 watts per square cm per steradian (0.037 W/(cm^2/sr)).

⚠ **WARNING:** Removal of the Laser Adapter from the SPPDI will void its FDA/CDRH registration as a Class 1 (IEC 60825-1) or Class I (old system) laser product, CDRH Accession Number 1811033-000. The laser point source provided with the SPPDI is comprised of a commercial collimated Class IIIa laser diode module (LDM) with the collimating lens removed. The NOHD (Nominal Ocular Hazard Distance) for the diverging beam produced by the lens-less LDM is about 6 inches. Viewing the diverging laser beam emitted by the lens-less LDM outside the SPPDI at a range closer than 6 inches without proper eye protection may result in ocular injury.

⚠ **Caution:** if the user chooses to remove the Laser Adapter and/or replace the laser module supplied with the SPPDI with their own laser source, the Laser Class designation and associated warning label supplied with the SPPDI will no longer apply. Furthermore, the SPPDI warranty will be voided.

Although caution when viewing light derived from a laser source is always advised, direct viewing of the laser light exiting the SPPDI instrument ports through the supplied Viewing Telescope is one of the available operational modes for the SPPDI. This is safe because the optical output power emitted from the instrument ports of an unmodified CDRH-registered SPPDI, when properly adjusted for viewing high contrast interference fringes, is typically in the sub-microwatt (nanowatt) range. When viewed with the viewing telescope supplied with the SPPDI, the test article appears as an extended source covering a large portion of the retina, at a comfortable and safe level of optical power.

As a further precaution, if the user is still concerned about observing the laser light exiting the SPPDI through the supplied Viewing Telescope, a digital camera with a sufficiently large sensor (*e.g.*, APS-C size sensor) and a mild telephoto lens (*e.g.*, 85 mm focal length) may be placed near the supplied eyepiece of the Viewing Telescope to intercept and display the light exiting the SPPDI instrument port. Alternatively, the Viewing Telescope may be completely removed, and a digital camera may be placed to intercept the beam without intervening optics except for the camera lens.

1.2.2. Video Camera Adapter

The SPPDI is supplied with a Video Camera Adapter comprising an installed “bullet” type security video camera. The camera output (signal) cable is terminated in a BNC connector. The camera requires 5-volt DC power to operate, which may be conveniently supplied by a USB power bank. A USB power cable is supplied, but the user must supply the USB power bank or battery. The camera output signal is of type AV2, which may be displayed on a video display or monitor which accepts AV2 type inputs.

The Video Camera Adapter is slidably attached to the enclosure by means of four screws. These four screws can be loosened and the x-y position of the Adapter adjusted so as to center the image of the pinhole and fiducial marks on the video display.

A relay lens assembly is located inside the Video Camera Adapter, which projects a magnified image of the SPPDI pinhole aperture and crosshair fiducial marks onto the video camera sensor. To focus the image of the crosshairs and pinhole aperture on the video camera sensor, it is necessary to loosen the Nylon thumb screw on the side of the Video Camera Adapter tube and slowly adjust the axial position and rotational orientation of the video camera while watching the video display. When the crosshairs and pinhole aperture are in good focus, with the crosshairs aligned vertically and horizontally on the display, the position of the camera is retained by tightening the Nylon thumbscrew located on the side of the Video Camera Adapter tube.

Note: The image that appears on the computer monitor will appear greatly magnified.

As a tip, the user may find it helpful to shine light from a desk lamp or flashlight into the Main Port of the SPPDI enclosure to provide illumination of the pinhole aperture and crosshairs while focusing the video camera. As shown in Figure 1.2.2.1., the pinhole aperture lies at the intersection of the crosshairs.

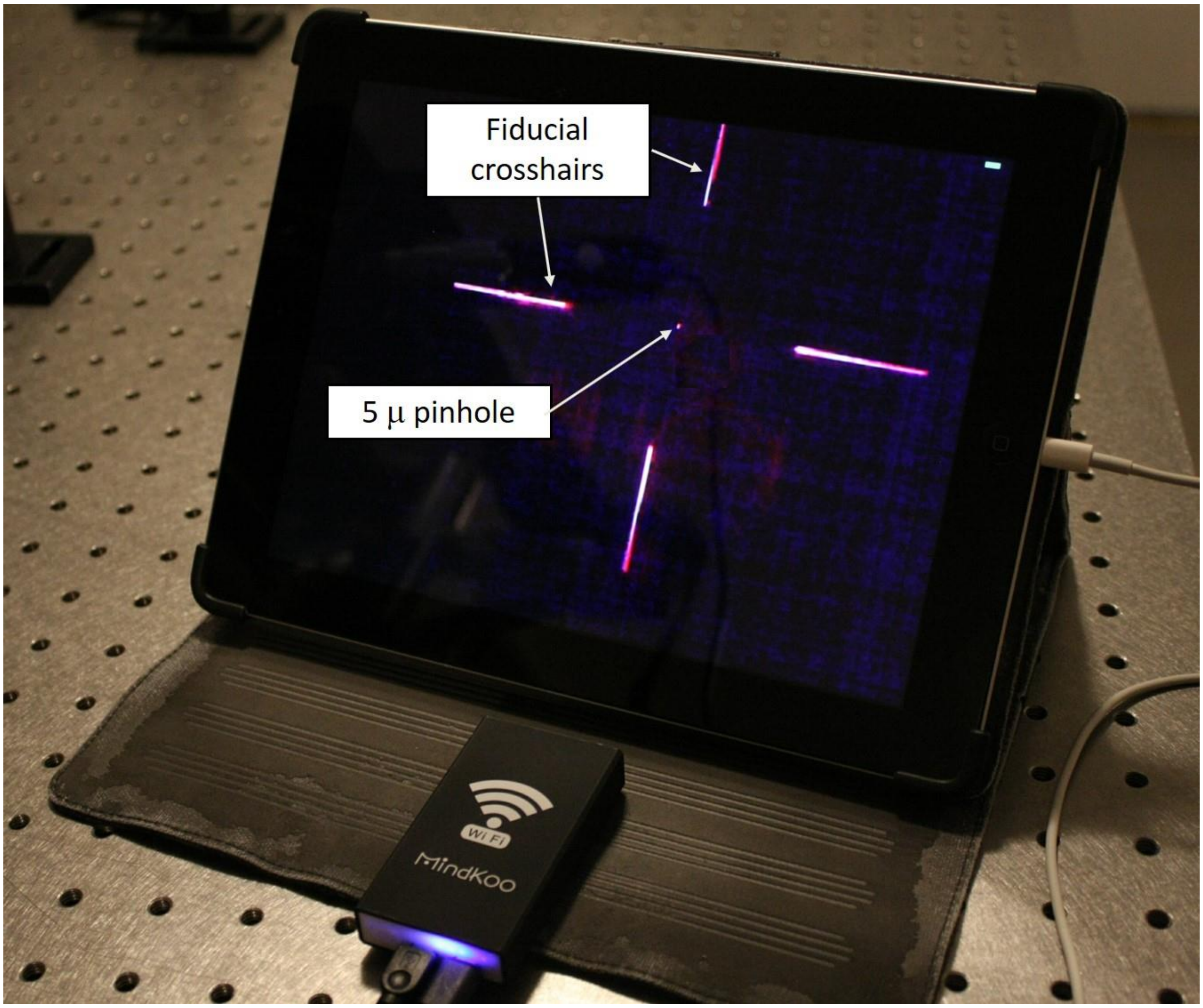
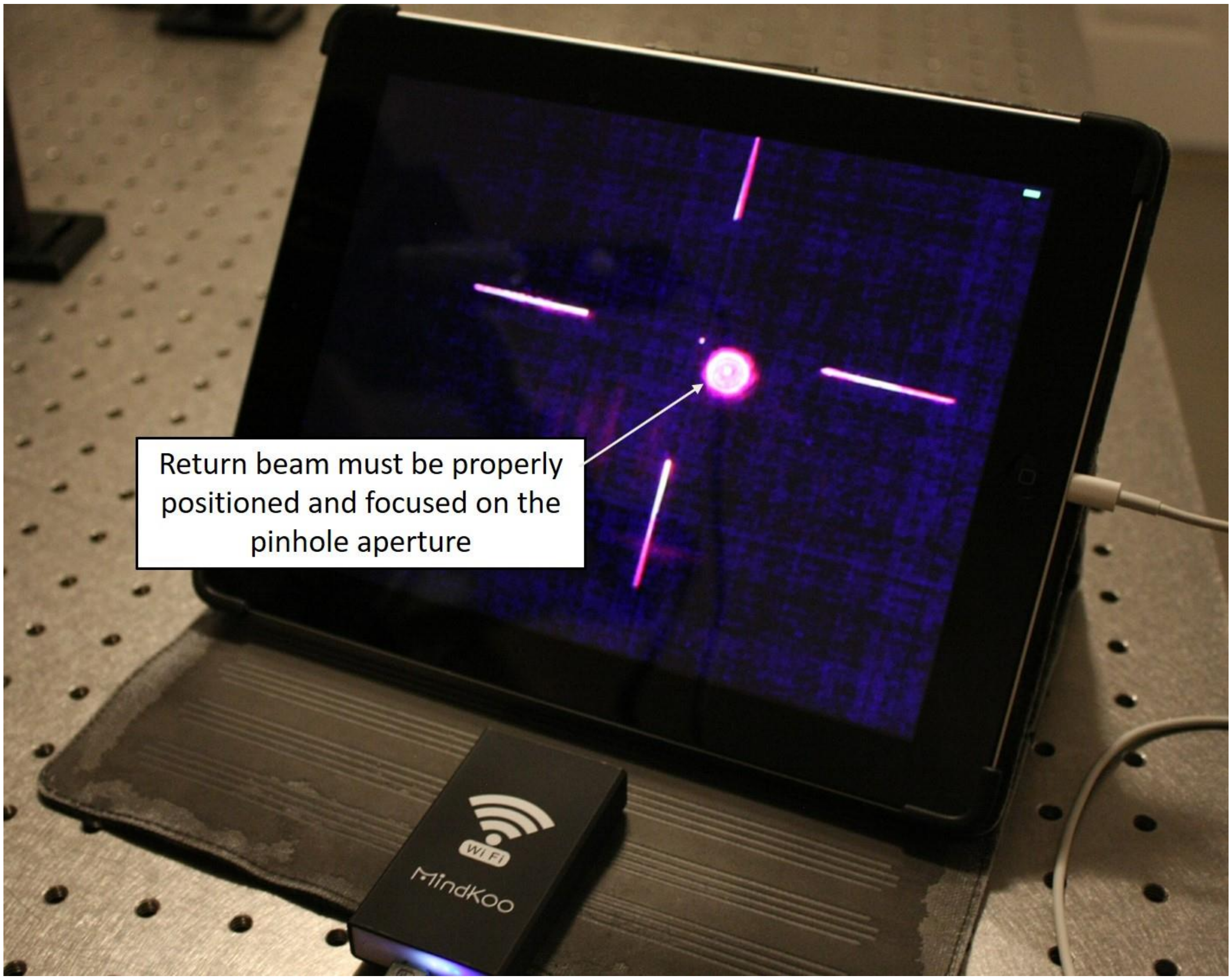


Figure 1.2.2.1. The SPPDI alignment video camera displays an image of the SPPDI pinhole aperture and crosshair fiducial marks, which are illuminated by light from a desk lamp or laser source shining through the SPPDI Main Port.

Figure 1.2.2.1. shows that there is a slight mechanical misalignment in the optical system which produces the image of the pinhole aperture and crosshairs. This misalignment is greatly magnified on the video display image, but does not indicate that there is a problem with the SPPDI.

When the SPPDI is in use, and the incoming signal beam is near the position of the pinhole aperture and is close to being focused on the pinhole aperture, there will be sufficient leakage of laser light through the coating on the pinhole aperture plate to enable completion of the focusing and alignment process, as shown in Figure 1.2.2.2.



Return beam must be properly positioned and focused on the pinhole aperture

Figure 1.2.2.2. Light leakage through the SPPDI pinhole aperture coating enables the incoming signal beam to be observed.

1.2.3. Eyepiece Adapter

The SPPDI Eyepiece Adapter is designed to accept the smaller (0.965” diameter) end of the Viewing Telescope supplied with the SPPDI. Use of the Viewing Telescope is optional, and is only used for visual inspection of interference fringes (*i.e.*, without a camera).

1.2.4. Viewing Telescope

The SPPDI Viewing Telescope is intended to enable visual inspection of interference fringes. The small end of the Viewing Telescope is designed to slide into the Eyepiece Adapter. The Viewing Telescope comprises a 17 mm diameter 40 mm focal length achromatic objective lens at the narrow end. A suitable 1.25” diameter telescope eyepiece must be supplied by the user, along with a linear polarizing filter to enhance fringe visibility. This Viewing Telescope may be focused by loosening the Nylon set screw and sliding the eyepiece in or out in order to bring the test article into proper focus. A digital camera may be positioned near the eyepiece to record interferograms using eyepiece projection. However, for improved image quality, the viewing telescope should be removed from the Instrument Port before using a digital camera to record interferograms.

