LDDM™
Laser Measurement System

User's Guide (LICS-100)
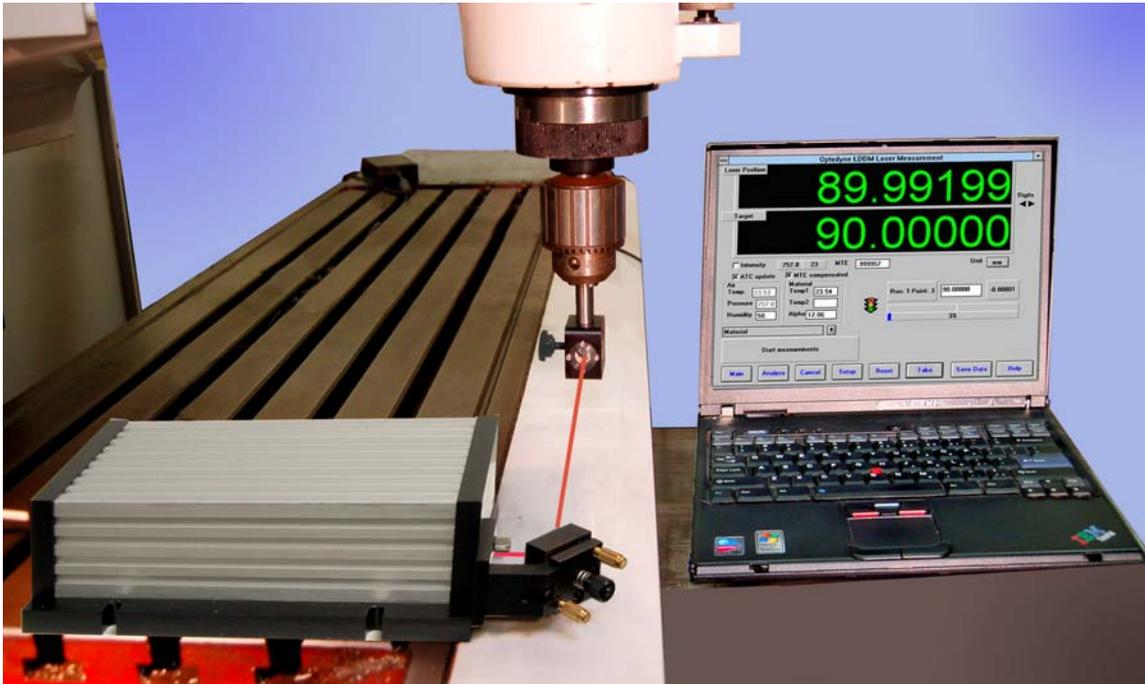
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OPTODYNE

This device is patented – U.S. Patents 4,715,706; 5,116,126; 5,394,233; 5,471,304; 5,724,130; 6,498,653 and 6,519,043 with other patents pending.

For technical assistance, please contact Optodyne's Service Department:

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310-635-7481 (Telephone)
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CONGRATULATIONS

Congratulations on your purchase of a measurement system, built around Optodyne's Laser Doppler Displacement Meter (LDDM™). This system offers an unprecedented combination of price, performance, ease of use, and compact made possible by the integration of state-of-the-art electronics and optics. Several different applications built around the LDDM™ are possible. The components in your system including this manual, have been carefully designed to best serve your specific application.

This manual is divided into the following three parts:

      1. Introduction

      2. Application

      3. Appendix

The Introduction will familiarize you with the LDDM™ system quickly. The Application section gives you step-by-step instructions on how to install and operate your LDDM™ system for the specific applications of its intended design. The Introduction and Applications sections should be read completely before using the LDDM™. The Appendix contains detailed explanations and reference material on topics related to the LDDM™. Information in this section is not normally needed for day-to-day operation.

For technical assistance, please call Optodyne's Service department at:
(310) 635-7481, or write to:

OPTODYNE, INC.
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Part I. INTRODUCTION

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1.0 Before we begin

1.1 Safety Precautions

This device is a Safety Class I system. It has been designed and tested according to IEC Publication 348, "Safety Requirements for Electronic Measuring Apparatus." This product is also a Class II Laser Product conforming to Federal Bureau of Radiological Health Regulations 21 CFR 1040.10.

> **Warning**: This equipment generates, uses, and can radiate radio frequency energy and if not installed and used in accordance with the instructions found in this manual, it may cause interference to radio communications. Temporarily allowed by current regulations the equipment has been tested for compliance within the limits for Class A computing devices pursuant to Subpart J of Part 15 of FCC rules, which are designed to provide reasonable protection against such interference. Operation of this equipment in a residential area is likely to cause interference. The user at his own expense, will be required to take whatever measures that may be necessary to correct the interference.

Warning: Do not clamp the Laser Head Module at any point other than the base plate. To do so can damage the unit.

> **Warning**: There is high voltage in both the Laser Head Module and the Processor Module. When the covers of these modules are removed, the operator is exposed to high voltage.

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1.2 Patent

This device is patented - U.S. Patents 4,715,706, 5,116,126, 5,394,233, 5,471,304; 5,724,130; 6,498,653 and 6,519,043 with other patents pending.

1.3 Unpacking and Inspection

As soon as you have unpacked the system please check for the following components:

1. Laser Head Modules
2. Retroreflector
3. DC Power Supply and Cable Set
4. Software and User's Guide
5. Accessories

Please check the condition of all components. Fill out the Warranty Registration, section 5.4, and return it to Optodyne, Inc., at the address shown on the cover page of this manual. All equipment should be tested as soon as it is received in accordance with the installation instructions. If any component fails to operate properly or is damaged in any way, a warranty claim should be filed with the carrier. A full report of the damage should be filed with the claim agent, and a copy made available to Optodyne, Inc., Service Department. Optodyne will then advise you of the disposition of the equipment and arrange for its repair or replacement. Include model number and serial number when corresponding about this equipment for any reason.

If a warranty claim is necessary, please provide detailed inform concerning equipment type, serial number, nature of the problem, etc. Send the claim to the Optodyne Service Department at the address at the front of this manual. Instructions for the disposition of the equipment will be returned to you. When ordering replacement components from the factory, always give the type and serial number of the equipment and the values, tolerances, ratings and Optodyne designation of all electrical components required.

