ZMI Compact Optical Wavelength Compensator Accessory Manual OMP-0415D

zygo®

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Manual Revision Information

The document (OMP) number and the applicable revision letter for this manual appear on the title page. The publication date appears below.

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original	April 1997		
B	April 1998		
C	December 2000		
D	March 2002		

Manual Notations

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

Note: Provides helpful information.

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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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Compact Optical Wavelength Compensator

Introduction

The Zygo Compact 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

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

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

Description

The Compact Optical Wavelength Compensator is comprised of a Differential Plane Mirror Interferometer (DPMI), a measurement cell, and a Fiber Optic Pickup. The Wavelength Compensator is available with or without a fiber optic pickup. The Compact Wavelength Compensator is shown in Figure 1.

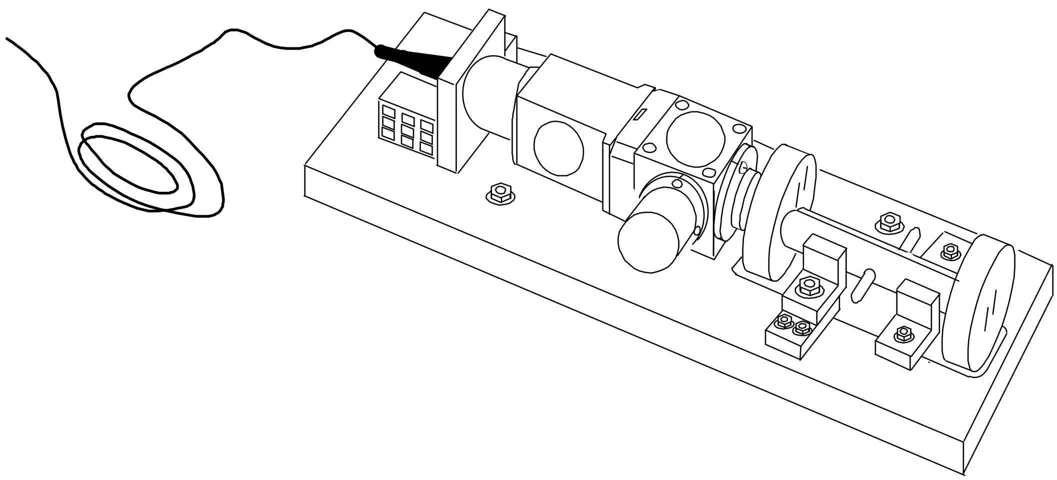

Figure 1 Compact Optical Wavelength Compensator

The measurement cell is an evacuated and sealed INVAR 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 2.

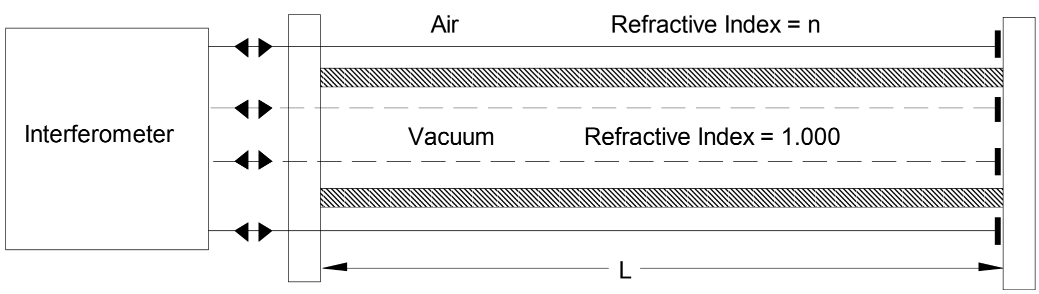

Figure 2 Wavelength Compensator Beam Paths

The two beams are recombined by the DPMI and directed to a Fiber Optic Pickup, which focuses the beam onto a fiber optic cable connected to the ZMI Measurement Board. Alternatively, the Fiber Optic Pickup may be removed, and the beam may be directed into a 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.

> **Note:** Use the millimeter dimension of the measurement cell length when calculating change in the refractive index of air in the host computer.

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, for example:

$M_{ZMI\ 510} = 16$ $M_{ZMI\ 501} = 128$ $M_{ZMI\ 2000} = 512$ $M_{ZMI\ 4000} = 1024$

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.