1.2.5. 2" (50.8 mm) Telescope Adapter

The SPPDI is provided with a 2" (50.8 mm) diameter Telescope Adapter, to enable the user to easily attach the SPPDI to telescopes which have 2" (50.8 mm) diameter focusers. The Telescope Adapter is slidably attached to the SPPDI enclosure with four screws, which permits precise alignment of the Telescope Adapter with the optical axis of the SPPDI during assembly. (The Telescope Adapter should not be removed by the user.) In addition, the Telescope Adapter has an internal diameter of 1.25”, which will accept the laser collimator which is supplied with the SPPDI. This laser collimator beam defines the optical axis of the SPPDI, and allows the optical axis of the SPPDI to be precisely aligned with the test article.

1.2.6. Fringe Adjustment Handles

The SPPDI is provided with two fringe adjustment handles. These handles are attached to internal rotatable and tiltable polarizing filters, which allow the user to adjust the overall brightness, contrast, and spacing of the interference fringes. Operation of the fringe adjustment handles is intuitive and very easy.

1.2.7. Focal Ratio Converters

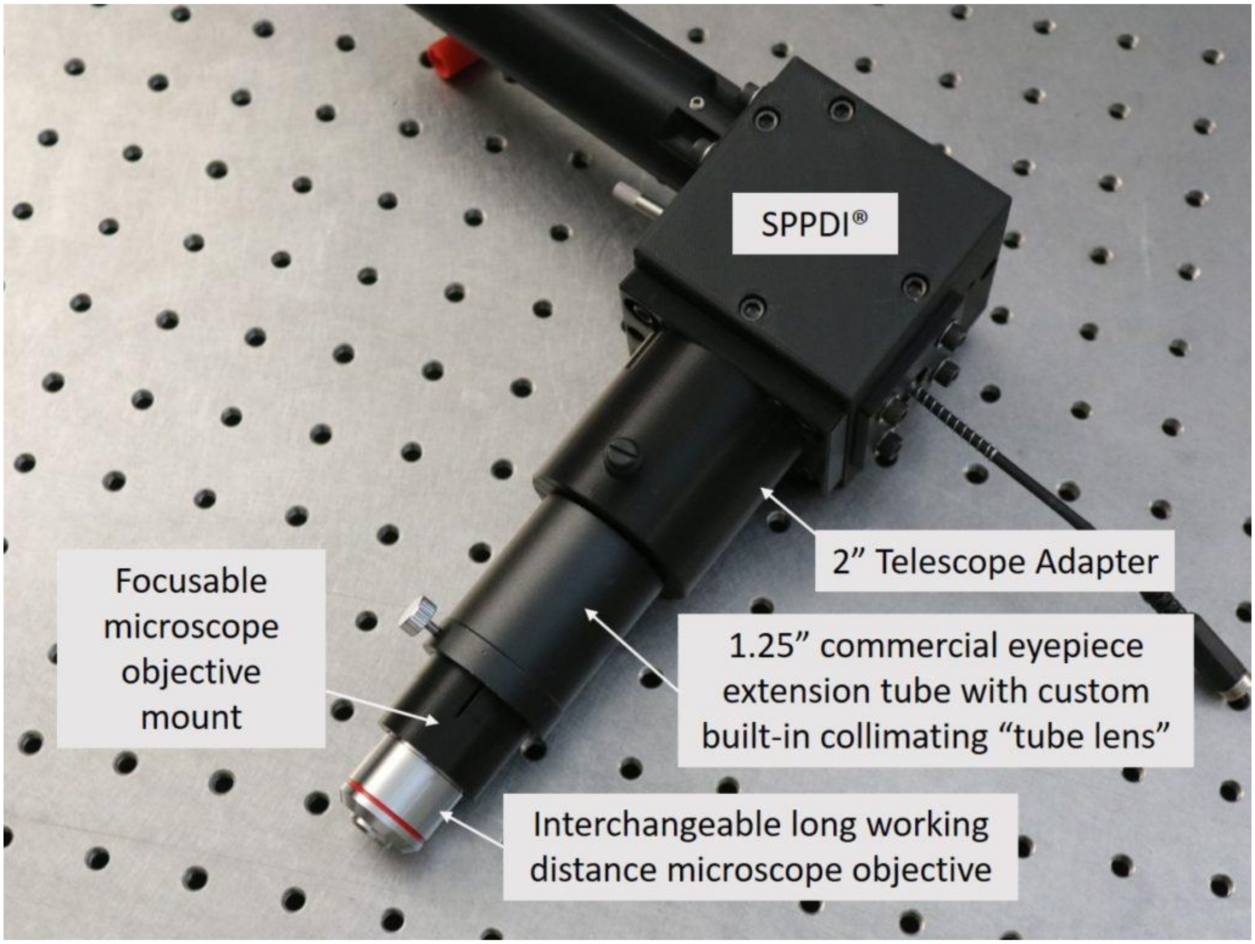
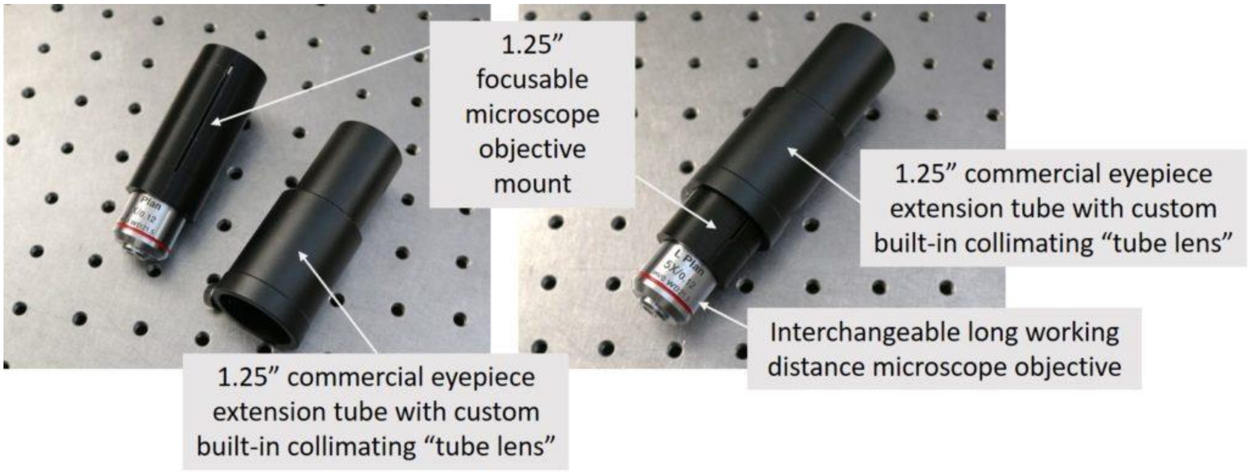


Figure 1.2.7.1. This figure shows the components that comprise an optional focal ratio conversion (FRC) setup, consisting of a 2" OD 1.25" ID Telescope Adapter (supplied with the SPPDI), a COTS (commercial off-the-shelf) 1.25" telescope eyepiece extender with an installed custom collimating lens (also known as a "tube lens") which can be purchased from Kerry Optical Systems, a 1.25" diameter focusable microscope objective mount which can be purchased from Kerry Optical Systems, and a user-supplied microscope objective.

Focal Ratio Converters (FRC units, Figure 1.2.7.1.) are highly recommended optional devices available from Kerry Optical Systems. The SPPDI by itself is limited to focal ratios no faster than about f/6, although f/8 is recommended as the lower limit. The beam emitted by the SPPDI is derived from an internal bare diode laser, which passes through several optical components before exiting the SPPDI. The signal beam returned by the test article encounters several internal beam splitters and other optical components inside the SPPDI, before the combined signal and internally-generated reference beams exit the SPPDI. The SPPDI internal optical components introduce small wavefront errors into the combined signal and reference beams. Careful choice and placement of the SPPDI internal components limit the errors to very small values, typically less than a hundredth of a wave.

However, these small errors, along with the f/6 or "slower" focal ratio constraint, limit the general usability and accuracy of the SPPDI. These limitations are addressed by the Kerry Optical Systems FRC units (commonly known as "transmission spheres"). Use of these FRC units provide the means to remove instrumental errors from measurements obtained with the combination of the FRC unit and the SPPDI.

These FRC units comprise two parts: (1) a 3D-printed Tube Lens Collimator (TLC) with an internal achromatic collimating lens mounted in the small (1.25" OD) end of the COTS (commercial off-the-shelf) eyepiece extender; and (2) a Microscope Objective Adapter (MOA) compression mount that fits in the eyepiece end of the COTS eyepiece extender. The "tube lens" receives the diverging beam from the SPPDI and collimates the beam to a diameter that just overfills the rear aperture (typically 8 or 9 mm) of interchangeable microscope objectives that screw into the RMS threaded end of the MOA.



Each microscope objective produces a converging output beam which has a focal ratio governed by the NA (numerical aperture) of the microscope objective. For example, a 10x objective with an NA of 0.25 will produce an output beam from the microscope objective with a focal ratio of f/2. A 5x microscope objective with an NA 0.12 will produce an f/4 output beam. "Faster" output beams can be achieved with higher NA objectives.

The combination of the FRC unit and SPPDI may be calibrated by means of either a "random ball test" (in the manner described in the literature) or by means of a suitably accurate reference sphere. In order to perform calibration via a random ball test, the user must provide a microscope objective with a long (>15mm) working distance.

We have found that calibration with the use of an accurate reference sphere is much less time consuming than with a random ball test. We have identified a source for very accurate (<1/10th wave at 633 nm) 2" diameter laser quality fused silica plano concave lenses with short radii on the concave side. One of these lenses is available with a radius of curvature of 50 mm. We have found the concave side of the 50 mm radius lens to be ideal as a reference sphere to cover a very wide range of focal ratio produced by various microscope objectives.

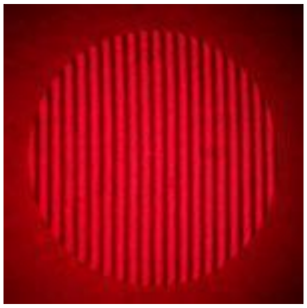
These FRC units allow correction wavefronts to be produced, which can then be subtracted from wavefronts obtained for the test article. This process allows removal of the errors associated with the FRC unit as well as the SPPDI. Microscope objectives with substantial optical aberrations can even be used with FRC units. If done correctly, the remaining wavefront errors will be only those associated with the test article.

Like most aspects of interferometry, there is a significant learning curve associated with becoming proficient with the use of our FRC units. Some cautions are listed below.

(1) FRC units should only be used in connection with measuring test articles in setups that produce converging spherical wavefronts. Otherwise, beam aberrations will introduce "retrace" wavefront errors in the FRC unit optics. Software-based correction of retrace errors within microscope objectives used in the FRC units is not possible.

(2) The MOAs are focusable within the eyepiece extender. This allows a focused image of the test article to be projected to infinity. The focus of the camera lens can then be adjusted to infinity to produce a focused image of the test article. Short and long MOAs are available to help obtain a focused image of the test article over a range of distances to the test article.

Some situations may not allow a focused image of the test article to be projected to infinity. This may require the use of a dedicated "macro" type camera lens in order to achieve a focused image of the test article, or a less expensive close-up or "macro" lens attached to the front of a standard camera lens.



Close-up attachment lenses can produce quite good results as shown in this interferogram of a 4.25” diameter 34" radius concave spherical mirror. This interferogram was obtained with an FRC unit operating at f/8 and a 10x close-up lens attached to the front of an 85 mm focal length f/1.8 telephoto lens.

(3) The interferogram and associated wavefront for the test article should be obtained first, with a DFTFringe measurement outline that is suitable for the test article. This same outline must then be used in obtaining the correction wavefront from the reference sphere interferogram. This will typically mean that the outline used in producing the wavefront for the reference sphere will be substantially smaller than the full clear aperture of the reference sphere interferogram.

Purchase of Focal Ratio Conversion units may be initiated by contacting Kerry Optical Systems, LLC.

1.2.8. Calibration Optics

1.2.8.1. Random Ball Test Kit

Kerry Optical Systems now offers 1" diameter Grade 5 silicon nitride balls for measuring and removing instrumental errors associated with the SPPDI® when used with a Focal Ratio Conversion ("transmission sphere") unit. The 1" balls are supported on a triangular base of three 0.5" diameter silicon nitride balls. The three balls at the base are potted with paraffin wax in a 3D printed triangular mount. This 3-point mount allows precise repositioning of the 1" ball as the ball is rotated randomly in yaw and pitch between successive interferograms.

After many interferograms are obtained, an average wavefront may be computed which can be subtracted from the wavefront of a test article in order to remove the instrumental errors associated with the SPPDI with its attached focal ratio conversion unit. Note that the 0.5" radius silicon nitride ball supplied with this kit requires a converging wavefront with a working or standoff distance of at least 15 mm.

The statistical procedure associated with the random ball test is described in the paper “Interferometer Calibration using the Random Ball Test,” Wenrui Cai, Dae Wook Kim, Ping Zhou, Robert E. Parks, James H. Burge. This paper provides experimental evidence that accurate interferometer calibration may be achieved with a Grade 5 silicon nitride sphere.

Purchase of the Random Ball Test Kit can be initiated by contacting Kerry Optical Systems, LLC.

1.2.8.2. Concave Spherical Reference Mirror

Kerry Optical Systems can provide very high accuracy (< λ/10 p-v at 633nm before coating over the clear aperture) 2" diameter concave fused silica (Corning 7980 1-D) spherical mirrors (uncoated) with radii of curvature of either 51.5 mm or 128.8 mm. These are ideal for obtaining a correction wavefront for removing all instrumental errors (including focal ratio conversion unit plus SPPDI) from measurements of a test article. Please note that the longer radius mirror is suitable for removing the instrumental errors of the SPPDI itself, but may not be suitable for use if the focal ratio conversion attachment is in use with a high NA microscope objective. Conversely, the short radius mirror will NOT work for measuring instrumental errors of the SPPDI by itself, due to lack of sufficient working distance between the mirror and the front of the SPPDI.