2.0 General Information

2.1 Product Description

The Laser Doppler Displacement Meter, referred to herein as LDDM™, is an instrument system which measures displacement to an accuracy of two part in one million (2 ppm). A laser is positioned on the axis along which the target moves. The laser beam is returned by a reflector mounted on the axis along which the target moves. The reflected beam is detected near the laser source: the original and reflected beams run the same paths. After detection the displacement information is calculated and sent to a Notebook PC through a USB interface for display the reading, data collection and analysis.

The LDDM™ instrument system consists of three components; a Laser Head with processor Module, Retroreflector and a Notebook computer as shown in Fig. 2-1, LICS System Block Diagram. Please note that because of the single aperture optical arrangement (same aperture for both the laser output beam and the return beam), the retroreflector and all the optical accessories are much smaller.

```
┌──────────────┐              ┌──────────────┐
│    HEAD      │              │   RETRO-     │
│     &        │◄────────────►│              │
│  PROCESSOR   │              │  REFLECTOR   │
└──────────────┘              └──────────────┘
      ▲ │
      │ ▼
┌──────────────┐
│ NOTEBOOK PC  │
│              │
│ NOT INCLUDED │
└──────────────┘
```
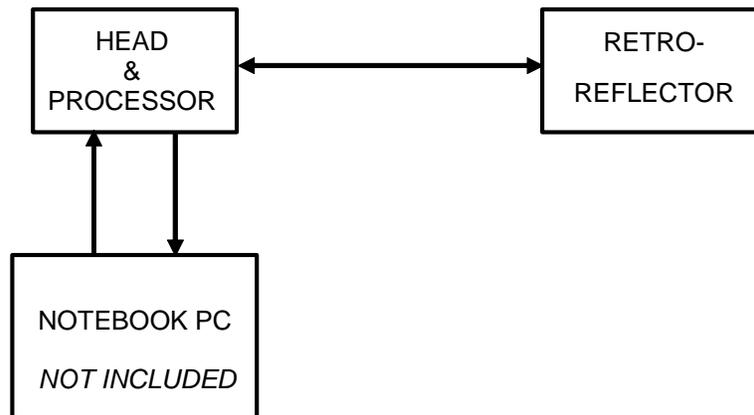
FIG. 2-1 SYSTEM BLOCK DIAGRAM OF LDDM
WITH A SINGLE APERTURE LASER HEAD

The following is a general description of these three components:

Laser Head Module:

The Laser Head Module houses a HeNe laser source, an electro-optic assembly, a photodetector, a stabilization circuit and a processor module. The laser is frequency stabilized. The detection is two-frequency or heterodyne in a

---

manner similar to the well known Doppler Radar. The displacement is determined by the Doppler effect and phase shift. See Fig. 2-2, Laser Head Module, Physical Layout. The signal from the photodetector is processed by the phase-demodulator and converted to displacement. The result is sent to the Notebook PC through USB. The resolution is 1 μin or 0.01 μm. A typical dimension of the laser head with processor module is shown in Fig. 2-4a.

Retroreflector:

The Retroreflector serves as a cooperative target. It is a corner cube, which reflects the laser beam back to the receiving aperture on the same path regardless of the angle of incidence. The use of a corner cube reflector provides significant advantages. Its alignment during installation is not critical in that it may rotate during measurements. See Fig. 2-3 Retroreflector, Physical Layout. The standard retroreflector has a diameter of ϕ0.5 in.

DC power supply and cable set

The DC power supply supplies 15 VDC to the laser head. The input is 90 to 230 VAC and 47 – 63 Hz. The maximum current is 1.6 A. There are 2 cables, one is the AC power cord for the DE power supply and the other is the USB cable.

Notebook PC

A notebook computer with standard USB interface can be used to display or collect data. A Windows software is used for data collection and analysis.

2.2 Theory of Operation

LDDM™ monitors the displacement of the objective or target, from an initial position where the display is zeroed, to any final position within the range of the instrument. Displacement is shown continuously as the target moves. At the final position, the displacement of the target is displayed. The sign of the displayed number indicates positive or negative displacement. Once set up the system operates without further adjustment.

