ZMI Optical
Wavelength Compensator
Accessory Manual
OMP-0233G

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MANUAL REVISION INFORMATION

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MANUAL NOTATIONS

⚠ **Warning!** Denotes a hazard that could cause injury to personnel, and can also cause damage to the equipment.

Note: Provides helpful information.

ZYGO TECHNICAL SUPPORT

For help within the United States, Canada, and Mexico, please use the contacts listed below. For help in other countries, please contact your local Zygo representative.

Be sure to supply the instrument model and serial number, and the software version.

PHONE (860) 704-5191 Customer Support Center, 8 a.m. - 8 p.m. (EST)
(860) 347-8506 Zygo Corporation

FAX (860) 347-3968, 24 hours per day

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ZYGO STATEMENT OF WARRANTY AND PRODUCT SUPPORT

Zygo Corporation provides this warranty to protect its customers from defects in product workmanship or product materials. This warranty covers all products manufactured by Zygo Corporation. Zygo warrants that the equipment purchased will be free from any defects in material and/or workmanship under normal operating conditions for a period of one year from the date of shipment.

In addition, being committed to providing our customers with superior service, Zygo will support all standard products for a period of five years after the sale of the last newly-manufactured unit. Beyond this five-year period, we will continue to support these products on a "best-effort" basis.

WARRANTY SERVICE

Zygo's responsibility under this warranty shall be limited to the repair or replacement (at Zygo's option) of defective equipment at no cost to the buyer, except for transportation, cleaning, and recalibration charges.

Zygo will perform warranty service by: (1) sending replacement parts with appropriate installation instructions to the buyer, the buyer returning his defective part to Zygo or; (2) repairing the product at a Zygo repair facility after it has been returned freight prepaid, or; (3) at the buyer's request, dispatching a service representative to the buyer's facility. The buyer shall pay Zygo's travel and living expenses as well as travel time.

Defective products or parts will be repaired or replaced with new or like-new parts. These replacement parts will be warranted for a period of 90 days after they are shipped, or for the remainder of the original warranty period, whichever is longer. Warranty service will be performed only if the buyer notifies Zygo within 14 days of discovering any defects. Equipment or parts that are to be returned to Zygo must be issued a Return Authorization number. This number can be obtained by contacting the Zygo Service Department. Should Zygo's subsequent inspection reveal that the parts were not defective, all expenses incurred by Zygo shall be charged back to the buyer. Defective equipment that is replaced shall become the property of Zygo.

Warranty period begins when the product is shipped from Zygo. Replacement parts, service workmanship, used equipment, and refurbished equipment are warranted for a period of 90 days.

RETURNS

Unused and undamaged products, in their original shipping containers, may be returned for credit within 30 days of receipt. All such products will be subject to a restocking fee equal to 20 percent of the purchase price. Custom products are not returnable.

EXCLUSIONS

The above warranty and product support statement applies only to equipment that is an integral part of a Zygo manufactured product. It does not apply to peripheral equipment manufactured by others, such as: computers, printers, vibration isolation tables, etc. In such cases, the warranty and the support that the original manufacturer supplies will apply.

In addition, warranty service does not include or apply to any product or part which, in Zygo's judgment:

a. Has been repaired by others, improperly installed, altered, modified, or damaged in any way.

b. Malfunctions because the customer has failed to perform maintenance, calibration checks or good operating procedures.

c. Is expendable or consumable (such as panel lights, fuses, batteries, windows, and filters) if such items were operable at the time of initial use.

d. Requires replacement because of decomposition due to chemical action.

e. Fails because of poor facility, operating conditions, or utilities.

Other than expressly described above, Zygo makes no express or implied warranties, including any regarding merchantability or fitness for a particular purpose relating to the use or performance of the equipment. Zygo will not be liable for personal injury or property damage (unless caused solely by its own negligence), loss of profit or other incidental or consequential damages arising out of the use or inability to use the equipment. Nor does this warranty apply to any equipment which has been subject to misuse, neglect or accident; or repaired or altered by other than service representatives qualified by Zygo.

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List of Illustrations

WAVELENGTH COMPENSATOR

INTRODUCTION

The Zygo Optical Wavelength Compensator* is used to adjust measurements for variations in the wavelength of the laser beam emitted by the displacement measurement Laser Head due to changes in the refractive index of the air through which the laser beam travels.