Kerry Optical Systems does not supply these mirrors, but will be happy to provide further details for where to obtain these mirrors.

2. SPPDI® Operation

2.0. Measurement Environment

Operation of the SPPDI requires that the signal beam produced by the user's test article be accurately focused and positioned on the SPPDI internal pinhole aperture. The pinhole aperture is very small (5 microns in diameter). As with any interferometry setup, it is essential to limit ambient vibrations and temperature variations to a low level, as well as to have precision positioning equipment to adjust the focus and lateral position of the incoming beam on the SPPDI pinhole aperture with micron-level precision. This is facilitated by use of stable mounting equipment and micropositioners and/or precision angle adjusters.

2.1. Measurement Setup

Two different methods or approaches can be used to set up the SPPDI for interferometry, as described in the Getting Started section. One configuration involves mounting the SPPDI on a stable optical bench, as shown in Figure 2.1.1. A second configuration is shown in Figure 2.1.2., where the SPPDI is directly attached to a telescope by means of the 2" (50.8 mm) diameter Telescope Adapter supplied with the SPPDI.

With either of these setups, fine positioning of the focused beam on the pinhole aperture requires very fine angular adjustments of either the telescope mount, or the optical flat used under autocollimation to return the beam for double-pass interferometry. Low backlash positioners are very helpful.

Higher end telescope mounts are typically supplied with fine adjustment mechanisms on the elevation and azimuth (or right ascension and declination) axes. Alternatively, an optical flat used under autocollimation for double-pass interferometry may be mounted in a gimbal type mount which has fine angular adjustment capability.

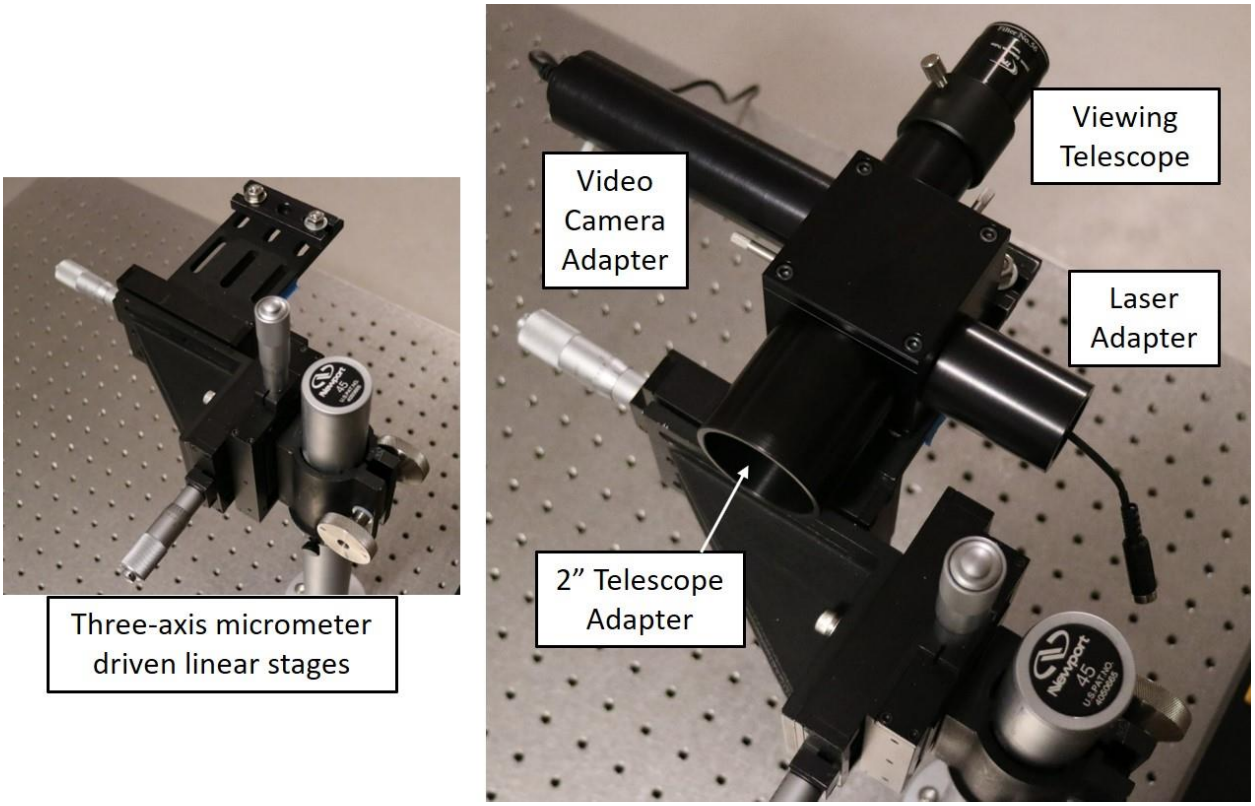


Figure 2.1.1. Micrometer driven precision linear stages are used to obtain micron-level focusing and positioning of the signal beam on the SPPDI pinhole aperture. (Note that the figure on the right shows an earlier version of the SPPDI.)

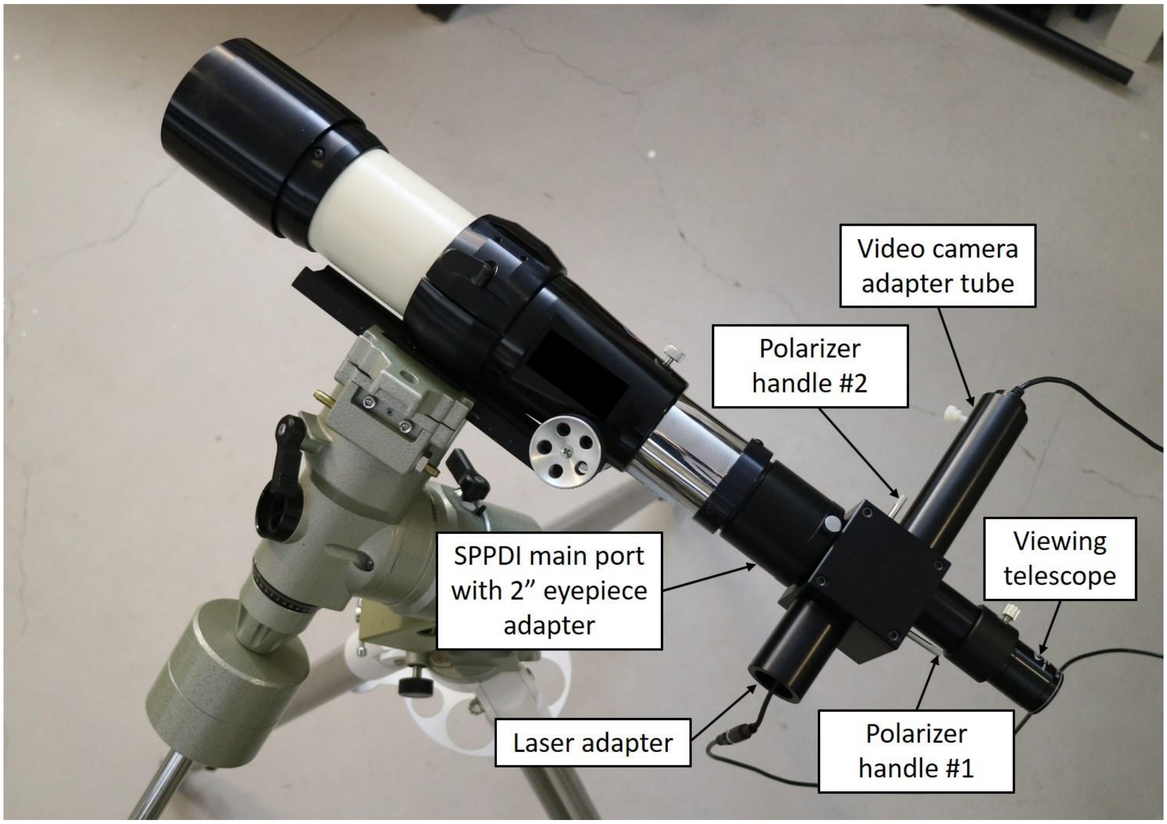


Figure 2.1.2. This type of setup may be used for in-situ interferometry of telescopes. Right ascension and declination slow motion controls on the telescope mount or optical flat mirror mount are used to achieve small angular adjustments for positioning the signal beam on the SPPDI pinhole aperture. Large aperture or long focal length telescopes will require very precise angular adjustments.

2.2. SPPDI Ideal Focal Ratio

The user's test article should have a focal ratio ("speed") greater (“slower”) than or equal to f/8. Although “faster” optical components or systems may be tested with the SPPDI, at focal ratios "faster" than f/6, internal aberrations (spherical aberration and astigmatism) arising within the SPPDI optics rapidly increase. In particular, a small amount of spherical aberration will be added to the signal beam due to the 32 mm of glass thickness within the SPPDI signal beam path. At a focal ratio of f/10, this additional spherical aberration is entirely negligible. It is still small at f/8, but increases rapidly at “faster” focal ratios. Astigmatism arises within the internal polarizing attenuators when the 2 mm thick attenuators are tilted by a few (1° - 3°) angular degrees in order to vary fringe spacing. Again, this amount of astigmatism is negligible at small attenuator tilt levels or focal ratios “slower” than f/10, but increases rapidly as the attenuators are tilted when operating at “faster” focal ratios.

If the user’s test article is “faster” than f/8, the user should consider the use of the Focal Ratio Converter products available from Kerry Optical Systems, as described in a previous section of this manual.

Use of a Barlow (negative) lens is also possible as a means for testing incident beams faster than f/8, but requires the eyepiece end of the Barlow to be removed so that the Barlow lens may be inserted into the 1.25” inside diameter of the Telescope Adapter in the proper orientation, *i.e.*, with the eyepiece end of the Barlow facing the SPPDI enclosure. In addition, the optical aberrations exhibited by an SPPDI setup comprising a Barlow lens will be difficult to assess without the use of a sufficiently “fast” calibrated concave reference mirror. If a suitable concave reference mirror is obtained, then a correction wavefront may be obtained with the Barlow lens, and then subtracted from the wavefront of the test article in the manner described previously for use of the Kerry Optical Systems Focal Ratio Converter units. (Note that a “random ball test” is not possible because there is no accessible focus outside the SPPDI enclosure).

2.3. SPPDI Operational Modes

The SPPDI can operate in either single-pass or double-pass mode, but in most cases double-pass mode is more convenient. In double-pass mode, the SPPDI provides a probe beam that is relatively uniform (typically <50% intensity variation) over the beam diameter. The emitting aperture of the laser point source (beam waist at the laser “chip” point source) is unresolved (angular size is below the diffraction limit) at focal ratios of f/8 or “slower.”

2.3.1. Double-pass Mode

A double-pass interferometry setup for transmissive optics requires an external flat mirror (optical flat) with a clear aperture that is larger than the output beam produced by the user’s test article. The probe beam from the SPPDI exits the SPPDI, enters and passes through the test article, is reflected by the external mirror back through the test article (under a condition known as autocollimation), where it then re-enters the SPPDI. The main requirement for a double-pass interferometry setup is that the external mirror have an optical figure (shape) of known high quality and be mounted in such a way as to enable precise angular control.

Reflective concave spherical mirrors are easily tested in double-pass mode, with the mirror positioned so that its center of curvature is coincident with the SPPDI pinhole aperture or laser point source. Telescope optics designed to operate at an infinite conjugate on the object side may also be tested in a DPAC (double-pass under autocollimation) arrangement in connection with an optical flat of known high quality, with the focus of the telescope objective positioned to be coincident with the SPPDI pinhole aperture.

"Fast" camera lenses (< f/6) can also be tested in double-pass mode, but must be placed in a collimated beam, with a beam diameter large enough to overfill the camera lens entrance aperture at its widest setting. A diffraction-limited collimated beam with a diameter of 2" (50.8 mm) (sufficient for testing most camera lenses) is easily produced by collimating an f/8 - f/10 portion of the diverging output beam from the SPPDI with an inexpensive achromatic lens. The camera lens may be placed in the collimated beam, with the front or object side (infinite conjugate side) of the lens facing the collimated beam. A concave or convex spherical mirror may then be placed on the opposite side of the lens to reflect the beam back through the camera lens, back through the achromatic collimating lens, and finally back into the SPPDI.

Note: Double-pass interferograms of this three-component camera lens test setup will reveal errors in the achromatic collimating lens and in the spherical mirror, as well as in the camera lens that is being tested. So, the interferometric quality of the achromatic lens and spherical mirror should be certified beforehand.

2.3.2. Single-pass Mode

The process for using the SPPDI in single-pass mode is very similar to the process for using the SPPDI in double-pass mode, except that the flat mirror used for the DPAC (double-pass under autocollimation) process is replaced by an external optical collimator. Also, of course, it is not necessary to power up the internal SPPDI laser.

It is important to ensure that the external laser source is polarized. The relative intensities of the test and reference beams within the SPPDI are varied by means of internal polarizer disks which are manipulated by handles which extend outside the SPPDI enclosure. Rotating the handles attached to these two polarizers varies the intensities of the test and reference beams respectively, and allow fringe contrast, spacing, and orientation to be adjusted.