4.10

2.43

1.08

0.96

Laser
Aperture

4.50   5.00

2x ¼-20
THD

5.00

8.00

8.50
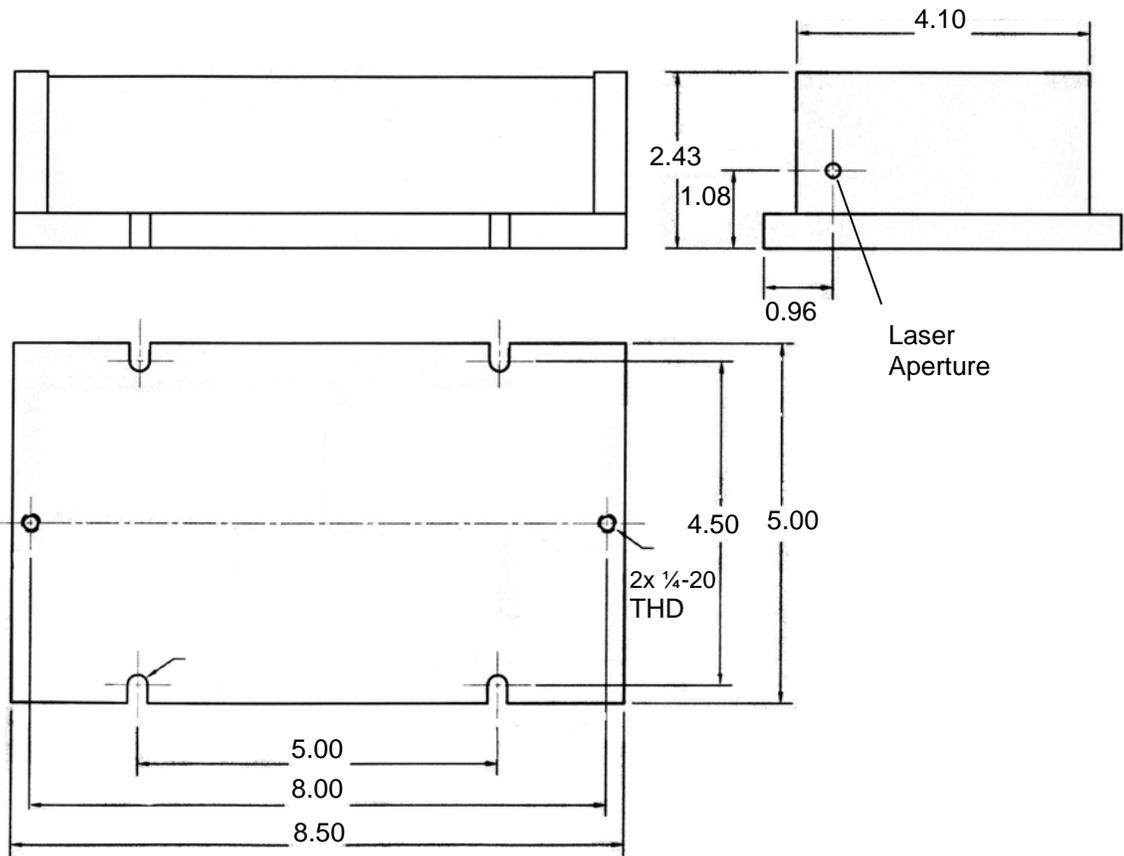
FIG. 2-2 LASER HEAD (LP-100)
OUTLINE & MOUNTING DIMENSIONS

φ.50 THRU

φ.50

1.00

1.50SQ

1.18

1.18

φ.15 THRU
4 PLACES

1/2" RETROREFLECTOR
(R-102A)

.50

.75

Ø.50

3.00

.40

.40

1.00

.50

2.00

3.80

ø1/2" CORNER CUBE WITH POST AND BASE (R-102)
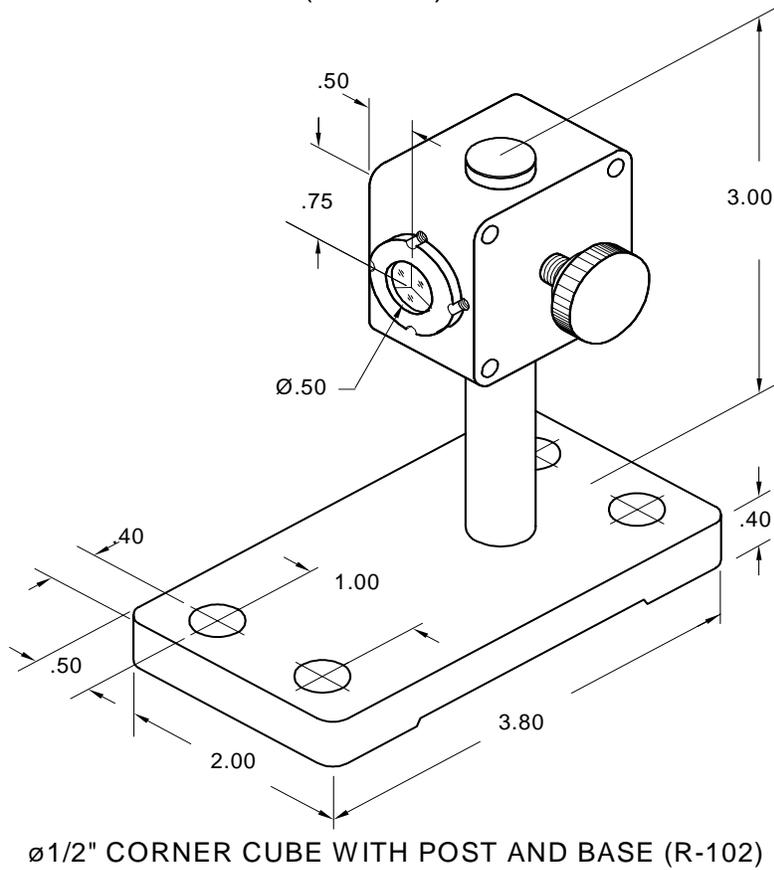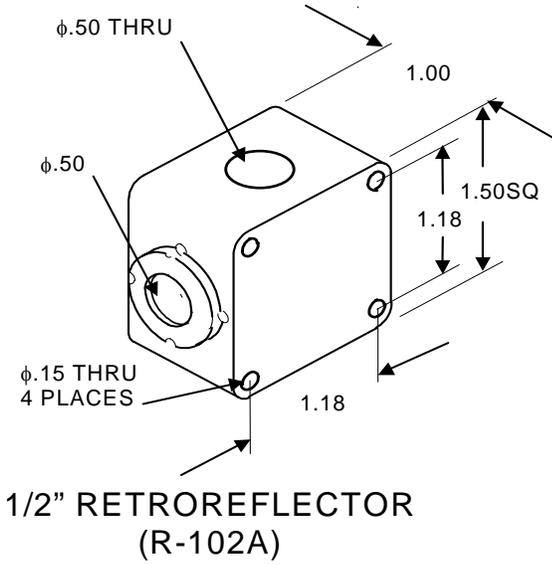
FIG. 2-3 1/2"RETROREFLECTOR

LDDM™ uses an electro-optical device which detects the Doppler shift of a laser frequency caused by a moving target to measure displacement with a high degree of accuracy. The range may be from a few microns to several meters. Other precision displacement measuring devices use interferometric techniques, requiring a sophisticated and bulky laser. This approach calls for critical, time consuming alignments, and causes additional expense. LDDM™ is based on the principles used in radar. Its construction is simpler, less costly, more rugged and much easier to use than a conventional interferometer.

The frequency of the reflected laser beam is shifted by the motion of the Retroreflector and is proportional to its velocity. The phase shift is proportional to the displacement. A phase-detector is used to sense the phase shift. For each half wavelength of displacement a counter is incremented. A microprocessor is used to read the counter and the phase angle, and converts them to inches or centimeters.

The Doppler frequency shift can be expressed as:

$$\Delta f = (2f/c)\, \Delta v$$

or:

$$\Delta \theta = 2\,\pi (2f/c)\, \Delta z$$

Where Δf and $\Delta \theta$ are the frequency and phase shift and Δv and Δz are the velocity and displacement respectively, of the Retroreflector. The variable f is the frequency of the laser, and c is the speed of light.

A counter is used in conjunction with the phase detector to record the number of half-wave lengths, $\lambda/2$, detected. A microprocessor reads the counter and the phase angle, converts them to output units, and controls the 10-digit display. Compensation for changes in the speed of light due to temperature, pressure and humidity variations is programmable.

2.3 Technical Specifications

	Standard	Units
Laser Stability:	0.1	ppm
Resolution:	1	μin
	0.01	μm
Range:	0-50	ft
	0-15	meters

Rate (max.):   40   inch/sec.
                               1000   mm/sec.

Outputs: computer interface, USB

Operating Environment: Temperature 60 to 90 °F (15 to 32ºC).