Temperature, pressure, humidity, and molecular composition of the air have a direct effect on its refractive index, and thus on the wavelength. Since wavelength is the unit of measure for all measurements made by Zygo's Motion Interferometer System, the value output by the system must be compensated when environmental factors limit the performance of the system.

The Compensator tracks changes in the refractive index of the surrounding air from some initial value. It does not measure the absolute refractive index. This is sufficient in many applications in which measurement precision is of primary concern. When absolute accuracy is required, the initial value of the refractive index must be provided by some additional means, as described in the section entitled “Determining the Initial Index”.

What This Manual Covers

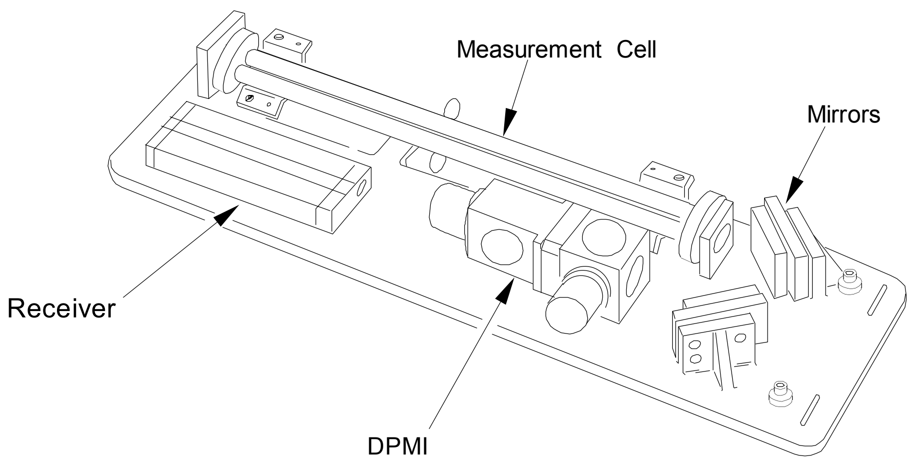
The following topics are covered:

- Description
  - Theory of Operation
- Installation
- Alignment
- Accuracy Considerations
  - Error Sources
  - Determining the Initial Index
- Maintenance
- Technical Support

*U.S. Patent 4,733,967. Foreign Patents Pending.

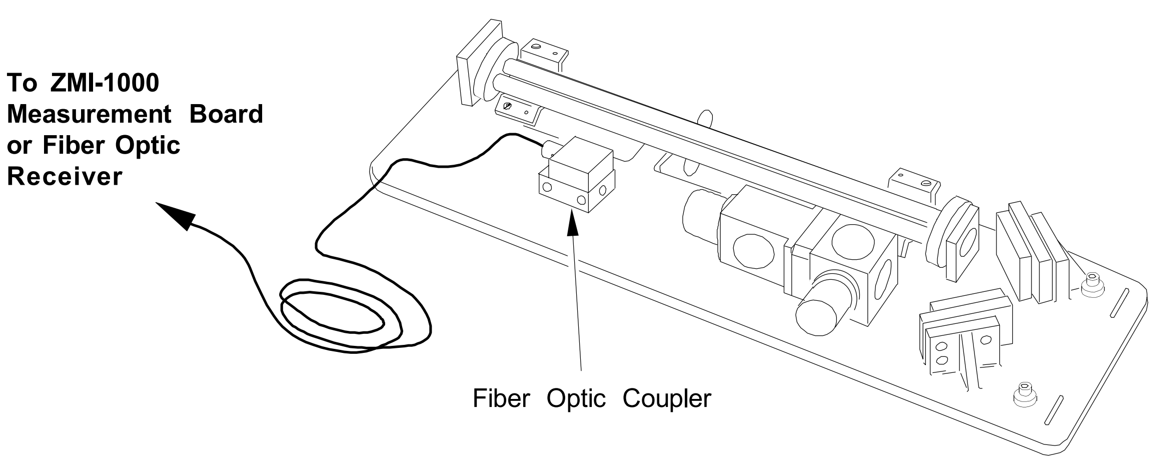
DESCRIPTION

The Optical Wavelength Compensator is comprised of a Differential Plane Mirror Interferometer (DPMI), fold mirrors, a measurement cell, and a receiver. Three models of the Wavelength Compensator are available: Model 7056, with a receiver; Model 7056A, without a receiver; and Model 7056C, with a fiber optic coupler for use with the ZMI-1000 Measurement Board or a fiber optic receiver. The Model 7056 Wavelength Compensator is shown in Figure 1; the Model 7056C Wavelength Compensator is shown in Figure 2.