Red diode lasers (650nm laser pointer type) are typically well polarized, so an external polarizer may not be necessary to achieve adequate fringe contrast. If a HeNe laser is used, it should be checked to see if it is polarized. If not, a polarizer must be placed in the beam immediately in front of the laser where the beam is collimated and relatively small (in order to reduce aberrations introduced by the polarizer). If a frequency-doubled diode laser, such as a green laser pointer, is used, it will be necessary to add a polarizer, since frequency-doubled diode laser beams are typically not highly polarized.

Great care must be exercised with respect to how much laser light is injected into the SPPDI. The SPPDI is registered with the FDA as a Class 1 laser product only when used in double-pass mode with its internal laser source. Operation in single-pass mode with an external laser and collimator places the SPPDI outside its FDA-registered operational mode.

The system under test will receive the beam from the external collimator, and focus the beam to a spot which must land on the pinhole aperture inside the SPPDI. This pinhole lies at a (virtual or apparent) distance of about 32.5 mm inside the front face of the cubical SPPDI enclosure, so any telescope focuser that is used must accommodate that amount of standoff distance. The SPPDI is supplied with a 2" diameter telescope adapter, which can be inserted into a typical 2" diameter focuser.

Just as in double-pass mode, it will be necessary to connect the SPPDI alignment camera to a suitable video monitor or display in order to observe the focal spot (PSF or point spread function) produced by the system under test. As best focus is approached, the PSF will become smaller and increasingly visible on the display. Note that a highly magnified image of the SPPDI pinhole aperture and surrounding fiducial cross hairs will be observed on the display, which will assist in aligning the PSF on the pinhole aperture. This will require the use of high precision angle adjusters located either on the system under test or on the external collimator.

As mentioned previously, the SPPDI is designed to operate best with an f/8 or "slower" beam, regardless of whether the SPPDI is used in double-pass or single-pass mode. The beam uniformity will start to suffer at f/#s "faster" than f/8. A Kerry Optical Systems FRC unit or Barlow lens is recommended if a "fast" optical system is to be tested. For an optical system that is "slower" than f/15 or so, a focal reducer may be helpful.

2.4. Viewing Interference Fringes and Recording Interferograms

There are several approaches that can be used to view interference fringes and record interferograms. As described previously, a Viewing Telescope attachment is supplied with the SPPDI, which can be used for direct observation of interference fringes. Methods for recording interferograms are described in the following sections.

2.4.1. Recording Interferograms using “Eyepiece Projection”

The Viewing Telescope supplied with the SPPDI can be combined with a typical consumer-grade digital camera to record interferograms using the so-called “eyepiece projection” method. Specifically, the Viewing Telescope, when coupled with a user-supplied eyepiece and eyepiece polarizing filter, projects a virtual focused image of the test article or interferogram into the “far field,” and the camera records the virtual projected image. A setup showing the “eyepiece projection” method is shown in Figure 2.4.1.1.

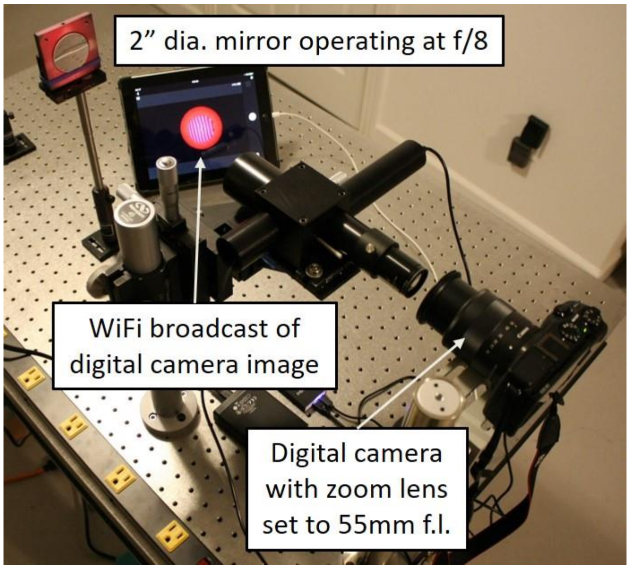


Figure 2.4.1.1. Typical setup for recording interferograms using “eyepiece projection” in combination with a consumer grade digital camera.

2.4.2. Direct Recording of Interferograms

Interferograms may also be recorded directly with a camera, without the use of the Viewing Telescope. The direct recording approach requires the use of a lens that has a sufficiently large aperture to avoid vignetting of the diverging beam exiting the SPPDI, along with a sufficiently long focal length to yield an image with acceptable size, and close-focus capability to produce a focused image of the test article and interferogram. A typical setup is shown in Figure 2.4.2.1.

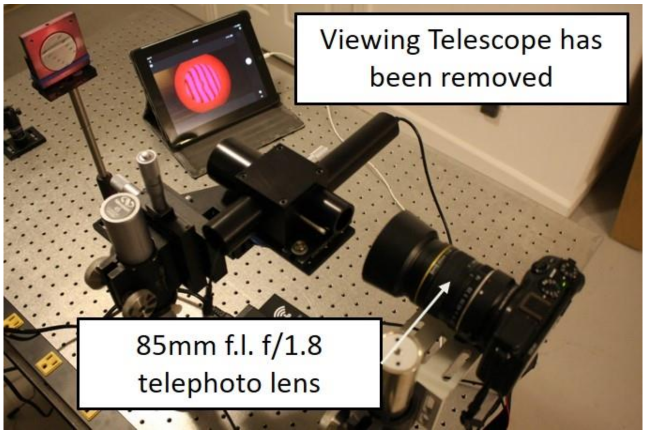


Figure 2.4.2.1. Typical setup for direct recording of interferograms. A digital camera with an APS-C size sensor and 85 mm f/1.8 telephoto lens is used.

For direct recording with a camera with an APS-C size sensor (e.g., 24 mm x 16 mm), such as used in mid-range DSLR or “mirrorless” cameras, a lens focal length of at least 50 mm is recommended. A longer lens focal length will produce a proportionally larger interferogram image on the sensor. For example, for a test article that produces an f/8 light cone, and for a camera comprising a lens with a focal length of 60 mm, the diameter of the interferogram image will be about 7.5 mm on the sensor.

The aperture diameter of the recording camera lens must be sufficiently large to avoid clipping or vignetting the beam as it exits the SPPDI instrument port. For example, for a test article that produces an f/8 light cone, the beam diameter at the exit port of the SPPDI will be about 0.2" (5.08 mm) and will continue to expand at f/8 until it enters the camera lens. On the other hand, the camera lens should not be placed closer than about 2" (50.8 mm) from the SPPDI exit port to avoid bumping the SPPDI and/or possibly damaging the camera lens. Once the expanding f/8 beam arrives at the recording camera lens aperture (pupil), the beam will have expanded to a diameter of around 0.5" (12.7 mm). For a camera lens with a 60 mm focal length, the minimum required aperture setting will be f/4.7. A lens with a larger aperture (*e.g.*, f/2.8) will provide additional pupil size and provide additional flexibility for camera positioning.

2.4.3. Interferogram Image Focus

When properly setup, the camera system will record interference fringes that appear to be superimposed on the test article aperture. It is important that the test article aperture be in proper focus to enable correct mapping of the slope errors across the test article aperture. If the test article aperture is not in proper focus, the interference fringes will exhibit a tight "swirling" or "ringing" appearance at the edges of the test article aperture, as shown in Figure 2.4.3.1.

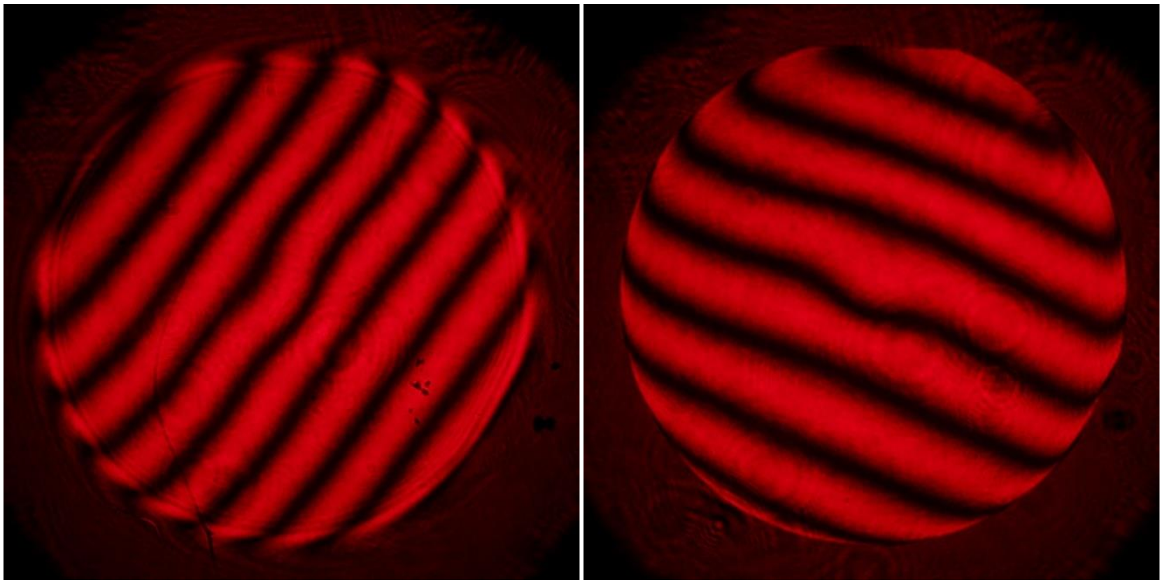


Figure 2.4.3.1. The left hand image of the concave mirror test article shows "edge fringing," which indicates the SPPDI Viewing Telescope and/or recording camera are not focused properly on the test article. The right hand image of the concave mirror test article is in better focus, with no edge fringing. These interferograms show clear evidence of a "turned edge" figure error, as well as a central "divot," which may be "print through" from the attachment used to polish this concave mirror.

2.5. Practical Considerations for Interferometry

2.5.1. Double-pass Interferometric Testing of Large Telescope Mirrors

There are several approaches for double-pass interferometric testing of large aperture concave telescope mirrors with aspheric curvature. The most common approach involves the use of an optical flat, which is placed in autocollimation against the collimated beam produced by the telescope mirror. This approach requires access to an optical flat whose clear aperture is larger than the telescope aperture. Large aperture high quality flats can be prohibitively expensive for the amateur astronomer who wants to test a telescope mirror. A high-quality flat will ideally be comprised of a substrate material with a low CTE (coefficient of thermal expansion, such as Schott Zerodur®) and have a thickness of at least 1/6th of the diameter. Also, it will be necessary to hold the flat without inducing bending stress in the flat.

A second much less costly approach does not require an optical flat. Instead, the mirror is tested under near-autocollimation against the diverging beam produced by the SPPDI. The computer software inserts an artificial null when processing the interferogram, which compensates for the spherical aberration which occurs due to the asphericity of the mirror. For a typical concave parabolic telescope mirror tested under these conditions, interference fringes will be spaced far apart toward the center of the mirror aperture, but will become closer and closer with increasing distance from the axis. The main requirement is that the camera and lens system have sufficiently high resolution to capture and resolve interference fringes that can be very closely spaced at the edges of the mirror.

Note that this procedure works best for test beams with focal ratios of f/6 or “slower.” For “faster” beams, a Barlow lens or Kerry Optical Systems Focal Ratio Converter will be required, but retrace errors through the Barlow or FRC will exhibit retrace errors that cannot be modeled or compensated in software. This will require a complicated procedure where the mirror is tested in annular zones.

2.5.2. Alignment Camera Options

As described previously, the SPPDI is supplied with a 5-volt DC USB-powered “bullet” or “lipstick” style security camera. The camera produces an AV2 type output signal which can be viewed on monitors or displays which will accept an AV2 signal.

Previous versions of the SPPDI were supplied with a digital microscope imager which required special software and a connection to a computer. This option is no longer available accept by special request.

2.5.3. Interferometric Testing of “Fast” Mirrors

The "raw" output beam from the SPPDI comes from an internal bare laser diode. The expanding beam from the laser diode chip has an elliptical profile, with the narrow or "slow" direction having a focal ratio of something like f/5 across the beam at the half-power point, and the wide or "fast" direction having a focal ratio of something like f/2 or f/1. The profile of the beam in both directions falls off with a Gaussian type intensity profile. So, in order to fill a test article with a beam that is relatively uniform, the portion of the beam from the diode laser should be limited f/8 or “slower.”

In order to test optics that are “faster” than f/8, we recommend the use of a Barlow lens or the Focal Ratio Converter (FRC) products available from Kerry Optical Systems, as described in a previous section of this manual. Due to manufacturing errors typically present in commercial Barlow lenses, or microscope objectives used in our FRC products, a means of testing and removing these figure errors is an absolute necessity. These figure errors may be measured, and a correction wavefront produced, using a “random ball test” procedure, or with the aid of a calibrated reference mirror. The compensating wavefront can then be subtracted from the test article wavefront in the manner described previously in this user manual.

2.5.4. Exporting Images from a Camera into Fringe Analysis Software

Typical equipment for recording interferograms with the SPPDI® will include a digital camera with a large (APS-C size or larger) sensor and a "fast" (f/2.8 or faster) lens. For test articles that are further than 3 or 4 feet away, Kerry Optical Systems prefers the combination of an 85mm f/1.8 mild telephoto lens attached to a digital camera. This combination has been shown to produce excellent results.