Altitude: 0 to 10,000 feet (0 to 3000 m)

Humidity: 0 to 95 percent (non-condensing)

Components:	Width (in)	Height (in)	Length (in)	Weight (lb)
Laser Head	5 (127mm)	2.43 (61.7mm)	8.5 (215.9mm)	5 (2.3kg)
Retroreflector	Ø0.5 (12.7mm)		0.35 (8.9MM)	0.1(90gm)

Interconnection

Cables: Number   Length
                       1   USB cable 12 ft (3.6m)

Power Requirements: 85-264 VAC, 50-60HZ, 100W

3.0 Operation

3.1 General Applications

The new LICS-100 calibration system is designed for the measurement, calibration and compensation of displacement errors of a CNC machine tools or a coordinate measuring machine (CMM).

3.2 Installation and Checkout

The LICS-100 system is extremely easy to set up and operate. The Laser Head, placed on the axis of interest, is mounted in a fixed position. The Retroreflector should be rigidly mounted onto the moving objective or target. The final position of these two components is determined by targeting the laser beam while moving the objective.

Mount the Laser Head Module at any of the four mounting holes. The laser head may be secured to a work surface in any fashion that will not generate and transmit excessive mechanical stresses to the Laser Head Module.

After the Reflector is mounted onto the target, and the Laser Head Module is in place, connect the USB cable between the Laser Head Module and the Notebook PC.

Connect the DC power supply to the Laser head module. After approximately five seconds, the laser will start up and a red beam of light can be detected from the center hole on the Laser Head Module.

> **Caution**: Do not look directly into the laser beam hole to detect the laser light beam. Instead, position a piece of white paper in front of the hole until a visible spot can be seen on the paper.

Connect the USB to the port on the Laser head module and the Notebook PC, and start the LICS software. The PC screen will show the Digital Display. When the system is properly aligned, the intensity reading should read more than 80%. When the beam is completely blocked, the intensity should read 0%.

If the laser does not start, disconnect the DC power supply and then connect again. If the laser still will not start after a few minutes see section 4 of this manual. Adjust the positions of the Laser Head Module and the Retroreflector so that the return beam is visible on the Laser Head Module front plate. Continue to adjust these two components until the spot of the return beam does not move while the objective, with the Retroreflector mounted on it, is moved over the desired range of measurement. Finally, move the Retroreflector so that the return beam enters the receiver aperture. Move the corner cube in the

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lateral direction until at the maximum intensity. Then move the corner cube to the full extreme of the travel while monitoring the beam intensity. After the unit is properly aligned, it will be able to travel the complete length of the rail with little change in the intensity. Click the reset to reset to zero. The LDDM™ system is now ready to use.

Even when the Retroreflector is stationary, the displacement readings will be affected by vibration, noise, variations in humidity, variations in barometric pressure and variations in temperature. These changes will affect the accuracy of the laser system as follows, approximately:

As a rule of thumb, temperature increase of 1°F is equivalent to a wavelength increase of 0.5 ppm, which is equivalent to 0.5 μin per inch of distance measured. A barometric pressure increase of 0.1 in. Hg is equivalent to a temperature decrease of 2°F or 1 μin per inch distance measured. A relative humidity increase of 30% RH is equivalent to a temperature decrease of 1°F or 0.5 μin per inch of distance measured.

However, usually the material thermal expansion is the dominant factor. For example, the thermal expansion coefficient of steel is 7.6 ppm/°F which corresponds to a 7.6 μin per inch of distance measured for each 1°F of temperature change. For further discussion see Section 7.7 and Appendix H.

3.3 Displacement Measurement

If installation and check out have been followed as described in section 3.2, the laser beam will be aligned parallel to the linear motion of the Retroreflector over the displacement range of interest. The system is now ready to start measuring displacement. The system will function immediately after turning power on. However, ultimate accuracy is achieved only after a warm-up period of 15 to 30 minutes during which the laser locks its frequency. The indicator light on the back of the laser head will light after the frequency is locked.

As the Retroreflector moves, the PC display will show displacement. The value displayed will constantly change as the Retroreflector moves. When motion stops, the display will show the displacement of the Retroreflector at its current position. If motion resumes, the monitor will again constantly change to show each instantaneous position of the moving Retroreflector. If the Retroreflector moves back to its original position, where the monitor was zeroed, and the monitor will again show zero displacement. If the Retroreflector moves closer to the Laser Head Module than it was at the point of zero, then displacement will be displayed with a minus sign to indicate a negative displacement.

4.0 Maintenance

4.1 Troubleshooting

The following paragraphs describe several diagnostic situations which the end user should be aware of in order to assure constant and reliable operation from the LDDM™ system:

No laser beam:

> Disconnect the DC power cable. Check the cable connector and make sure it is pushed in all the way. Connect the DC power cable again. If there is no laser beam after 30 seconds, repeat the same. If there is still no laser beam after a few tries, return both the Laser Head Module and the DC power supply for factory diagnosis.

Intensity less than 50%:

> This is an indication that the return beam is not properly aligned or that cables are not properly connected. Check all cables and connectors, and realign the Retroreflector. If this problem persists return the system for factory diagnosis.

4.2 Preventive Maintenance

There is no preventive maintenance required for the LDDM™. The system is designed to operate for an extended time without attention. The laser tube has an estimated life of 20,000 operating hours. Replacement of this tube is indicated by no laser beam and is accomplished by returning the Laser Head Module to the factory. Please contact your local sales office to identify nominal charges associated with this repair when done out of warranty. During the warranty period, repairs must be done by Optodyne in order to maintain the warranty. The cases of both the Laser Head Module is sealed with foil seals to prevent tampering. The **BREAKING OR REMOVING OF THESE SEALS VOIDS THE WARRANTY**.

After the warranty expires, Optodyne strongly recommends that subsequent defective components be returned to the factory for authorized service. Special tools, test equipment and know-how are required to evaluate LDDM™ component performance and to match replacement parts to maintain optimum system performance to specifications.

It is recommended that the LDDM™ be sent back to Optodyne Service Department annually for maintenance service and calibration. An extended warranty of up to three years is also available.