Model 7056 Wavelength Compensator

Figure 1

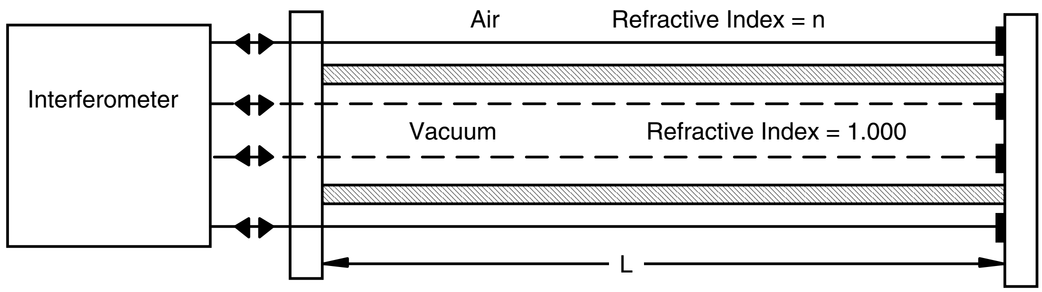


Model 7056C Wavelength Compensator

Figure 2

The measurement cell is an evacuated and sealed quartz tube with a mirror bonded at one end and a window bonded at the other. The reference and measurements beams of the DPMI travel through the front window of the measurement cell and are reflected from the back mirror at the end of the cell.

The reference beam of the DPMI travels inside the cell through the evacuated path, while the measurement beam travels precisely the same distance through the surrounding air. The beam paths of the measurement cell are shown schematically in Figure 3.



Wavelength Compensator Beam Paths

Figure 3

In Model 7056, the beams are recombined by the DPMI and the interference is detected by the receiver. In Model 7056C, the beams are recombined by the DPMI and directed to a Fiber Optic Coupler, which focuses the beam onto a fiber optic cable connected to the ZMI Measurement Board or a remote receiver.

Since the measurement and reference beams are reflected from the same mirror, and the wavelength of the reference beam traveling through the vacuum is fixed, any measured changes will be caused by the change of wavelength in the air path due to changes in the refractive index of air. The Compensator measures the variations of the refractive index from an initial value, rather than measuring the refractive index absolutely. The change in the refractive index may be output directly to the control computer using the data obtained from the Measurement Board.

Theory of Operation

The Wavelength Compensator operates on the principle that as the index of refraction of the air changes, it introduces an optical path change. By interferometrically comparing two beams (one that passes through the air and one that passes through a vacuum), this optical path change can be measured. Knowing the parameters of the measurement cell, the refractive index change can then be calculated.

The optical path difference (OPD) between the measurement and reference beams for an initial value of the refractive index (n_o) is given by:

$$OPD_o = 4L(n_o-1) \tag{1}$$

where L is the length of the measurement cell. The optical path difference at a later time is given by:

$$OPD = 4L(n-1) \tag{2}$$

where n is the current refractive index of the air.

The system measures the optical path change (OPC), which is given by:

$$OPC = OPD-OPD_o = 4L(n-n_o) \tag{3}$$

The electronics measure the OPC in terms of accumulated counts, N, as:

$$OPC = \frac{N\lambda_v}{M} = \frac{Nn\lambda}{M} \tag{4}$$

Where λ_v is the vacuum wavelength of the laser beam and M is a resolution factor.

Substituting Equation (3) into Equation (4) and solving for n, gives:

$$n = n_o \pm \frac{N\lambda_v}{4L(M)} \tag{5}$$

Equation (5) is used to calculate the current refractive index of air (n). The first term (n_o) is the initial value of the refractive index and the second term is the measured change. The M factor varies per system, $M_{ZMI} = 128$ and $M_{ZYGO\ 2/20} = 127$.