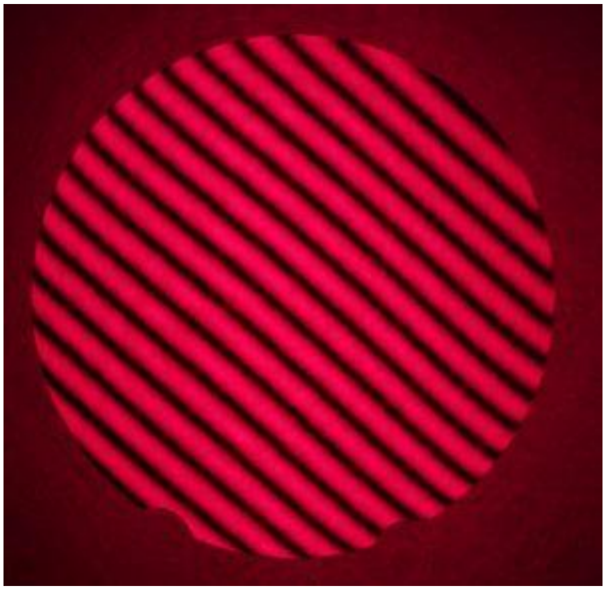
In use, the camera is aimed through the empty Instrument Port (the other Instrument Port carries the alignment camera), and the camera lens is focused on the test article. Once the SPPDI polarizer handles, the linear polarizing filter attached to the camera lens, and the camera exposure settings have been set for optimal fringe contrast on the digital camera display screen, a picture of the interference fringes (that will appear superimposed over the test article) are captured with the digital camera.

When a satisfactory interferogram has been obtained with the digital camera, the image (typically .jpg) recorded on the camera memory card is exported onto a computer which hosts the interference fringe analysis software. Mr. Dale Eason has developed an excellent fringe analysis program called DFTFringe which can be downloaded from the internet. After this software is installed and launched on the host computer, the interferogram may be imported and analyzed by the software.

It is important to note that the camera lens must be positioned as close as possible to the empty SPPDI Instrument Port, so as not to vignette the expanding beam exiting the SPPDI. For example, the footprint of an f/8 beam expanding from inside the SPPDI will have grown to a diameter of 4 or 5 mm by the time the beam exits the SPPDI enclosure, and will be even larger by the time the beam enters the camera lens.

For best results the Viewing Telescope supplied with the SPPDI should be removed from the Viewing Telescope Adapter, before using a camera to record interferograms.

2.5.5. Importance of Having Access to a Reference Mirror



The interferogram at left is of a 4.25” diameter concave spherical reference mirror with a focal length of 34 inches. This mirror is used internally at Kerry Optical Systems to certify the performance of each individual SPPDI unit before it is sold. This mirror has been certified by Zygo, and is used at our facility as our reference standard.

It should be noted that NIST (National Institute of Standards and Technology) uses interferometers produced by the Zygo Corporation. NIST defers to Zygo when approached by customers who need to certify their reference standards.

Any company or organization which produces optics or assembles optical instruments intended to achieve or exceed an advertised level of performance, as attested by interferometric measurement, must invest in a certified reference standard. This reference standard can be used to periodically certify the performance of their interferometric measurement tool, whether it be an SPPDI or another interferometer.

Amateur astronomers would also be well advised to secure their own reference mirror, to assure that whatever interferometric instrument they use has the accuracy and precision needed to assure that their measurements are valid.

2.5.6. Guidelines for Selecting Cameras and Lenses

The following questions are relevant when selecting cameras and lenses for making interferometric measurements. Are larger sensors better? Are longer focal length lenses better? Are camera lenses with large apertures better? This section addresses these considerations.

It is important to understand that the SPPDI does not modify the f/# of the test article. So, the diverging beam exiting the SPPDI will have the same f/# as the beam entering the SPPDI. In order to not vignette the beam exiting the SPPDI with the camera lens, it will be necessary to choose a camera lens with a clear aperture that is larger than the beam footprint. This drives the selection of lenses toward “fast” lenses with physically large apertures.

For example, the beam exiting the SPPDI will appear to diverge from a point that lies around 1.5” deep inside the SPPDI body. So, by the time the beam exits the SPPDI, it is already fairly large in diameter (depending on the f/# of the test article). "Faster" test articles will produce beams that grow faster as they exit the SPPDI. Also, the SPPDI fringe adjustment handles require a clearance of between 2” and 2.5” in order to avoid contact with the front glass element of the camera lens. Again, a “fast” camera lens with a physically large aperture is indicated.

As an example, at the minimum external standoff distance of 2" and an internal standoff distance (internal to the SPPDI) of about 1.5”, an f/7 beam from a test article will have grown to a diameter of 3.5"/7 = 0.5", which is not a particularly stressing aperture size for “fast” standard or mild telephoto lenses.

The physical size of the camera image sensor must also be considered. If an 85mm focal length camera lens is used to measure a test article that produces an f/7 beam, the image on the camera sensor will have a diameter of 85mm/7 = 12mm. An APS-C size sensor as used in some mid-range digital cameras has a physical size of 22.2mm x 14.8mm. So, the 12mm diameter image of the test article will just underfill the size of the sensor. If the camera has a “full frame” (24mm x 36mm) sensor, then the image will be half the size of the small dimension of the sensor. And, with an f/1.8 maximum lens aperture and a lens aperture physical diameter of 47mm (85mm / 1.8), there will be ample standoff room before the exiting beam will grow larger than the lens aperture.

As a final example, a “Micro4/3” sensor has dimensions of 18 x 13.5mm. So, a 42.5mm f.l. lens will produce an image of an f/7 test article which is 42.5mm / 7 = 6mm. The resulting image will be rather small on the sensor, but should still be acceptable.

Generally, it is desirable to produce interferogram images that have a diameter at least 50% of the size of the small dimension of the image sensor, in order to achieve the highest possible sensor pixel resolution across the image. Or, in other words, longer focal length lenses produce larger images with a higher pixel count.

2.6. SPPDI® Precision and Accuracy

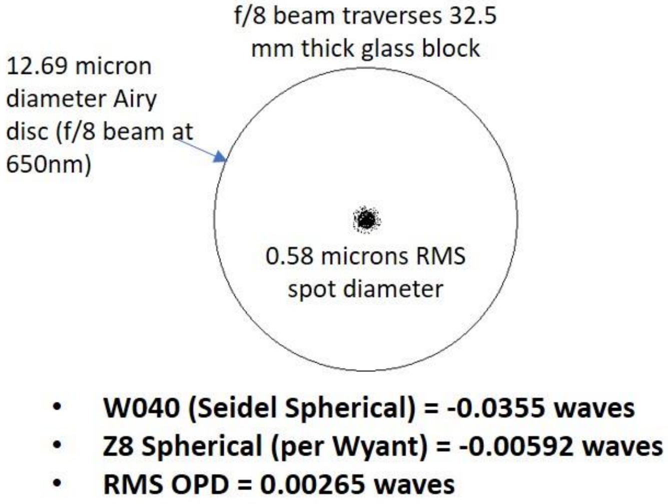
2.6.1. Known Sources of Aberration in the SPPDI

- The SPPDI produces a non-collimated output probe beam of laser light derived from an internal diode laser
    - Low-cost bare diode laser chips emit radiation into a highly elliptical radiation pattern
    - The apparent emission point of the radiation which leaves the laser chip depends on the angular position within the radiated elliptical beam, which leads to **diode laser astigmatism**
    - The effect of the diode laser astigmatism is reduced to a negligible level by using only the central f/8 (or “slower”) central portion of the radiation leaving the laser chip
- The non-collimated laser probe beam will accumulate wavefront errors as it leaves and re-enters the SPPDI
    - **Spherical aberration** is introduced as the probe beam traverses the internal SPPDI cube beam splitters and polarizer plates
    - **Astigmatism** is introduced in proportion to the tilt of the internal SPPDI polarizing tilt plates
- Interference between expanding spherical wavefronts (signal and reference beams) produced internally within the SPPDI will produce **hyperbolic interference fringes**, but the departure from straightness over a centered f/8 beam is extremely small and can be neglected

2.6.2. SPPDI Theoretical and Experimental Tests

- Theoretical performance characteristics were predicted with the aid of ray trace software
- Experimental performance characteristics were evaluated with an f/8 beam produced by a 4.25” diameter concave spherical mirror (reference mirror) with a radius of curvature of 34" (864 mm)
- Reference mirror was measured by Zygo Corporation
- Precision was evaluated by comparing results obtained with eight production SPPDI units against each other
- Accuracy was evaluated by comparing SPPDI results against the Zygo measurements, with the Zygo measurements considered as the "standard"

2.6.3. Theoretical Limiting Performance: Spherical Aberration



- **W040 (Seidel Spherical) = -0.0355 waves**
- **Z8 Spherical (per Wyant) = -0.00592 waves**
- **RMS OPD = 0.00265 waves**

Compensating Wavefront Computation: Spherical aberration arises as the non-collimated signal/probe beam traverses 32.5 mm of optical glass inside the SPPDI. This small level of spherical aberration is intrinsic to the design of the SPPDI and is constant for a given focal ratio and wavelength. Because of this, it is possible to generate a compensating wavefront, which may be subtracted from the wavefront of the test article obtained with the SPPDI. The compensating wavefront is produced with the aid of a free software package known as DFTFringe, which is a general purpose interferometric fringe and wavefront analysis program produced by Mr. Dale Eason. DFTFringe may be downloaded from the internet and installed on a Windows®-based PC.

DFTFringe may be used to generate the required compensating wavefront by clicking "Simulations" -> "Wavefront" which will bring up the small "Wavefront terms" screen. All default setting can be left as-is, but the "Z8" radio button should be enabled by clicking it. The data field labeled Spherical (under the "Zernike Term" column) needs to be filled in with a value obtained with the aid of Equation 73 reproduced below, from Page 43 of the technical paper titled "Basic Wavefront Aberration Theory for Optical Metrology" by James C. Wyant and Katherine Creath. Equation 73 as given by Wyant and Creath, is:

$$\Delta W_{\mathrm{sph}} = -\frac{TU^4(n^2-1)}{8n^3}$$

$$= -\frac{T}{(f\#)^4}\left[\frac{(n^2-1)}{128n^3}\right],$$

Delta W-sph (the output of the equation) is also known as W040 or Seidel Spherical aberration. The value yielded by this formula is either **divided by 6** (for analysis of a wavefront without regard to the surface which produced it) or **divided by 12** (if evaluating the shape of the surface which produced the wavefront) to obtain the Zernike Z8 Spherical value. This value is entered in the "Spherical" data field in the Zernike Term column mentioned above. All other Zernike Term data fields should remain at 0.000. Generation of the correction wavefront for the SPPDI is then launched by clicking the "OK" button.

After the wavefront is computed, a graphical display of the correction wavefront will appear on the DFTFringe main screen. The Zernike Z8 Spherical value entered previously in the simulation screen will now appear on the left side of the DFTFringe main screen in the "Spherical" Zernike Term data field, under the column labeled "Wyant." A value will also appear adjacent to it under the column labeled RMS. The RMS value will be equal to the Wyant value divided by the square root of 5.

T in Eq. 73 is the total thickness of the internal polarizer plates and beam splitter cubes through which the diverging/converging wavefront passes as it exits and then re-enters the SPPDI. T should be expressed in terms of the wavelength of light emitted by the SPPDI laser, which is typically 651.3 nm. f# is the focal ratio of the beam that exits and re-enters the SPPDI, and n is the refractive index of the internal polarizer plates and beam splitter cubes at the operating wavelength of the SPPDI. Alternatively, U in the upper version of the formula, is one half of the full angle in radians of the incident light cone which enters the SPPDI. The refractive index n is the refractive index of the Schott® BK7-equivalent glass comprising the SPPDI internal optical components. The value of n is 1.5145 for BK7 at a wavelength of 0.650 microns.

EXAMPLE: Given a thickness T equal to 50,000 waves (32,500 microns of optical glass / 0.65 microns per wave), an f/# of 8, and a value of n = 1.5145 at 0.65 microns, the amplitude of W040 obtained with Equation 73 above will be -0.03552 waves. This value is divided by 6 to obtained -0.00592 waves, which is then entered into the "Spherical" data field in the Simulations -> Wavefront screen. After clicking "OK," the SPPDI spherical aberration compensation wavefront will be computed and displayed on the DFTFringe main screen.

The Spherical data field in the Zernike Term column on the left side of the main screen will be displayed with the value -0.006 (rounded from -0.00592), along with the value -0.003 in the RMS field (= -0.00592 divided by square root of 5 = -0.00265, rounded to -0.003). This SPPDI spherical aberration compensation wavefront may now be saved for future use by clicking the "Save Wavefront/s" option under the "Files" menu. This compensation wavefront may be subtracted from wavefronts obtained with the SPPDI for test articles which produce an f/8 beam. Other compensation wavefronts for other focal ratios may be computed and used in a similar manner.

NOTE: It is sometimes difficult to know if the wavefront computed by DFTFringe from an interferogram of a test article has the correct "sense," i.e., whether or not the reported Zernike Z8 Spherical term should be positive or negative. The correct sense is easily determined by obtaining a second interferogram of the test article after slightly moving the SPPDI toward the test article. This should be reported by DFTFringe as a more negative value of the Z3 Zernike Defocus term. If the reported value of Z3 is positive, then the DFTFringe "invert" button should be clicked in order to invert the observed wavefront before subtracting the correction wavefront. Also note that the Z8 value produced by Eq. 73 will always be negative.