5.0 Warranty and Certification

5.1 Warranty

Optodyne, Inc., warrants that each new instrument which it manufactures and sells is free from defects in material and workmanship under recommended use and service conditions. Liability under this warranty is limited to servicing or adjusting any unit returned to the factory for that purpose and replacing any defective parts thereof. If a problem is limited to a single module, it is preferred that only the defective module be returned to Optodyne. This warranty is effective for one year from the date of delivery and to the original purchaser only. When the unit is returned (transportation charges prepaid by the original purchaser) and when upon examination, it is found to be defective, if the fault has been caused by misuse or abnormal conditions of operation, repairs will be billed at cost. In this case, an estimate will be submitted before the work is started. Optodyne, Inc. shall not be liable for damages by reason of failure of the instrument to perform properly or for any consequential damage. This warranty does not apply to any unit that has been subject to neglect, accident, misuse, improper operation or that in any way has been tampered with, altered or repaired by any person other than an authorized Optodyne personnel or to any unit whose serial number has been altered, defaced or removed.

Exclusive Remedies: The remedies provided herein are the buyer's sole and exclusive remedies. Optodyne, Inc., shall not be liable for any direct, indirect, special, incidental or consequential damages, whether based on contract, tort or any other legal theory.

5.2 Certification

Optodyne, Inc. certifies that this product meets its published specification (see section 2.3) at the time of shipment from the factory.

5.3 Calibration

The fundamental accuracy of the LDDM™ is based upon the wavelength stability of the laser used in the system. This wavelength has been measured to be 632.81934 ±0.0005 nm (24.914154 μin) at ambient conditions defined as follows:

Temperature:	68° Fahrenheit
Pressure:	29.90 inches of mercury
Relative Humidity:	40%

A calibration constant of 80275.65 counts per inch has been programmed into the microprocessor within the Processor Module. Recalibration service is available from Optodyne, Inc., for a nominal charge. A certificate of calibration

which is traceable to the National Institute of Standards and Technology, NIST, will be provided upon request. Optodyne is accredited to ISO/IEC 17025 by L.A.B. The certificate number is L1085.

5.4 Warranty Registration

Please complete this sheet as soon as the system is unpacked and return it to Optodyne, Inc. at the address shown below. Registration establishes the warranty period and enables Optodyne to keep you informed of product changes or upgrades.

End user's name:_____

Title:_____   **Dept.:**_____

Company:_____   **Phone Number: (___)_____**

                                                         ext.:_____

Address:_____

City:_____   **State:____   ZIP:_____**

Date of Purchase:_____

Model Number:_____

Laser head   **Processor**
S/N:_____   **S/N:_____**

Description of intended use or application:

_____

_____

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Mail to:
    Optodyne, Inc.
    1180 Mahalo Place
    Compton, CA 90220

or FAX to 310-635-6301.

Part II. APPLICATIONS

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6.0 LDDM™ Measurement System

6.1 Introduction
The LICS-100 is a very small and compact laser measurement system. It consists of 2 major components, the laser head and the retroreflector. Displacement information is transferred from the laser head directly to the Notebook PC through an USB interface. The Windows software can automatically collect and analysis the positioning data. The system does not include any weather station or pressure or temperature sensors. For speed of light correction manually enter the barometric pressure and air temperature. For material thermal expansion correction, manually enter the material temperature and the thermal expansion coefficient, the correction factor, MTE, can be calculated automatically..

6.2 Hardware and Accessories

For a general description of the laser head module and retroreflector, see section 2.1.

6.2.1 Laser Head module

The Laser Head Module houses a HeNe laser source, an electro-optic assembly, a photodetector, a stabilization circuit and a processor module. The laser is frequency stabilized. The detection is two-frequency or heterodyne in a manner similar to the well known Doppler Radar. The displacement is determined by the Doppler effect and phase shift. See Fig. 2-2, Laser Head Module, Physical Layout. The signal from the photodetector is processed by the phase-demodulator and converted to displacement. The result is sent to the Notebook PC through USB. The resolution is 1 μin or 0.01 µm. A typical dimension of the laser head with processor module is shown in Fig. 2-4a.

6.2.2 Retroreflector

The Retroreflector serves as a cooperative target. It is a corner cube, which reflects the laser beam back to the receiving aperture on the same path regardless of the angle of incidence. The use of a corner cube reflector provides significant advantages. Its alignment during installation is not critical in that it may rotate during measurements. See Fig. 2-3 Retroreflector, Physical Layout. The standard retroreflector has a diameter of ϕ0.5 in. The dimensions of a Ø0.5 in. retroreflector is shown in Fig. 6-1.   It is noted that the laser beam is non-polarized (random polarized), special coatings are not necessary and any flat first surface mirror can be used to steer the laser beam with any incident angle. Precise interferometer optical components will easily work with

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the LDDM™. However, less precise and therefore less expensive components may be used with the LDDM™ without sacrificing measurement accuracy and precision.

φ.80

4 OPEN PLACES
FOR #2-56 SCREW
ON φ.75 EQUAL SPACED

φ.60

.10

.57

φ.50
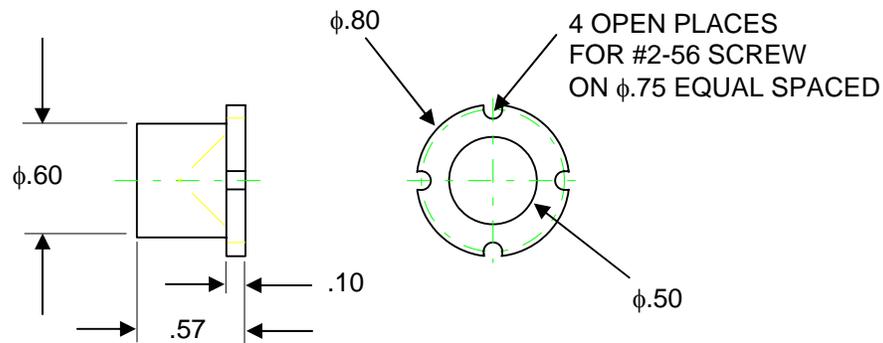
FIG.6-1 φ0.5" RETROREFLECTOR
DIMENSION & OUTLINE

6.2.3 Manual temperature and pressure compensation

The speed of light correction and material thermal expansion correction can be performed by manually enter the barometric pressure, air temperature, the material temperature, and thermal expansion coefficient for the corrections.

6.2.4 Beam bender

The output laser beam is random polarized. Hence any first-surface flat-mirror can be used to reflect the laser beam to any desired direction. A beam bender is a flat mirror used to reflect the laser beam 90° from the incident beam. Two fine threaded screws are turned to adjust the mirror angle, or for fine tuning the output laser beam direction. With this beam bender, the laser beam is easily aligned to be parallel to the travel of the bed or table. A typical 90° beam bender is shown in Fig. 6-3.