When the *lower* frequency beam (F2) travels through the vacuum in the measurement cell, the second term of the equation is *subtracted* from the first term. This is the case when the plane of the base of the Wavelength Compensator is parallel to the base of the Laser Head.

When the *higher* frequency beam (F1) travels through the vacuum in the measurement cell, the second term of the equation is *added* to the first term. This is the case when the base of the Wavelength Compensator is not parallel to the base of the Laser Head but is rotated at 90 degrees about the beam from the Laser Head.

Refractive Index n is represented mathematically by:

$$n = n_o \pm \frac{N\lambda_v}{512L} \quad \text{(ZMI)} \qquad n = n_o \pm \frac{N\lambda_v}{508L} \quad \text{(ZYGO 2/20)}$$

The length of the measurement cell (L) is recorded on the cell.

For the nominal value of L , which is 280 millimeters, the smallest detectable refractive index change (for one count, N=1) is:

$$n = 4.4 \times 10^{-9}$$

which is the resolution of the system.

The values listed for the wavelength of f1 and f2 are always described for a vacuum condition. The "correct" wavelength used for the calculation of a displacement should consider the index of the laser path media.

A more precise statement for the value of the wavelength is:

$$\lambda f1a = \lambda f1v / n$$

$$\lambda f2a = \lambda f2v / n$$

where

λf1a = wavelength frequency f1 in air

λf1v = wavelength frequency f1 in vacuum (632.991501 nm)

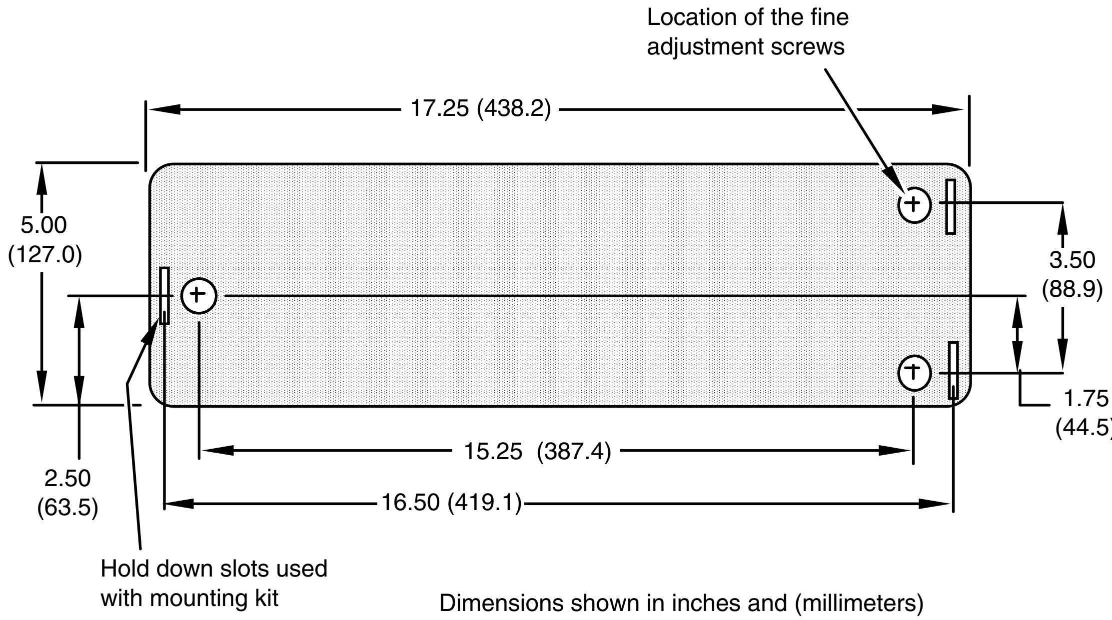
λf2a = wavelength frequency f2 in air

λf2v = wavelength frequency f2 in vacuum (632.991528 nm)

For the usual case, where the base plate of the Wavelength Compensator is parallel to the base of the Laser Head, f1 sees the effect of the change in the index of the local media, and f2 follows the vacuum path of the compensator. For the alternate mounting, with the base plate of the Wavelength Compensator at a right angle to the base of the Laser Head, f2 sees the effect of the change in the index of the local media, and f1 follows the vacuum path of the compensator.