2.6.4. Theoretical Limiting Performance: Astigmatism

Compensating Wavefront Computation: Astigmatism arises within the SPPDI as the internal polarizing tilt plates are tilted away from being "normal" (perpendicular) to the internal signal and references beams. The larger the tilt, the higher the resulting fringe count (number of interference fringes) in the interferogram, and the higher the induced level of astigmatism.

If one of the two internal tilt plates is held "normal" (perpendicular) to the beam, the correlation between the number of fringes and the angular tilt of the tilt plates is given by the empirical formula Tilt = 0.3105 angular degrees per fringe. Thus, given the number of fringes in an interferogram, and the tilt predicted by the empirical relation, Equation 77 in the previously referenced Wyant and Creath document can be applied to predict the amplitude of the Delta-W-astig Seidel astigmatism.

$$\begin{aligned}\Delta W_{\text{astig}} &\simeq -\frac{TU^2\bar{U}^2(n^2-1)}{2n^3}\cos^2\theta \\ &\simeq -\frac{T\bar{U}^2}{(f\#)^2}\left[\frac{(n^2-1)}{8n^3}\right]\cos^2\theta.\end{aligned}$$

In Equation 77 U-bar is the angular tilt of the tilt plate in radians, T is the thickness of the tilt plate, f# is the focal ratio of the beam which enters the SPPDI, n is the refractive index of the tilt plates, and theta is the angular orientation of the tilt plate with respect to the local x and y axes. Cosine theta can be assumed to be 1 for the purpose of calculating the amplitude of the wavefront correction, which must then be apportioned in an RSS fashion between the local x and y axes. The actual amplitude of the Z4 (x-axis) and Z5 (y-axis) Zernike astigmatism terms is obtained by dividing Delta-W-astig by 2.

EXAMPLE: The tilt plates used in the SPPDI have a thickness of 3 mm and are comprised of glass which may be assumed to have a refractive index at 650 nm of 1.5145. For an f/8 beam and a tilt value of 3 degrees (0.0524 radians), the resulting Seidel astigmatism is 0.00595 microns, or 0.00915 waves at 650 nm. If the tilt plate is oriented so that astigmatism is only found in the x axis, the resulting Z4 Zernike term (after dividing the Seidel value by 2) is thus 0.0046 waves. The angular tilt of 3 degrees is obtained from the empirical relation Tilt = 0.3105 angular degrees per fringe. So, the interferogram relating to this example must have had 9.7 fringes.

2.6.5. Experimental Performance Tests -- Evaluation of Precision

Fifty-six full aperture interferograms of the reference mirror were obtained with eight different SPPDI units. When converted from the SPPDI measurement wavelength of 650 nm to the HeNe laser wavelength of 632.8 nm used in interferometric measurements provided by the Zygo Corporation, the results of these measurements are as follows:

- The average value of the RMS surface figure error was 0.0089 ±.0010 waves @ 632.8 nm, or 5.63 ±0.63 nm
- The average value of the PV (peak-to-valley) error was 0.0464 ±0.0059 waves @ 632.8 nm, or 29.4 ±3.7 nm

The standard deviation of these measurements indicate that the RMS and PV wavefront errors are consistent to better than 0.01 waves at 632.8 nm from one SPPDI unit to another. This is the basis for stating that the SPPDI measurements are precise (repeatable from one measurement to another and from one SPPDI unit to another) to within 0.01 waves.

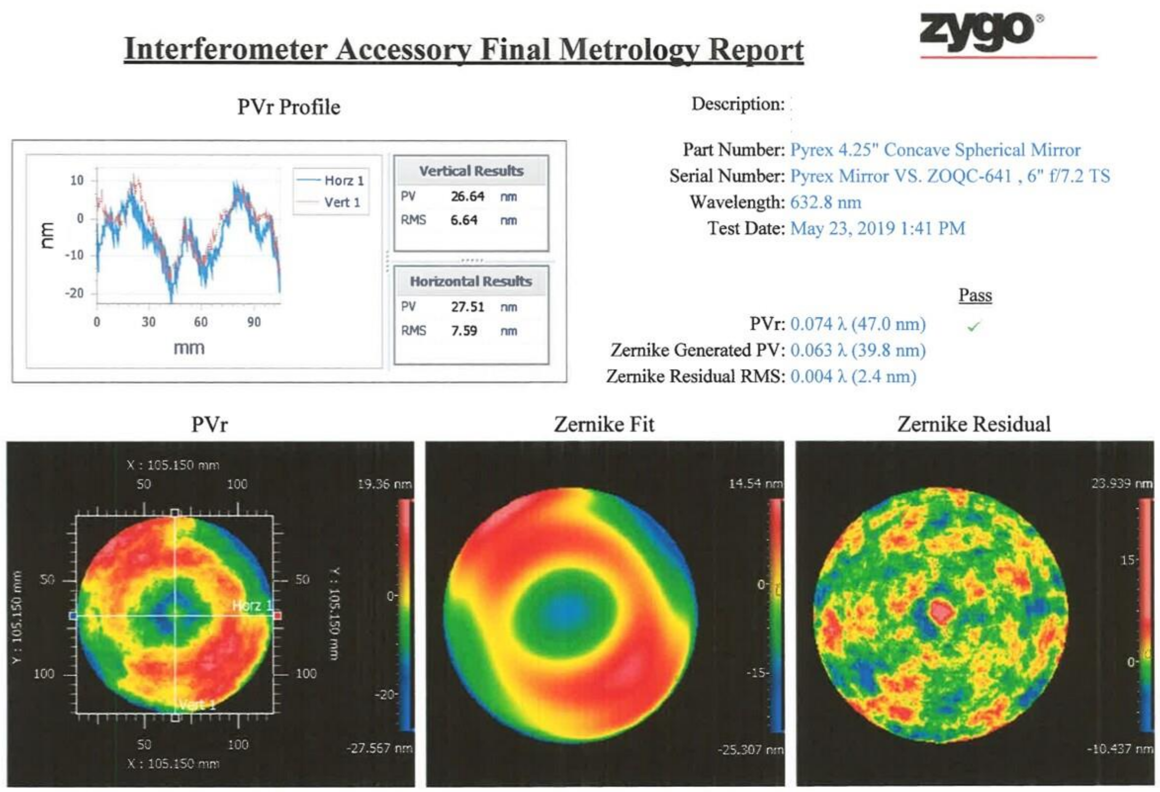
Extreme care is taken to eliminate internal alignment errors as SPPDI units are constructed. Variations in precision of the alignment of the internal components will cause small differences on the order of a few thousandths of a wave in the values of the Zernike values. However, we believe that most of the variation in measurement results from one SPPDI unit to the next are due to variations in the quality (surface figure) of the beam splitters and polarizing tilt plates used within the SPPDI. Miniaturization of the SPPDI package and internal components guarantees that the footprint of the beam is kept small as it traverses the internal components, thus minimizing the accumulation of wavefront errors due to figure errors in the internal components.

Interferograms that form the basis of these statements about precision were recorded using a commercial 85 mm focal length f/1.8 mild telephoto lens connected to a digital camera with an APS-C size sensor. The amount of distortion added to the recorded interferograms by this lens and sensor system has been determined to be very small. This inference is based on measurements obtained with a variety of commercial camera lenses, and is affirmed by the Zygo results.

2.6.6. Experimental Performance Tests - Evaluation of Accuracy

Round Robin Test: A Round Robin test of a 6" f/8 CerVit® concave spherical mirror was conducted by a large number of private individuals with access to interferometers of various types. The results of the Round Robin testing demonstrated that the SPPDI produces measurements that are very consistent with results obtained by other contributors.

Zygo Corp. Certification: Measurements of the reference mirror were made by the Zygo Corporation. Summary results at 632.8 nm are shown here.



Interferometer Accessory Final Metrology Report

zygo®

PVr Profile

Vertical Results		
PV	26.64	nm
RMS	6.64	nm

Horizontal Results		
PV	27.51	nm
RMS	7.59	nm

Description:

Part Number: Pyrex 4.25" Concave Spherical Mirror
Serial Number: Pyrex Mirror VS. ZOQC-641 , 6" f/7.2 TS
Wavelength: 632.8 nm
Test Date: May 23, 2019 1:41 PM

Pass
PVr: 0.074 λ (47.0 nm) ✓
Zernike Generated PV: 0.063 λ (39.8 nm)
Zernike Residual RMS: 0.004 λ (2.4 nm)

PVr

Zernike Fit

Zernike Residual

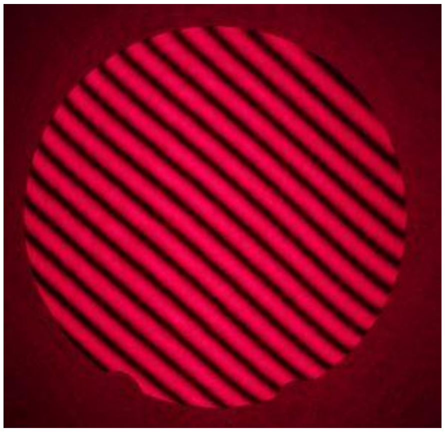
Summary of Zygo results vs. SPPDI results:

- Average PV error:
  - Zygo: 27.08 nm
  - SPPDI: 29.4 ±3.7 nm
- RMS surface figure error at 632.8 nm:
  - Zygo: 0.0112 waves
  - SPPDI: 0.0089 ±.0010 waves
- Zernike Term Z8 (Spherical) at 632.8
  - Zygo: -0.0155 waves
  - SPPDI: -0.01865 ±.0023 waves

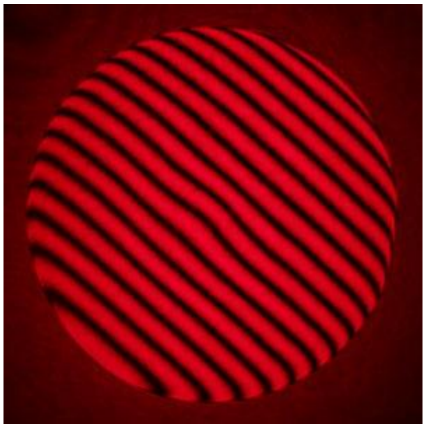
Conclusion: These results provide confidence that the surface figure results predicted by the SPPDI units used in this study are both accurate and repeatable to better than 0.01 wave.

2.7. Gallery

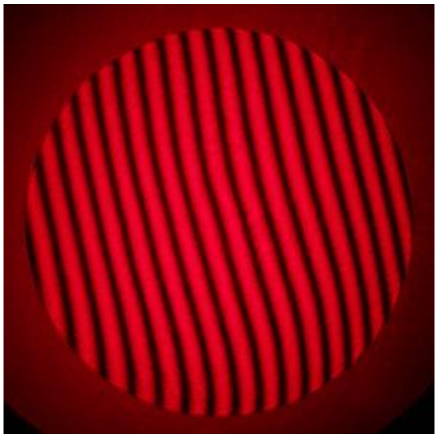
Here are a few double-pass interferograms of various items of optical equipment located at our facility. Note that the actual surface figure error is half of what is evident in these interferograms, due to double-pass operation of the SPPDI®.



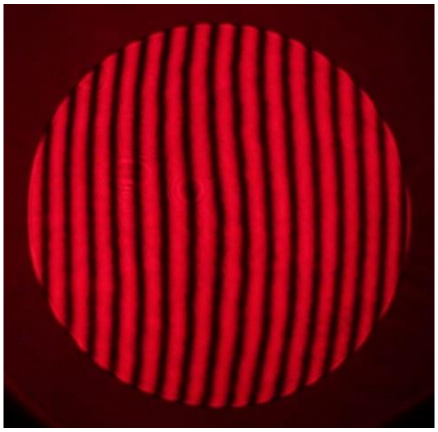
Interferogram of 4.25″ diameter f/8 (by radius) concave spherical mirror, used at Kerry Optical Systems, LLC as a reference mirror, with surface figure certified by the Zygo Corporation. This mirror is used as a master reference tool for validating and certifying the performance of each SPPDI unit prior to sale. Each SPPDI unit must yield a set of interferograms of this master reference mirror that match the Zygo results to within +/-.01 waves of astigmatism and +/-.01 waves of spherical aberration before the unit is considered acceptable for sale. We are indebted to Mr. Dale Eason for his excellent DFTFringe interferometric fringe analysis software.



2-inch diameter f/8 (by radius) aluminized concave mirror. A “turned edge” is evident, as well as a central divot possibly due to mechanical “print-through” from the polishing spindle during manufacture.



Interferogram of a commercial 70mm aperture f/6.8 two-element apochromatic refractor objective. Some residual aberration is evident.



Interferogram of a 6-inch aperture f/5 two-element air-spaced achromatic lens. This is the objective lens of a moderately low cost telescope sold by a well known telescope manufacturer. The f/5 beam produced by this telescope cannot be measured directly with the SPPDI. A 2x Barlow lens was inserted in the beam just ahead of the SPPDI. This increased the focal ratio of the f/5 beam to f/10, which is well within the acceptable focal ratio range suitable for use with the SPPDI. Some of the aberration evident in this interferogram may be due to aberrations in the 2x Barlow lens.