FIG. 6-2 90° BEAM BENDER (LB-100)

6.3 Calibration and Compensation of CNC machines and CMM machines

The use of CNC machines and CMM machines can result in significant productivity gain and better quality control. However, these machines also require greater accuracy. Hence, acceptance testing and periodic calibrations become necessary and important.

Also, many machine controllers can provide compensation for repeatable errors on each axis of motion. These repeatable errors, caused by the inaccuracy of machine ways, lead screws, or encoders, may change after wear and settling. The LICS-100 laser system can be used to generate a new compensation file and re-calibrate the machine tool position accuracy (see sections 7.9).

Using the metrology program, various mean values and statistical fluctuations can be calculated based on the National Machine Tool Builders Association (NMTBA) and ASME B5 used in USA and the German VDI/DGQ3441 used in Europe, and the ISO 230 international standard.

For the ASME B5 and B89 standard, the position error is defined as the LDDM™ reading - target position. The accuracy is the maximum averaged position error in the forward direction minus the maximum averaged position error in the reverse direction. The maximum reversal error is the maximum difference between the averaged forward position error and the averaged reverse position error at the same point. The new ASME B5.54 standard is similar to ISO 230-2 standard.

7.0 Displacement Measurement

7.1 Introduction

The LDDM™ LICS-100 Calibration System is designed to calibrate CNC machine tools, CMMs (Coordinate Measuring Machines), and other precision measurement machines and stages.

Based on the LDDM™, Optodyne's innovative Dopplometry technology has broken through the technological barrier of bulky, cumbersome laser heads, time consuming set-up and alignments, and costly measurement methods. LICS-100 Calibration System allows for a large misalignment tolerance making it possible to setup the system and have it operational in a matter of minutes.

7.2 Hardware Required

The basic hardware and software required for linear calibration are listed below:

a. Single Aperture Laser Head   L-100
b. Ø05" Retroreflector   R-102
c. Metrology/Analysis Program   W-100
d. 90° beam Bender (Ø0.5")   LB-100
e. DC power supply and cable set   IP-100
f. Soft carrying case   CC-100
g. Notebook PC (Not included)   LTC

FIG.7-1 CALIBRATION HARDWARE

7.3 Operating Specifications

Accuracy: The laser stability at an atmospheric pressure of 29.9 in Hg and an air temperature of 68°F is 0.1 ppm. At other pressures and temperatures, the measurement accuracy depends upon the velocity of light compensation and the material thermal expansion correction. With manual compensation and correction, the accuracy depends upon the accuracy of the measured air temperature, air pressure, and the material temperature. For more detailed discussion on accuracy see Appendices H and J.

Resolution: Standard resolution is 1 μin (0.01 μm).

Maximum Velocity: 40 inch/sec (1000 mm/sec)

Measurement Range: Up to 50 ft (15 m)

Temperature Range: 60°F to 90°F or (15.5°C to 32°C)

7.4 Reference Material

  Appendix H, ATC and Calibration
  Appendix J, Accuracy

7.5 Installation and Alignment

  7.5.1 Important Considerations

    1. Check that all cables are firmly connected before connecting the power
        cable and switching the power switch to the on position.

    2. Always mount the laser head on a stationary part and the retroreflector
        on a moving part. Never use a tripod to mount the laser head. The tripod
        may introduce an error.

    3. When installing the laser head, make sure that the laser beam coming
        out from the 90° beam bender will travel in the direction of the
        displacement measurement.

    4. Vibration and loose connections must be minimized by proper mounting.
        Make sure that all supports and cables are completely stationary. A
        spindle, for example, must be secured by a brake so it will not rotate.

    5. The output laser beam and the retroreflector must be aligned properly
        such that the beam intensity is above the minimum requirement along the
        entire measurement path.

  7.5.2 Installation

  7.5.2.1 Set up LDDM Program

        To setup LDDM program from Windows 95/98, Windows Millennium,
        windows 2000, NT and XP.

    1. For optimum performance exit all other applications before setting up LDDM
        program.
    2. Insert LDDM CD into CD-Rom driver and wait for the folder to appear from
        My computer Icon. Double click on setup.exe to install the software.
    3. Follow the instructions on your screen to continue through the setup progress.
    4. After the setup is installed successfully, an LDDM icon will show in the
        screen. The LDDM program is ready to run.

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7.5.2.2   Starting LDDM Program

To start LDDM from windows, run Windows and double clicking on the LDDM icon. The main menu of LDDM program will appear on your screen (see figure 7-2). Click on Linear for linear measurement. The measurement program will appear on your screen (see figure 7-3).

7.5.2.3 Setup Laser Head and Retroreflector

Attach the 90° beam bender to the front of the laser head. Mount the laser head on the bed and the retroreflector and post on the spindle.

7.5.3 Description

1. Decide which axis of travel you want to measure, which part is moving and which part is stationary for this axis of motion.

    Mount the laser head on the bed, and the retroreflector on the spindle. Move the movable part of the machine to the starting point or the end point, then mount the retroreflector as close to the laser head as possible.

2. Setup the notebook PC and the Windows software to display the LDDM readings.

3. Adjust the laser head or the 90° beam bender such that the output beam is parallel to the direction of travel. (See Section 7.5.4 Alignment Procedure).

4. Move the retroreflector perpendicular to the laser beam direction such that the return beam enters the receiving aperture of the laser head.

5. Move the movable part from the starting point to the end and make sure that the beam intensity is above the minimum requirement along the entire measurement path.

6. Now the laser is aligned and ready to do the measurement.

7.5.4 Alignment Procedure

1. Make sure the Laser beam is parallel to the stage travel by using a cross or masking tape as a target.

A) When the target is near the laser head, move the cross to the center of the beam.
B) When the target is away from the laser head, move the laser beam to the center of cross, by steering the beam.
C) Repeat A and B until the laser beam is parallel to the stage travel.

2. Move the retroreflector, not the laser beam, to be certain that the return laser beam is centered in the receiving aperture and the intensity reading is maximun.