INSTALLATION

The Wavelength Compensator must be mounted with the long dimension of the base parallel to the incoming laser beam. The plane defined by the base of the Compensator must be parallel or perpendicular to the Laser Head mounting plane within ±1 degree. The space required by the Compensator is shown in Figure 4.



Wavelength Compensator Mounting Dimensions
Figure 4

The Compensator is shipped with a protective cover in place. This cover must be removed for the Compensator to function properly. The Compensator has three fine adjustment screws in its base; this arrangement is for simple horizontal bench applications where the Compensator is not secured in position.

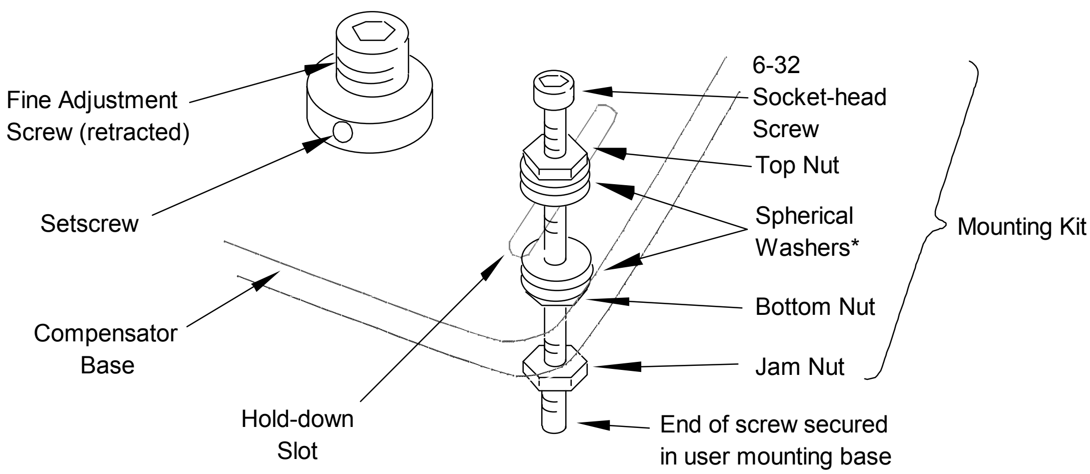
For other applications, where it is necessary to secure the Compensator in either a vertical or horizontal position, retract the fine adjustment screws and use the supplied mounting kit. The mounting kit contains: 6-32 socket-head screws, spherical (two-piece) washers, and 6-32 nuts.

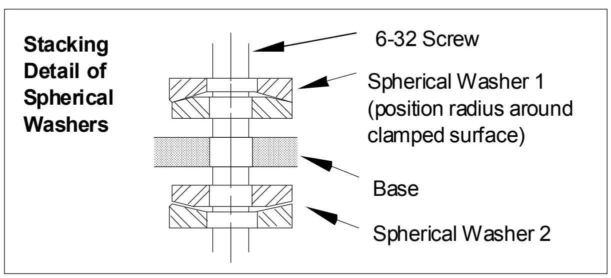
Installation Procedure

1. Using a 3/32 Allen wrench, remove the four socket-head screws from the protective cover and then remove the cover from the Compensator.
2. Locate the Compensator such that: a) the air volume that will surround the Compensator will be representative of the air in the measuring axes and is not exposed to turbulent air from fans, air conditioning or other sources, and is not heated or cooled by adjacent surfaces; and b) the Compensator is positioned in respect to the Laser Head so the input beam is parallel to one of the X, Y, or Z coordinates of the Laser Head.

   ⚠ **Warning!** When securing the Wavelength Compensator in position, use the supplied mounting kit and retract the fine adjustment screws to ensure that the base of the Compensator is not placed under stress.
3. If it is necessary for your application, secure the Compensator in position by using the mounting kit as shown in Figure 5. To use the mounting kit you must drill and tap three 6-32 holes in the mounting surface for the Compensator, spaced for the hold down slots as shown in Figure 4.