The Refractive Index (n) is represented mathematically by: $n = n_o \pm \frac{N\lambda_v}{XL}$, where:

$X_{ZMI\ 510} = 64$ $X_{ZMI\ 501} = 512$ $X_{ZMI\ 2000} = 2048$ $X_{ZMI\ 4000} = 4096$

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

For the nominal value of L , which is 70 millimeters, the smallest detectable refractive index change (for one count, N=1) is:

$n_{ZMI\ 510} = 1.4 \times 10^{-7}$ $n_{ZMI\ 501} = 1.8 \times 10^{-8}$ $n_{ZMI\ 2000} = 4.4 \times 10^{-9}$ $n_{ZMI\ 4000} = 2.2 \times 10^{-9}$

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

$\lambda f1a$ = wavelength frequency f1 in air

$\lambda f1v$ = wavelength frequency f1 in vacuum
(Laser Head 7702 = 632.991501 nm, Laser Head 7705 = 632.992 nm)

$\lambda f2a$ = wavelength frequency f2 in air

$\lambda f2v$ = wavelength frequency f2 in vacuum
(Laser Head 7702 = 632.991528 nm, Laser Head 7705 = 632.992 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 and Alignment

The Compact 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 3.

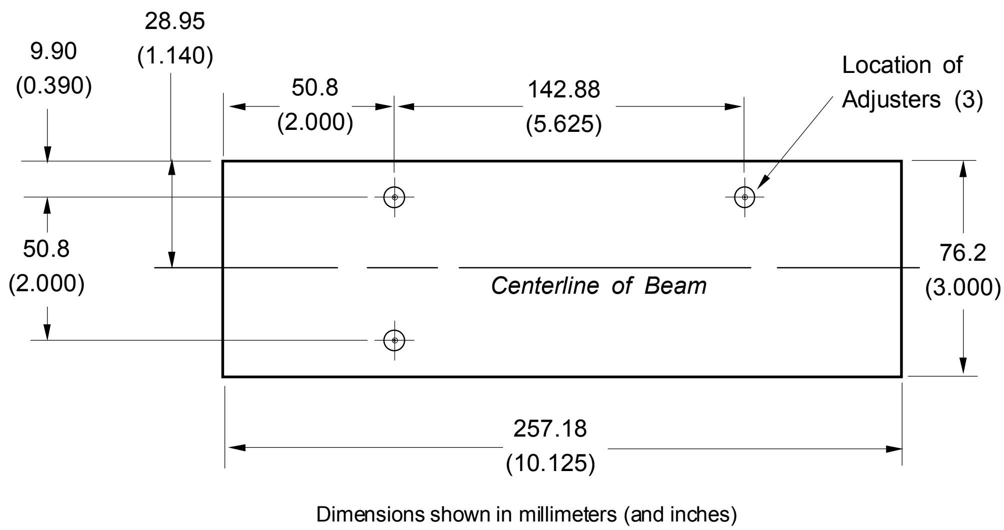

Figure 3 Mounting Dimensions (Top View)

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 with respect to the laser head so that the input beam is parallel to one of the X, Y, or Z coordinates of the laser head.

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

For most applications, it is necessary to secure the Compensator in either a vertical or horizontal position. To firmly mount the compensator, use the supplied mounting kit. The mounting kit contains 4-40 x 1.25 inch socket head capscrews, spherical washers, and Belleville washers.

Note: For metric installations, use M3 x 30 mm screws.

Installation Procedure

⚠ **Warning!** 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.

1. Using a 3/32 Allen wrench, remove the three capscrews from the protective cover at the locations shown in Figure 3. Remove the cover and standoffs.
2. Equally adjust the three adjusters to the mounting elevation required.
3. Use the mounting kit provided to secure the Compensator in position. Drill and tap three 4-40 holes in the mounting surface, spaced according to the dimensions shown in Figure 3. The mounting kit detail for the Compensator is shown in Figure 4. Slightly tighten the three capscrews securing the Compensator to the mounting surface by tightening the screws one turn past contact.
4. Temporarily remove the Fiber Optic Pickup and the adapter plate from the Wavelength Compensator. Perform alignment as described in the next section.