3. Move the stage in and out and make sure the intensity reading remains maximum. Otherwise, repeat steps 1 and 2.

7.6 Software Description

The Metrology program is used to determine the positioning discrepancy of machine tools, coordinate measuring machines, XY-stages, or any other linear measuring device. The calibration system utilizes an extremely sensitive LDDM™ to detect any measurement discrepancy. After the LDDM™ is attached to the device to be calibrated, the device is operated to exercise a typical calibration procedure, and the LDDM™ senses any discrepancies from a theoretically perfect measurement. The discrepancies are recorded for later analyses and data reduction to produce correction factors for the device to be calibrated. The LDDM™ is supported by a Notebook PC with Windows software to direct the operator through the setup and execution of measurement procedures. The software includes several default and operator selectable measurement parameters that are used by calibration equations. Interim or final reports can be created to show the results of any calibration procedure.

7.6.1 LDDM for Windows

Here you will find descriptions about each choice and action on every screen in the software. You will also find instructions on how to take a measurement run for each type of measurement.

Bolded characters

In this manual, you will find **bolded** characters. When prompted, these bolded characters should be typed where specified.

Using the Mouse

In the **LDDM for Windows** package, only the left mouse button is used. In the program, a single click on the left button is usually sufficient to carry out an

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action, with a few exceptions. When prompted to click on a button, please move the mouse marker to that particular button, and simply click the left mouse button on it.

Text Boxes:

Instead of clicking on buttons, there are some boxes in the software where you must type in text.

7.6.2 Set up and Start LDDM Program

To setup LDDM program from Windows 95/98 and Windows Millennium, Windows 2000 and Windows XP.

1. For optimum performance exit all other applications before setting up LDDM program.
2. Insert LDDM CD into CD-Rom driver and wait for the folder to appear from My computer Icon. Double click on setup.exe to install the software.
3. Follow the instructions on your screen to continue through the setup progress.
4. After the setup is installed successfully, an LDDM icon will show in the screen. The LDDM program is ready to run.

To start LDDM from windows, run Windows and double clicking on the LDDM icon. The main menu of LDDM program will appear on your screen (see figure 7-2). Click on Linear for linear measurement. The measurement program will appear on your screen (see figure 7-3).

7.6.3 Main Menu
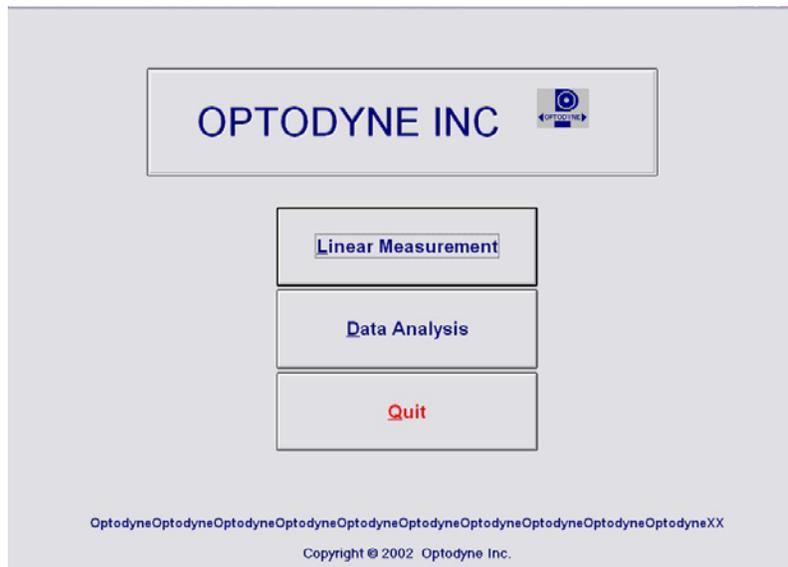
Fig. 7-2 Main Menu

Click on **Linear Measurement** if you would like to take a linear measurement.
Click on **Data Analysis** if you would like to analyze a data file
Click on **Quit** if you would like to exit the program.

7.6.4 Linear Measurement

After clicking the **Linear Measurement Box** on the Main Menu, you will be
greeted by the Linear Measurement Data Screen (Fig. 7-3). If the LDDM is not
connected properly, an error message box will appear indicating that the LDDM
interface not found, either turn off or not connected.   Please check your
connections and the LDDM reading on the display should appear. If the dashed
lines should persist, press the **In/mm** button.