   When the Compensator is secured in position with the mounting kit the fine adjustment screws should *not* contact the mounting surface. To retract the fine adjustment screws, loosen the set screw with a 5/64 inch Allen wrench and turn the adjustment screw counterclockwise with a 1/8 inch Allen wrench. This mounting arrangement may also be used to adjust the Compensator during alignment.
4. For Model 7056, connect the receiver cable to the electronics. For Model 7056A, the user must provide mounting brackets for the remote receiver, and then connect the receiver to the electronics. For Model 7056C, connect the fiber optic cable from the Coupler to the ZMI-1000 Measurement Board or Fiber Optic Receiver.
5. Align the entire Compensator in reference to the incoming beam. Refer to the Alignment section.
6. Use the millimeter dimension of the measurement cell length when calculating change in the refractive index of air in the host computer.





Using the Mounting Kit
Figure 5

ALIGNMENT

Maximum accuracy is attained with the Wavelength Compensator when it is properly installed and aligned to the laser beam. It is assumed that the laser beam will be directed through a volume of air which will be representative of the air surrounding the other measurement axes.

> **Note**: The optical components within the Wavelength Compensator have been prealigned; DO NOT adjust or disassemble these components. Only the total Compensator assembly requires alignment to the incoming laser beam.

The alignment of the Wavelength Compensator to the laser beam is performed by completing the following steps. Refer to Figure 6.

> **Note:** Before proceeding, ensure that the Laser Head is aligned to the measuring axes of the system.

1. Adjust the three alignment screws to the mounting elevation for the application. Ensure that the screws extend through the base equally.
2. Select the small aperture (3 mm beam) at the front of the Laser Head. Put scotch tape on the front of the DPMI to visualize the beam placement. Place the alignment card (7106) in front of the Laser Head so that the beam passes through the pinhole in the flag.
3. Attach the alignment mirror (included with the Compensator) to the output face of the interferometer.

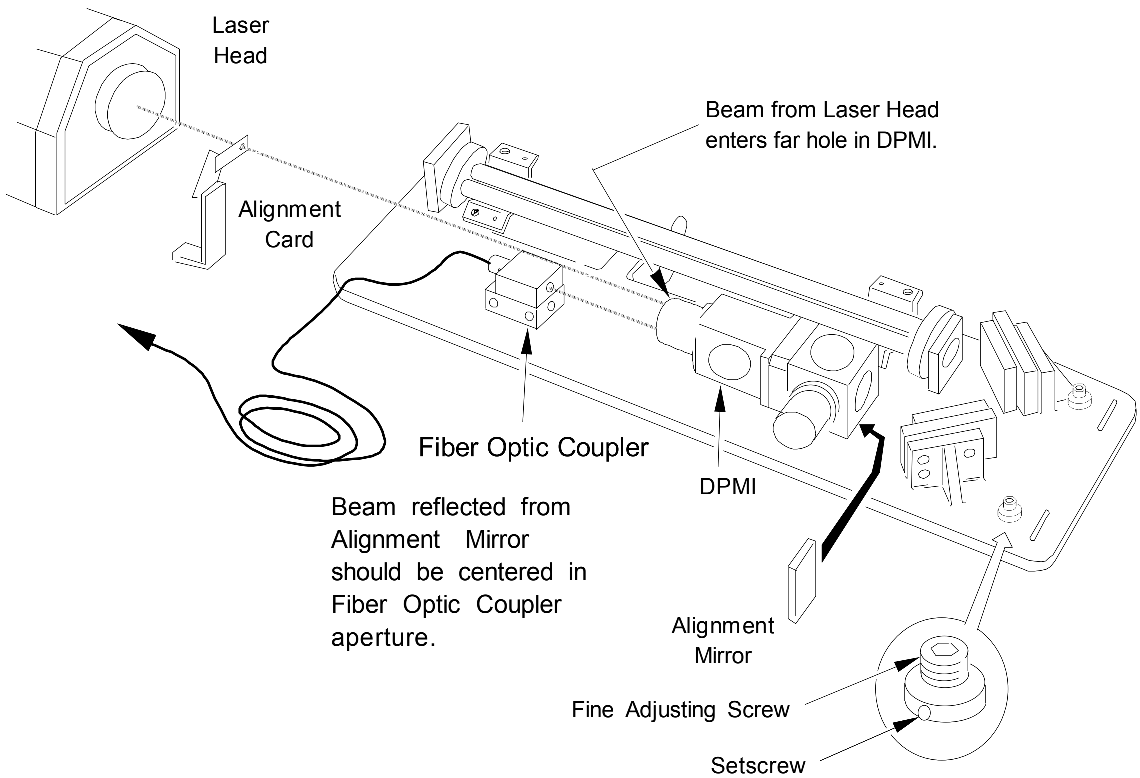
   > **Note**: DO NOT tighten the screws any more than is necessary to hold the mirror face against the metal cell, or the mirror may bend. If the Wavelength Compensator is being installed on a level surface, it may be easier to lightly hold the mirror against the cell with your fingers while performing the next step.