Alignment Procedure

1. Set the output beam of the laser head to the 2 millimeter alignment beam. Place an alignment card with a 2 millimeter hole at a convenient location along the beam path, so the beam passes through the pinhole in the card, as shown in Figure 5.
2. *Coarse Alignment.* The beam from the laser head should be centered in the incoming (left) hole in the DPMI. If the beam is not centered, insert the DPMI alignment aid provided into the DPMI and adjust the location of the Compensator until it is. Remove the alignment aid.

   ⚠ **Warning!** Do not touch the optical cell when attaching or removing the alignment waveplate.

3. *Fine Alignment.* Attach the magnetic alignment quarter waveplate to the output face of the DPMI. Using a 5/16-inch (8 mm) open end wrench, turn the three Compensator adjusters until the reflected beam passes back through the DPMI to the hole in the alignment card.
4. Tighten the three 4-40 capscrews to secure the Compensator. Check the alignment again; then remove the alignment waveplate. Reinstall the Fiber Optic Pickup.
5. *Fiber Optic Pickup Alignment.* Connect a fiber optic cable to the Fiber Optic Pickup. Shine the output end of the cable on white paper. Loosen the two Philips head screws attaching the Pickup and adjust the location of the Fiber Optic Pickup until maximum brightness is achieved. Tighten the two Phillips head screws.
6. Switch the laser head to the 3 or 6 millimeter beam.

   Note: For multi-axis systems, use the test point on the Measurement Board to check alignment. Adjust the location of the Fiber Optic Pickup until the voltage is maximized.