2.8. Tips and Tricks

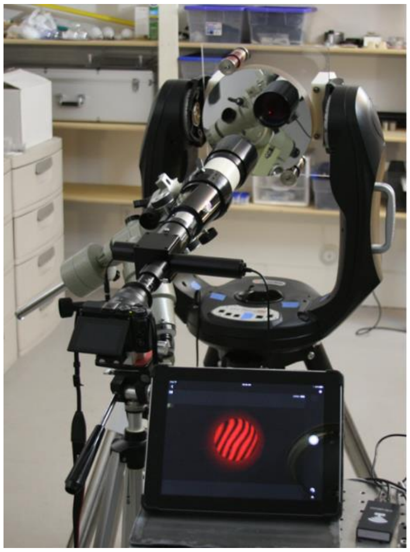
2.8.1 Wavefront "Sense"

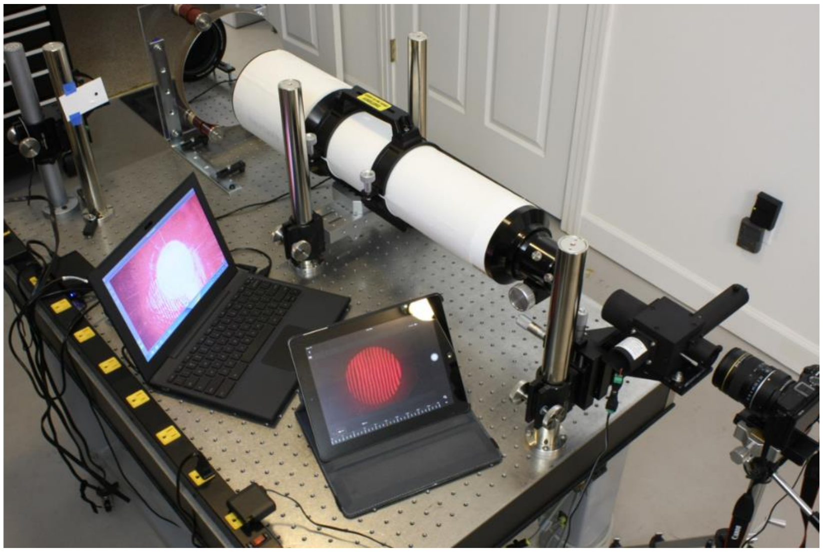
An interferogram is a topographic map of a wavefront. Just as in reading a topographic map of a mountain, it is often difficult to know whether traversing the map from fringe to fringe leads uphill or downhill. For optical interferometry, sophisticated and expensive optics can be introduced in the beam path that eliminates the confusion. Fortunately, there is a very simple method for determining the wavefront "sense" which does not require expensive add-on optics. The method involves defocusing the wavefront, and observing the algebraic sign of the Zernike Z3 Defocus term, as displayed by DFTFringe. If the interferometer has moved closer to the test article, the algebraic sign of the Z3 term should become more negative, but all other Zernike terms should remain approximately the same. If the Z3 term becomes more positive, then the DFTFringe "Invert" function should be launched to invert the defocused wavefront. If the Z8 terms of the defocused and non-defocused wavefronts no longer have the same algebraic sign, then the non-defocused wavefront should be inverted.

2.8.2. Mounting Schemes

Although the SPPDI unit itself is rugged, engaging in interferometric measurements can be challenging. As with any optical interferometer, operation of the SPPDI requires a stable, vibration-free environment with low ambient temperature variations. In addition, a successful interferometric setup requires that the SPPDI and the optical system under test be mounted in stable optical mounts with precision angle and linear motion adjusters.

There are optical benches (mounting platforms) and optical component mounts available from a variety of suppliers which offer the required degree of precise motion control. A web search will quickly reveal a variety of suppliers which serve this market. Alternatively, there are surplus equipment suppliers that offer used equipment obtained from large governmental or commercial laser labs, for a fraction of the cost of new equipment.





A 2-inch diameter Telescope Adapter is provided with the SPPDI to facilitate direct attachment of the SPPDI to the 2" eyepiece holder typically provided with higher-end commercial telescopes. Such an arrangement is shown in the photo on the left.

For larger refractors, such as the 5" refractor shown in the photo on the right, the prime (far-field) focal plane for the telescope objective is so far distant from the rear of the scope that two extension tubes are required in order to position the SPPDI at prime focus. This does not lend itself to precise positioning of the SPPDI with respect to the optical axis of the objective lens. Use of the diagonal mirror eyepiece holder typically provided with these telescopes would enable prime focus to be reached without the use of extenders, but could compound the errors in the objective lens with errors in the diagonal mirror.

So, to avoid these complications, the SPPDI is mounted separately on a three-axis translation stage setup as shown in the photo on the right. This requires that the telescope first be brought into autocollimation with the "optical flat" (high precision flat mirror) used for double-pass interferometry. This is easily accomplished by means of the laser alignment tool supplied with the SPPDI. Then the SPPDI is positioned along the x, y, and z axes by means of the translation stages. For reflector type telescopes with low-profile focusers, the SPPDI may be easily positioned at prime focus. Note that the SPPDI pinhole aperture is located at a depth of about 32.5 mm inside the SPPDI enclosure.

As the telescope focal length increases, isolation from ambient vibration becomes increasingly difficult. It is very helpful to have all equipment co-located on a stable platform, such as on an optical table like the one shown in the photo on the right.

The 10" optical flat seen in the photo above left is mounted in a fork mount obtained by disassembling a large (11" aperture) commercial Schmidt-Cassegrain type telescope. The optical tube assembly was replaced with a purpose-built saddle capable of supporting a 12-inch diameter optical flat. The electronic slow-motion control associated with the fork mount is used to bring the telescope under test into near autocollimation against the optical flat. Final precision alignment is achieved by means of a set of three 1/4x20 jack screws mounted on the ends of three long lever arms which support and raise and lower the tripod feet.

2.9. Q and A

Q: I’ve looked at the products offered on the website and read the User Manual but there was very little information about using the SPPDI for single pass measurement besides pointing out the impediments. Assuming one has a large collimator, how can the SPPDI be configured to perform single pass measurement of a telescope or lens system?

A: The process for using the SPPDI in single-pass mode is very similar to the process for using the SPPDI in double-pass mode, except that the flat mirror used for the DPAC (double-pass under autocollimation) process is replaced by the external collimator. Also, of course, it will not be necessary to power up the internal SPPDI laser.

You will first need to ensure that your external laser is polarized. The relative intensities of the test and reference beams within the SPPDI are varied by means of internal polarizer disks which are manipulated by handles which extend outside the SPPDI enclosure. Rotating the handles attached to these two polarizers varies the intensities of the test and reference beams respectively, and allow fringe contrast, spacing, and orientation to be adjusted.

Red diode lasers (650nm laser pointer type) are typically well polarized, so an external polarizer may not be necessary to achieve adequate fringe contrast. If you plan to use a HeNe laser you should check to see if it is polarized. If not, you should place a polarizer in the beam immediately in front of the laser where the beam is collimated and relatively small (in order to reduce aberrations introduced by the polarizer). If you plan to use a frequency-doubled diode laser, such as a green laser pointer, you will need to add a polarizer, since frequency-doubled diode laser beams are typically not highly polarized.

Be very careful with respect to how much laser light you are injecting into the SPPDI. The SPPDI is registered with the FDA as a Class 1 laser product only when used in double-pass mode with its internal laser source. Operation in single-pass mode with an external laser and collimator places the SPPDI outside its FDA-registered operational mode. So, be careful.

Your system under test will focus the beam from your collimator to a spot which must land on the pinhole aperture inside the SPPDI. This pinhole lies at a (virtual or apparent) distance of about 32.5 mm inside the front face of the cubical SPPDI enclosure, so your telescope focuser must accommodate that amount of standoff distance. The SPPDI is supplied with a 2" diameter telescope adapter, so you can slide the SPPDI right into a typical 2" diameter focuser.

Just as in double-pass mode, it will be necessary to connect up the SPPDI alignment camera to a suitable computer monitor or video monitor in order to observe the focal spot (PSF or point spread function) produced by the system under test. As you approach best focus, the PSF will become smaller and increasingly visible on the display. Note that you will also see a highly magnified image of the SPPDI pinhole aperture and surrounding fiducial cross hairs, which will assist you in aligning the PSF on the pinhole aperture. This will require the use of high precision angle adjusters located either on the system under test or on your collimator.

Another thing to keep in mind, which applies equally to both single-pass and double-pass operation, is that the SPPDI is designed to operate best with an f/8 or "slower" beam. For optical systems with focal ratios "faster" than f/8, I recommend use of the Kerry Optical Systems Focal Ratio Converter. The FRC will allow conversion to virtually any focal ratio, while enabling production of a correction wavefront for removing the residual errors in the SPPDI as well as the FRC optics. A Barlow lens can also be used to product “fast” focal ratios, but the options for removing instrumental errors are more limited due to the lack of an external focus which precludes testing with a “random ball” process. For an optical system that is "slower" than f/15 or so, a focal reducer may be helpful.

Q: I'd like to test mirrors and assembled telescopes. For assembled scopes I guess I'll need an optical flat of equivalent or larger diameter to the scope- correct? I'd like to be able to get up to 12" diameter systems and a 12" flat looks prohibitively expensive.

A: Basically, there are two approaches. One approach involves the use of an optical flat (as you suggested), and the other approach relies on direct measurement of the parabolic mirror (with no optical flat) in combination with specialized interferogram analysis software.

The method which relies on the use of an optical flat can obviously be rather expensive. For best results, your flat should comprise a Schott Zerodur® substrate with a thickness of at least 1/6th of the diameter. Also, you will need to have the means to hold the flat without inducing bending stress in the flat. A mirror cell typically used to hold an astronomical mirror would work OK.

It is also possible to test a parabolic mirror (such as used in a Newtonian type telescope) without the need for an optical flat. This involves placing the SPPDI at the center of curvature of the vertex of the mirror. In technical terms, the SPPDI will be located at the center of curvature of the "osculating" radius of the mirror. An interferogram obtained in this way will show extreme levels of spherical aberration, due to the parabolic shape of the mirror. However, Dale Eason's excellent DFTFringe software includes an "artificial null" capability, which should eliminate the spherical aberration from the computations of the surface figure. This software is available for free download from the internet.

Q: You now offer two different video camera options for aligning the SPPDI. Are there performance tradeoffs?

A: The Celestron® Digital Microscope Imager option is no longer available, except by special request. The current supported option is a "bullet" type security camera which produces an AV2 output signal.

Q: Are there limitations when testing fast mirrors? I'm eventually hoping to make a Dall Kirkham which means fighting a pretty fast primary ellipsioid.

A: There are several things to keep in mind. First, the "raw" output beam from the SPPDI comes from an internal bare laser diode. The expanding beam from the laser diode chip has an elliptical shaped Gaussian intensity profile, with the narrow or "slow" direction having a focal ratio of something like f/5 at the half-power point and the wide or "fast" direction having a focal ratio of something like f/1 or f/2. So, in order to fill a test article with a beam that is relatively uniform across the diameter of the test article, only the central f/8 portion of the laser output should be used. The SPPDI will work just fine at f/6, however the beam intensity profile gets less uniform with "faster" f/#s.

The SPPDI introduces increasing amounts of spherical aberration as "faster" focal ratios are measured. This is caused as the test beam traverses (out and back) an internal thickness of 32.5 mm of flat optical glass (mainly beam splitter cubes) located inside the SPPDI. For example, about 0.005 waves of spherical aberration are introduced in measurements of an f/8 beam. Fortunately, this excess spherical aberration can be easily and completely removed by applying a correction wavefront. This correction wavefront is generated by the DFTFringe software which can be downloaded from the internet.

There are two methods (and perhaps others) for producing and measuring test beams that are faster than f/8. One easy method is to insert a Barlow lens into the beam path. However, the transmitted wavefront error introduced by some commercially available Barlow lenses is quite high. So, it's a good idea to test the optical quality of a Barlow lens before it is used in an interferometric setup. This can be done by use of a high-quality concave spherical reference mirror. A wavefront representing the combination of the Barlow and the SPPDI can then be subtracted from the wavefront of the test article. Kerry Optical Systems can provide guidance on where to obtain high quality reference mirrors.

Before proceeding with the use of a Barlow lens, you will first need to unscrew the Barlow lens from the eyepiece receptacle portion of the Barlow lens assembly. The eyepiece receptacle portion may be set aside for later reassembly. The Barlow lens may then be inserted into the SPPDI Telescope Adapter. Make sure that the Barlow lens is facing in the correct direction, with the flat or less curved portion of the Barlow lens facing away from the SPPDI.

If you want to be very particular, you can position the Barlow lens so that it is located at the proper distance from the internal focal point of the SPPDI (position of the laser diode chip or pinhole aperture). This internal focal point is located 32.5 mm inside the front face of the SPPDI. Note that for a typical Barlow lens, the eyepiece receptacle is designed to allow incoming light from a telescope to come to focus at a distance of about 6 mm inside the end of the Barlow eyepiece receptacle, which (depending on the particular brand of Barlow) will be 50 or 60 mm from the Barlow lens itself. So, you would position this nominal focal point to coincide with the SPPDI internal focal point. In practice, the actual position of the Barlow inside the SPPDI Telescope Adapter does not really affect the optical performance very much.

The second (and technically preferrable) method for measuring a "fast" mirror is to use one of the Focal Ratio Conversion (FRC or "transmission sphere") products offered by Kerry Optical Systems. These will enable certification of the wavefront quality of the SPPDI in combination with the FRC. The wavefront obtained in this manner may be subtracted from the wavefront obtained for the test article, thus removing instrumental errors from the measurements of the test article.