4. Position the Compensator so that the laser beam enters the left hole in the DPMI. This requires adjusting the alignment screws and rotating the Compensator. Adjust the Compensator until the reflected beam passes back through the hole in the card.

   > **Note**: When beam alignment is close, the beam reflected from the alignment mirror will strike the back surface of the alignment card.

5. Tighten the Compensator setscrews that hold the alignment screws in place. Secure the Compensator in position using kinematic mounting techniques.
6. For Models 7056 and 7056A, ensure that the beams overlap properly at the receiver lens; if they do not, make a slight adjustment of the receiver or Compensator position. Then proceed to step 8.
7. For Model 7056C, ensure that the beams from the interferometer are centered on the lens of the Fiber Optic Coupler. Connect the fiber optic cable to the Coupler and observe the end of the cable on a white piece of paper and adjust the location of the Fiber Optic Coupler until the maximum brightness is achieved.

8. Remove the alignment card and the alignment mirror. Select the large aperture (6 mm beam) at the front of the Laser Head. For multi-axis systems where optical power is at a premium, the signal on the test point of the receiver or ZMI-1000 Measurement Board may be monitored and maximized when following the above procedure.



Aligning the Wavelength Compensator

Figure 6

ACCURACY CONSIDERATIONS

Error Sources

There are several sources of error that will affect the accuracy and precision of the refractive index. Some of these are described below:

1. A prior knowledge of n_o:

   For measurements where the value of the refractive index is inconsequential, such as in interferometers where the measurement and reference path lengths are nearly equal, the use of the Wavelength Compensator is not essential.

   The value of the refractive index used for computations in these cases is usually taken as $n = n_o$=1.00027, a value for normal atmospheric conditions in the workplace. For unequal path interferometers where high accuracy is needed, the Wavelength Compensator in conjunction with Equations (5) and (7) is required. There is no simple method to determining n_o. Typically the temperature, pressure, and humidity are measured, and refractive index is calculated using Edlen's formula.[1] However, this does not take into account the molecular composition of the air, such as CO_2 and solvent concentrations, which will affect the refractive index.

   The error in refractive index (Δn) is to first order given by:

   $$\Delta n = \Delta n_o$$

   Refer to the next section for information on how to determine the initial value of n_o.

2. Uncertainty in L:

   Each measurement cell that is fabricated has a slightly different length. They are individually measured and the length is recorded on the mirror end of the cell. The length has a measurement error associated with it as well as thermally induced variations which result in some uncertainty on the calculated refractive index.

   This uncertainty in the measurement cell length is given by:

   $$\Delta n = \left\lfloor \frac{N\lambda_v}{4L(M)} \right\rfloor \frac{\Delta L}{L}$$

   Under normal atmospheric conditions, the term in brackets can have extreme values of $\pm 10^{-4}$, while the uncertainty in the length is ±10 micrometers. This results in maximum error in the refractive index of:

   $$\Delta n_{max} = 3.8 \times 10^{-9}$$

3. Alignment errors:

   Another error that can arise is due to alignment of the Compensator to the laser beam. When the beam travels through the Compensator non-normal to the end mirror, the apparent length of the measurement cell increases. The error in length is given by:

   $$\Delta L = L\,(1 - \cos\alpha)$$

   where α is the misalignment angle. If the alignment procedure (described in the next section) is followed, α should be no greater than one minute of arc. With that accomplished, the contribution to the uncertainty in the refractive index is usually of no consequence.