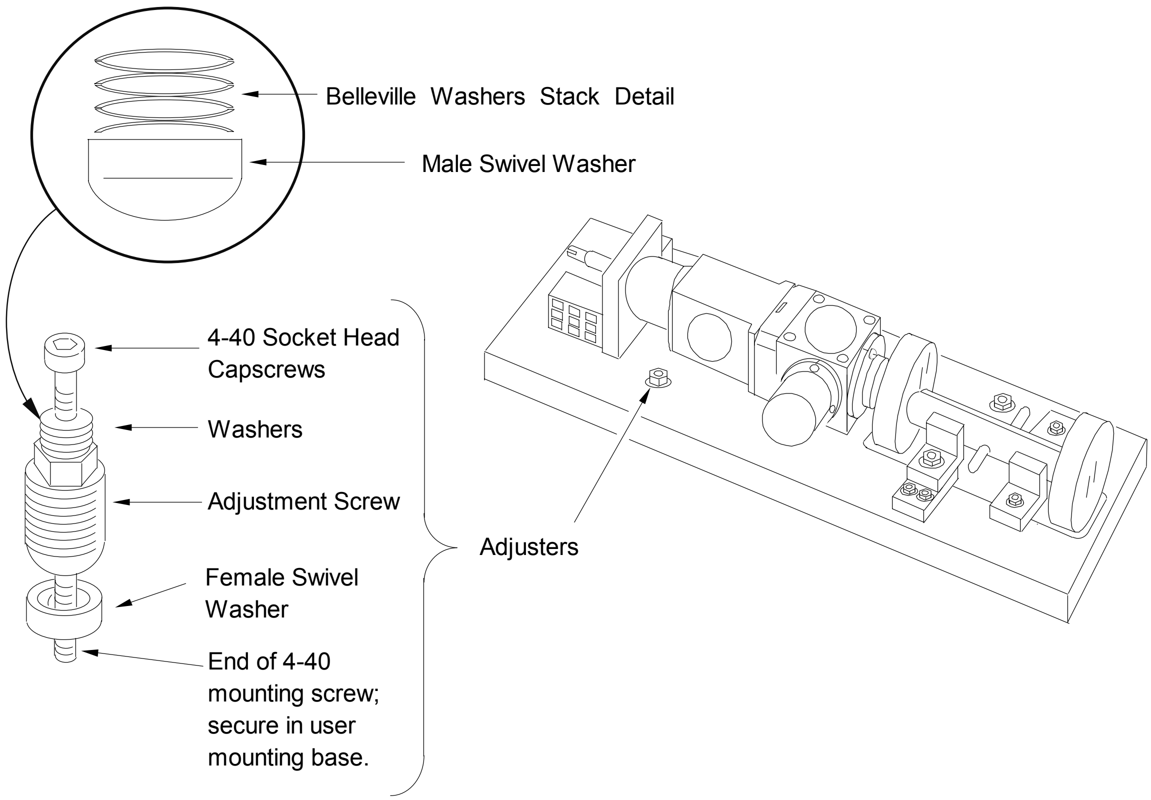

Figure 4 Mounting Detail

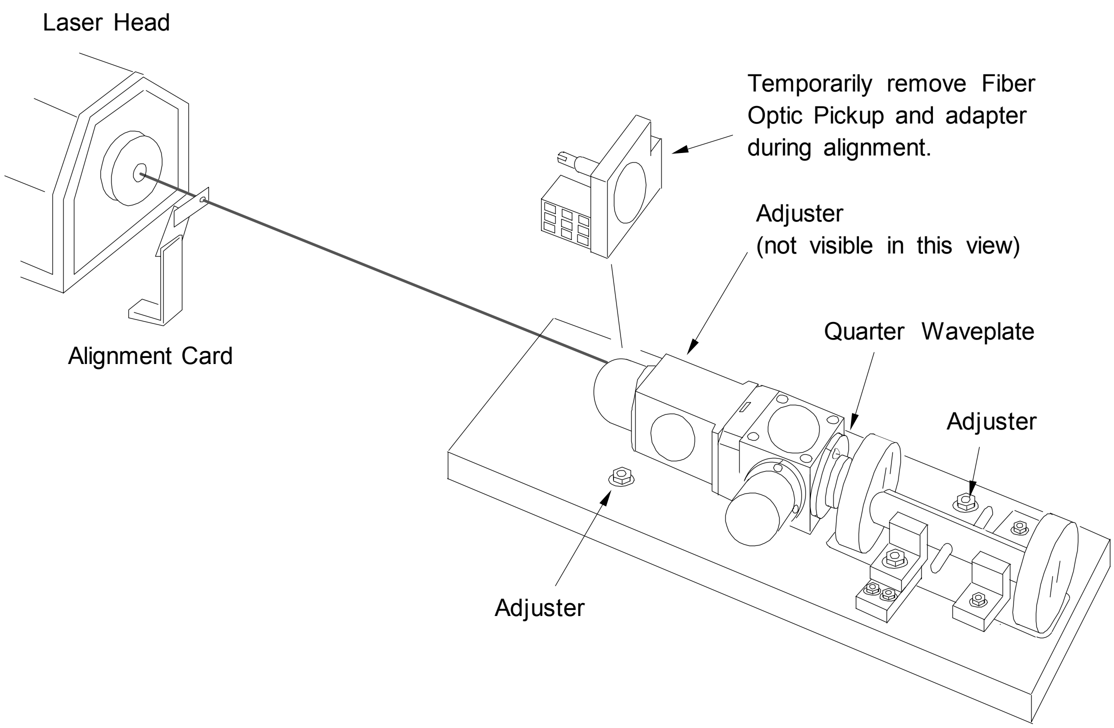

Figure 5 Aligning the Wavelength Compensator

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 about 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:

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

   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:

   $$\Delta n_{max} = 1.4 \times 10^{-8}$$

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

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:

   $$\Delta n = \left[\frac{N\lambda_v}{4L(M)}\right]\frac{\Delta\lambda}{\lambda}$$

   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 determined by the user. 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]:

$$n_o = 1 + (3.83639\text{x}10^{-7}P)\left[\frac{1 + P(0.817 - 0.0133T)\text{x}10^{-6}}{1 + 0.003661T}\right] - 5.607943\text{x}10^{-8}F$$

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 (such as the 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.

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.

Compact Optical Wavelength Compensator

Zygo Part Number: 6191-0584-01

Model: 7057

Dimensions: See Figure.

Weight: 1.3 kilograms (44 oz)

Components Included: Polarization Beamsplitter, Half Waveplate, Retroreflector, Polarization Shear Plate, Beam Translator, Quarter Waveplate, Measurement Cell Mirror Assembly, Fiber Optic Pickup

Materials:
Base: Aluminum Alloy
Measurement Cell Mirror Assembly:
INVAR and Zerodur

Optical:
Measurement Resolution (nominal):
1.4×10^{-7} (ZMI 510)
1.8×10^{-8} (ZMI 501)
4.4×10^{-9} (ZMI 2000)
2.2×10^{-9} (ZMI 4000)
Range Accuracy: ± 0.1 ppm

Optical Signal Efficiency: > 50%

Operating Environment Temperature:
10°-30 ° C