In order to test your fast ellipsoid, you will need to become very familiar with the operation of the "artificial null" feature of the DFTFringe software. Bear in mind that this nulling feature is totally handled by the DFTFringe software. You will end up with an interferogram that exhibits VERY fine fringes, maybe to the point that the camera and camera lens system that you are using to record interferograms cannot resolve the finely spaced fringes. You might want to do some preliminary experimenting with DFTFringe. Apparently, there is a capability within DFTFringe to generate "fake" interferograms, which should allow you to see how closely spaced the fringes will be for your particular mirror.

Of course, the other option is to simply place your primary mirror into its final configuration within a telescope, and then test your telescope in connection with an optical flat in autocollimation mode.

Q: How do the images get from the camera into the analysis software?

A: You will need a digital camera with a large-ish (APS-C size or larger) sensor and a "fast" (f/2.8 or faster) lens. You will aim the camera through the empty Instrument Port (the other Instrument Port carries the alignment camera), and focus the digital camera lens on the test article. Once you have adjusted the SPPDI polarizers and the camera polarizing filter for optimal fringe contrast, you will simply take a picture of the interference fringes (that will appear superimposed on the test article) with the digital camera.

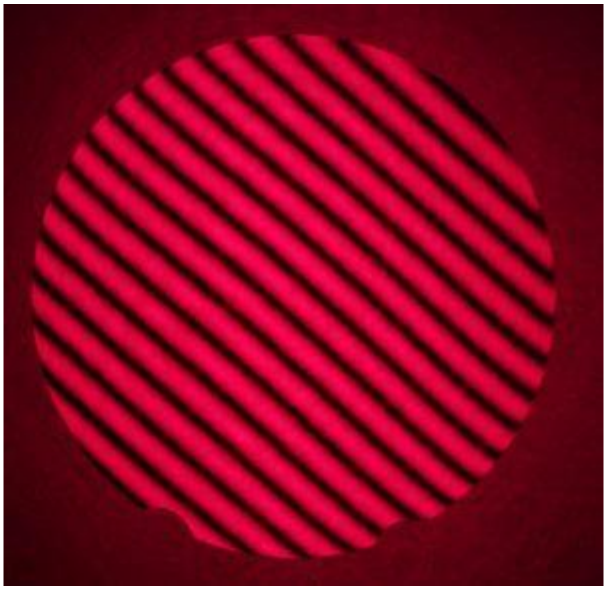
Once you are satisfied with the interferograms that you have photographed with the digital camera, you will export the images (typically .jpg format) off of the camera memory card onto your computer where the fringe analysis software is installed. Then launch the fringe analysis software and import the interferogram images for analysis.

We have had great success using a "mirrorless" digital camera with a removable lens and APS-C size sensor, in combination with an 85mm f/1.8 mild telephoto lens.

Whichever camera and lens you use, you must position the lens close to the empty SPPDI instrument port, so as not to vignette the expanding beam exiting the SPPDI.

If the small Viewing Telescope supplied with the SPPDI is installed in the Instrument Port, you should remove it before using your camera to obtain interferograms.

Q: What's your reference mirror? It looks stunningly good!



A: This mirror was made by Carl Zambuto (see https://zambutomirrors.com/). We purchased this mirror from Carl and sent it to Zygo for certification. It is indeed as good as it appears on the interferogram.

Q: I have a large number of cameras and fast lenses. What will give the absolute best results?

Larger sensors = better?

Longer lenses = better?

Absolute aperture size in mm larger = better?

For example would you prefer an 85mm f1.2 on a Canon full frame, or a 42.5mm f1.2 on a Panasonic Micro4/3?

A: There are several things to consider. When you test any optical system with the SPPDI, you must position the internal pinhole of the SPPDI at the focus of the optical system you are testing. The SPPDI pinhole lies 32.5 mm deep inside the SPPDI front face (side facing the test object). The SPPDI does not modify the f/# of the system you are testing. So, the beam exiting the SPPDI will have the same f/# as the beam entering the SPPDI. So, in order to not vignette the beam exiting the SPPDI with your camera lens, you must choose a camera lens with an aperture that can accept the expanding beam without vignetting the beam, i.e., before the beam footprint grows too large for your camera lens aperture.

You can assume that the beam exiting the SPPDI will appear to diverge from a point that lies around 1.5" deep inside the SPPDI body. So, by the time the beam exits the SPPDI, it is already fairly large in diameter (depending on the f/# of what you are measuring). "Faster" test articles will produce beams that grow faster as they exit the SPPDI. And also, you will need to avoid bumping into the SPPDI fringe adjustment handles with your camera lens. So, altogether, you should plan to accommodate a minimum standoff distance to your camera lens of something like 3.5".

Lenses with larger apertures will provide a larger standoff distance, before you begin to vignette the beam with your camera lens. So, choose a lens with a larger aperture so that you don't vignette the beam. As an example, at the minimum standoff distance of 3.5", an f/7 beam from a test article will have grown to a diameter of 3.5"/7 = 0.5", which is not a particularly stressing aperture size for standard or mild telephoto lenses.

The next thing to consider is the required size of the camera sensor. If you are going to use an 85mm focal length camera lens, and you are going to measure a test article that produces an f/7 beam, you will end up with an image on the camera sensor that has a size of 85mm/7 = 12mm. An APS-C size sensor as used in mid-range digital cameras has a physical size of 22.2mm x 14.8mm. So, the 12mm diameter image of the test article will just underfill the size of the sensor. In other words, your 85mm f.l. lens will work just fine. If your sensor is even bigger ("full frame"), then all the better. And, with an f/1.8 maximum lens aperture and a lens aperture physical diameter of 47mm (85mm / 1.8), you have ample standoff room before the exiting beam will grow larger than your lens aperture.

So, your 85mm f/1.2 lens attached to a full frame digital camera should produce good results!

A Micro4/3 sensor has dimensions of 18 x 13.5mm. So, a 42.5mm f.l. lens will produce an image of an f/7 test article which is 42.5mm / 7 = 6mm. Your image will be rather small on your sensor, but should still be acceptable.

Bottom line: just use the longest focal length, largest aperture lens you can, while still getting an image that does not overfill the size of your sensor.

For a given test article, the interferogram image size on your sensor would be twice the size when shot with your 85mm lens as it would be if shot with your 42.5mm lens. Generally, you want a larger interferogram image, with more pixels covering the image.

3. LIMITED WARRANTY and RETURNS POLICY

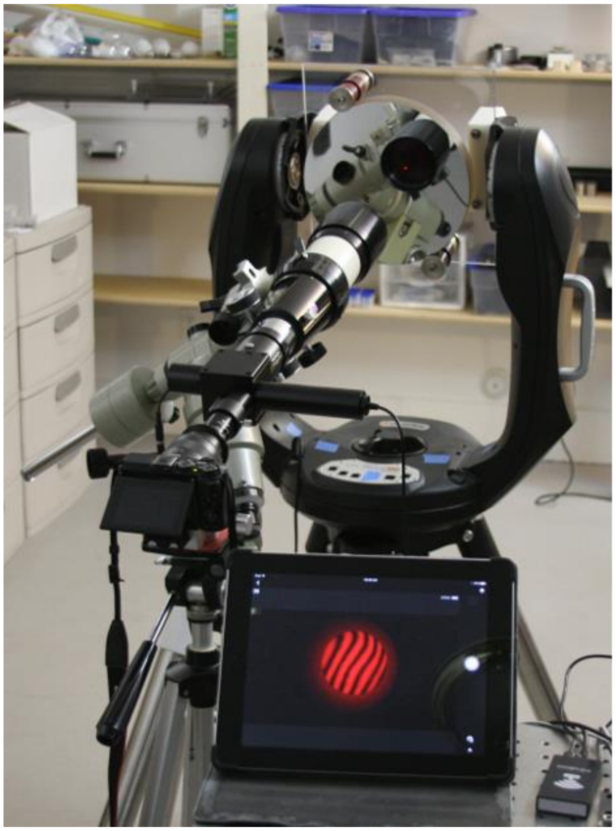
RETURNS: Any of the SPPDI® products may be returned to Kerry Optical Systems, LLC for a full refund for a period of 30 days following purchase. If buyer mishandling or abuse is noted upon return of the unit, a restocking fee may be assessed, or the refund denied, at the sole discretion of Kerry Optical Systems. Returns after 30 days and up to a period of 6 months will be accepted at a month-by-month pro-rated refund rate. Returns after a period of 6 months will not be accepted.

LIMITED WARRANTY: If the SPPDI fails for any reason within a period of 6 months after sale, other than for the cause of damage due to operator mishandling or abuse, the SPPDI unit may be returned to the factory for repair at no cost to the buyer. Buyer will pay the shipping cost to return the unit for repair. Kerry Optical Systems will pay the return shipping cost. Cost of repairs occasioned by operator mishandling or abuse will be negotiated at the time of repair. This warranty shall be null and void upon evidence that the buyer has opened the SPPDI enclosure, or that the buyer has removed and/or replaced the SPPDI laser source.

4. History

Kerry Optical Systems, LLC, home of the Light Whisperer®, is a new high-tech optical equipment manufacturing and consulting firm located in the family-oriented community of Rexburg, ID. Why Rexburg? Located in the Upper Snake River Valley, 30 miles south of the Yellowstone caldera escarpment, and 50 miles west of the Grand Tetons, a more beautiful place is difficult to imagine.

Rexburg, with about 28,000 permanent residents, is home to BYU Idaho, a major university with over 34,000 degree-seeking students. The intellectual capital, creative energy, and entrepreneurial spirit found within the BYUI community is significant and distributed over many disciplines, much of it currently untapped within the permanent resident community: a situation we hope to help rectify!



Versatile Wilcken Interferometer

Model 5011
Wilcken Interferometer

The Model 5011 Wilcken interferometer* is ideal for people who need a quick and inexpensive way to inspect optical components for the presence of aberrations or manufacturing defects. It can be used to test a variety of lens systems, such as telescope objectives and eyepieces, photographic and video lenses, as well as simple lenses and mirrors. This device is a split-path, point-diffraction interferometer based on the Smartt point-diffraction interferometer. It comes with a 635-nm diode laser in a compact, rugged package. A 9-V DC diode laser power supply is included. One arm of the interferometer contains a pinhole aperture to spatially filter the beam, thereby creating a diffraction-limited, spherically expanding reference wave. At the interferometer output, this reference wave is interfered with the beam from the test optic. Alignment is easy since all you provide are the optical elements to be tested. Position the optical element of interest in the path of the diode laser beam that exits the interferometer case, then reflect the beam back into the the case. The resulting fringe pattern can be observed from two exit ports by eye or with camera equipment.

The Wilcken interferometer's fringe pattern can be interpreted in the same way as that from a Twyman–Green interferometer. The deviation of the fringes from straight lines indicates the presence of aberrations or manufacturing defects. The fringe spacing, orientation, brightness, and contrast are each independently adjustable to allow for optimal fringe pattern readability.

The Model 5011 Wilcken interferometer (actual size).

Typical fringe pattern from a Wilcken interferometer

The basic interferometer can be used to test f/10 to f/15 optics. Additional beam shaping lenses and/or mirrors permit testing optical systems as fast as f/1. Contact us for more information.

Projected availability: September, 1995.

** Technology licensed from Stephen K. Wilcken. (Patent Pending)*

Wilcken Interferometer Characteristics

Model #	5011
Laser Source	[illegible]
Test Focal-Ratio Range	[illegible]
Min. Aberration Resolution	[illegible]
Dimensions	[illegible]
Price	[illegible]

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Stephen Wilcken founded Kerry Optical Systems in 2018 after a 45-year career in optical and laser engineering and software engineering. Stephen’s skill set is wide ranging, with particular expertise in optical engineering and laser technology. Stephen holds fourteen technical patents, covering a range of fields including laser communications, and laser-based instrumentation for making precision optical measurements.

This wide range of expertise is now focused on bringing innovative optical and laser-based products to the educational and optical manufacturing communities, and to professional and amateur astronomers.

Kerry Optical Systems' flagship product, the SPPDI® (Split-path Point Diffraction Interferometer), was conceived in a conversation with a co-worker back in 1988. The co-worker suggested seeking patent protection for the SPPDI, which was accomplished in 1994 during a 2-year period when Stephen worked as an optical engineering consultant. A prototype of the SPPDI was developed and tested and found to yield excellent performance. Unfortunately, personal funds were too limited at that time to proceed with further development of the SPPDI.

An attempt was made to engage the services of New Focus, Inc., a Silicon Valley laser equipment company founded in 1992 by Dr. Milton Chang. The SPPDI was introduced as the "Wilcken Interferometer" on Page 52 in the 1995 issue of the New Focus catalog. Unfortunately, limited engineering resources at New Focus caused the abandonment of the effort to further develop and market the Wilcken Interferometer. With the Wilcken Interferometer back under Stephen’s control, it sat on the shelf for many years.

Stephen’s retirement from a major aerospace company provided the opportunity to resume part-time development of the SPPDI, while continuing to work part-time as a contract engineer. Termination of contract engineering finally afforded the opportunity to focus full-time on bringing the SPPDI to market readiness.

The success of the SPPDI will lead to opportunities for further work in developing and marketing novel optical products to serve the needs of the high-tech industry. Kerry Optical Systems, LLC is looking forward to expanding our product offerings in the future.