4. Selection of F1 or F2 for the measuring beam:

   The variation in n, caused by arbitrary selection of F1 or F2 for the measuring beam, in the Wavelength Compensator is given by:

   $$\Delta n = \left[\frac{N\lambda_v}{4L(M)}\right]\frac{\Delta\lambda}{\lambda} \qquad M_{ZMI} = 128 \text{ and } M_{ZYGO\ 2/20} = 127$$

   As stated above, the term in brackets can have extreme values of $\pm 1 \times 10^4$. With the difference in wavelength, between F1 and F2 being less than
   0.3×10^{-4} nanometers compared to the nominal λ of 633 nanometers, the uncertainty in n would be less than 5×10^{-12}.

Determining the Initial Index

The initial value of the refractive index of air, n_o, used in equation 5 is to be determined by the user. The tracking accuracy of the Wavelength Compensator, due to changes in n, is better than 0.1 parts-per-million (ppm), however, absolute measurement accuracy also depends on n_o.

In applications where absolute measurement accuracy is required (better than a few ppm), the user must provide sensors to measure the pressure, temperature and the relative humidity close to where the Wavelength Compensator is being used.

The initial value of the refractive index can be calculated from the values obtained, using Edlen's general formula[1]:

$$n_o = 1 + (3.83639x10^{-7}P)\left[\frac{1 + P(0.817 - 0.0133T)x10^{-6}}{1 + 0.003661T}\right] - 5.607943x10^{-8}F$$

where: P is the atmospheric pressure in Torr.
T is the temperature in degrees Celsius.
F is the partial pressure of the water vapor in the air in Torr.

F can be calculated by knowing the relative humidity (H) in percent and the water vapor pressure of saturated air ($f_{saturated}$) in Torr using:

$$F = \frac{H\, f_{saturated}}{100}$$

The water vapor pressure of saturated air may be interpolated from available tables (for example: American Institute of Physics Handbook) or calculated using the polynomial below:

$$F_{saturated} = 4.07859739 + 0.44301857T + 0.00232093T^2 + 0.00045785T^3$$

Where T is the temperature in degrees Celsius.

You must keep in mind that a change in temperature of only 0.1°C, a change in barometric pressure of 0.3 Torr, or a change in relative humidity of 10% will cause a change in n of one part in 10^7, therefore the measurements, calculation of n_o and storage of the value n_o in the user's computer must be done in as short a period of time as practical, while the Wavelength Compensator is already functioning.

For applications in which only relative values of n are significant, rather than the absolute values, a nominal value for n_o can be calculated and stored in the user's computer.

1. B. Edlen, "The Refractive Index of Air", Metrologia, Vol. 2, no. 2, p. 71 (1966).

MAINTENANCE

All the optical surfaces of the Wavelength Compensator should be kept completely free of contaminants. Improper or unnecessary cleaning can damage optics.

⚠ **Warning!** Zygo is not responsible for any damage that occurs to an optical component as a result of improper cleaning.

Guidelines for handling and cleaning optical components:

- Handle the Wavelength Compensator as little as possible.
- Do not touch the optical surfaces of the Wavelength Compensator. Acids and salts in the skin can cause permanent degradation of surfaces.
- Keep the working environment as clean as possible to prevent contaminants building up on the Wavelength Compensator. Smoke, airborne lint, dust, and moisture will degrade the performance of the Compensator.
- Do not attempt to clean the optical surface of the Compensator unless experienced in optical cleaning techniques. Clean only if necessary.

Note: Detailed cleaning procedures for optical components are located in Chapter 6 of the ZMI Optics Guide, OMP-0326.

Optical Wavelength Compensator

Configuration	Zygo Part Number	Model
With Receiver	6191-0295-01	7056
With Fiber Optic Pickup	6191-0295-04	7056C

Dimensions: See Figure.

Weight: 2 kilograms (72 oz)

Components Included: Polarization Beamsplitter, Half Waveplate, Retroreflector, Polarization Shear Plate, Beam Translator, Quarter Waveplate, Mirror Assemblies (2), Measurement Cell

Materials:
Base: Aluminum Alloy
Measurement Cell: Fused Quartz
Mirrors: Zerodur

Optical:
Measurement Resolution (nominal):
4.4 x 10 $^{-9}$ (ZMI 1000)
Range Accuracy: ± 0.1 ppm

Optical Signal Efficiency: > 50%

Operating Environment Temperature:
10°-30°C