A. Linear Measurement Main Display
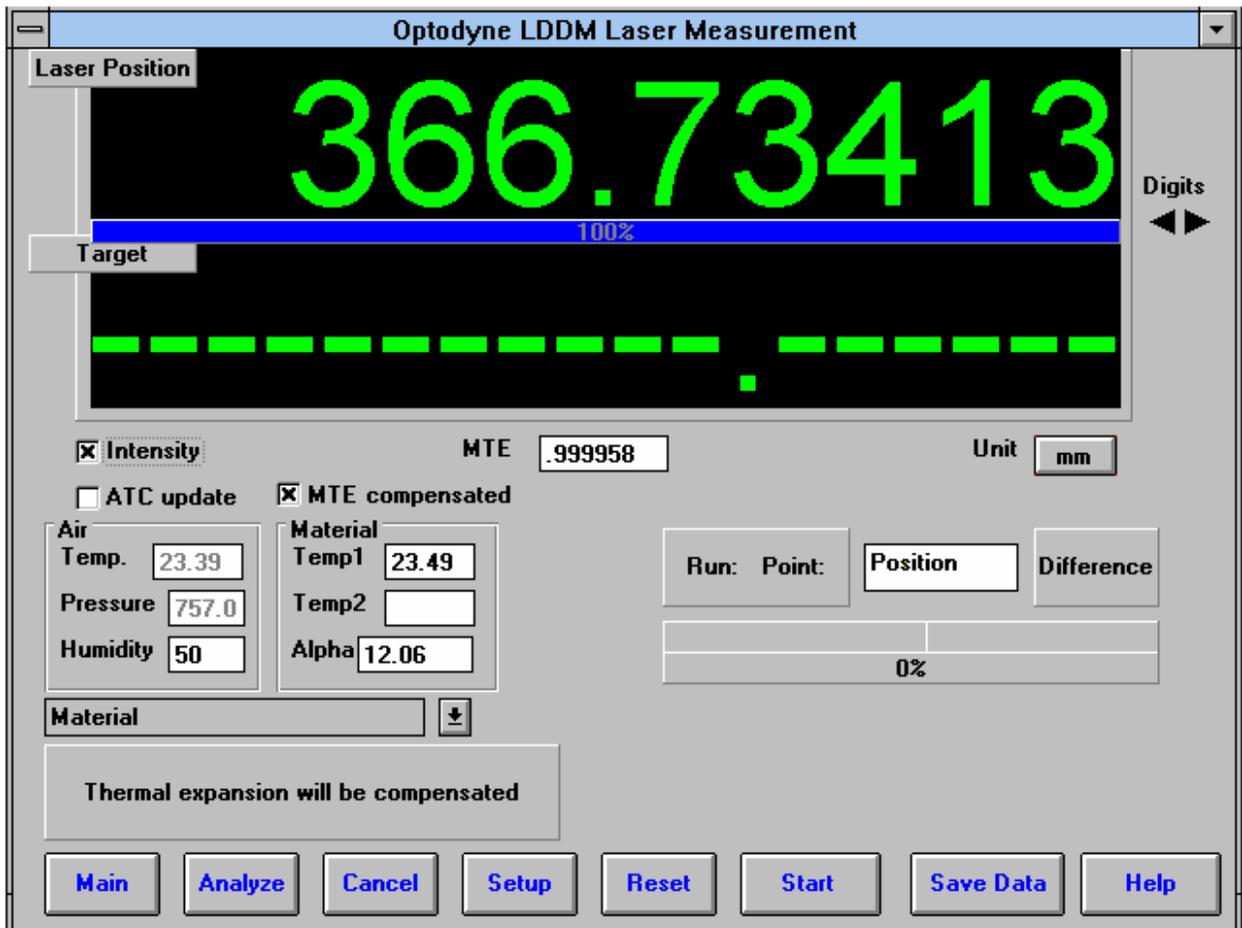
FIG.7-3 LINEAR MEASUREMENT MAIN DISPLAY

Choices on the Main Display are as follows:

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Intensity: Align your system visually, then check your alignment by clicking on this box. A blue bar will appear in-between the Laser Position window and the Target window. This blue bar will range from between 0 and 100%. Please make sure that the intensity is at least 80% over your whole run. Press the intensity box again to return the system to its original state.

The two boxes next to the Intensity box show the Pressure and Temperature that the Processor Box is reading. If you have an ATC probe, these numbers will be continually changing. If you do not have an ATC probe, the values will be 68 degrees and 29.9 inHg. When the Intensity Box is clicked on, these values will disappear.

MTE: The MTE value can be manually changed in this box.

Unit: This box, when clicked on, will allow the user to change between the inch and metric systems.

Digits: Clicking the left arrow will decrease the amount of digits shown (data will still be taken to 6 digits). Clicking the right arrow will increase the amount of digits shown (max 6). To decrease the amount of digits shown, click the right arrow once, and then the left arrow.

Air/Material Environmental, Alpha Boxes: Values may be entered in the Air Temperature and Pressure boxes. Humidity should be entered 50% (or 20% for dry weather and 80% for wet weather). The Material Temperature may be entered to get the MTE factor. The material alpha can also be manually changed if the material list does not include the material of the machine being calibrated.

Run: Point:, Position, Difference: The values in these boxes are the respective values during a measurement. They show the Run number that you are taking (up to 7), the point number, the target position, and the difference between the LDDM reading and the target position.

The percentage bar shows how much of the current measurement is done.

For automatic measurements, a stoplight will appear. The green light indicates that the program is ready for the system to go to the next data point. The yellow light indicates that the retroreflector has dropped below the velocity threshold and is waiting for the set delay to complete. The red light indicates that the system is taking the data point.

Material Box: The material list and their corresponding alpha values are listed here. Click the mouse on the down arrow and a list of materials are shown. Please choose from the material list or enter your own value to the alpha box above.

The dialog box is just underneath the material box. This box displays messages and describes the actions you are taking.

Buttons at the bottom of the screen:

Main: exits the linear measurement package and loads the main menu.

Analyze: exits the linear measurement package and enters the analyze data package.

Cancel: By pressing this button, the popup screen allows you to cancel the last data point taken during a run, or the second popup screen allows you to cancel the whole measurement.

Setup: Opens the setup window, where measurement specifications may be edited or viewed.

Reset: Using this key allows for the reset of the LDDM.

Start Measurement: This button starts the measurement defined in the setup window.

Save Data: This button will allow for the data storage of the last measurement taken.

The Laser Position window shows the current position of the retroreflector. This value always shows a value compensated for air temperature, pressure and relative humidity with manually entered barometric pressure, air temperature, material temperature and material thermal expansion coefficient.

The Target window will show a value during a measurement. This value is the next point where data collection will take place.

B. Linear Measurement Setup Screen (Fig. 7-4)

FIG.7-4 LINEAR MEASUREMENT SETUP SCREEN

Identification Box:

The identification of the machine, i.e. the machine type, serial number, the person doing the calibration, and the date, is entered here and is saved in the data file. The date is automatically entered using the computer system date.
Laser head direction/Measurement Axis Box:

You may choose either the x-axis, y-axis, or z-axis for on-axis measurements, or if you have the diagonal measurement kit, you may choose other for a volumetric measurement. Click on the circle closest to the type of measurement you would like to take.

Linear Measurement:

Start Position: Enter the coordinate of the machine position that you are going to be starting at (for that given axis).

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End Position: Enter the final coordinate of the machine position that you will be ending at (for that given axis). Please make sure that the end position is always large than the start position.

Number of points: Counting the zero point as the first point, please enter the number of points for the run.

Number of Runs: Choose the number of runs for this measurement, 1 through 7.

Verify/Edit: Click on this button to see the data acquisition setup. Make sure that your increments are correct. If there are increments to be changed to an irregular interval, you may edit the box.

Forward Only: Click the box to an X mark if the measurement is to be forward only. Leave the box blank if it is to be a bi-directional measurement.

ATC Board: To manually set the speed of light correction, click the ATC board on and off, then enter the barometric pressure in mmHg and the air temperature in °C. The barometric pressure and air temperature values will be reset to 760 and 20 automatically once leave the program to avoid possible double correction.

ATC Continuous Update: Do not click this.

Please choose the type of measurement you wish to take:

Manual: The Start Measurement button will turn into a "TAKE" button after the measurement begins. At every collection point, this button will have to be pushed.

Automatic: The software will collect data every time the retroreflector comes within a "Target Window", drops under a certain velocity and sits still for a designated dwell time.

On-The-Fly: There is no On-The-Fly capability for the Linear Measurement.

Auto Measurement Box:

Part Prog: Click on this button to generate a sample part program to move the machine for the measurement. A screen will popup to enter the header (up to 5 lines) the dwell time, the backlash, the line ending (blank or ;) and the filename. The part program generated will have an extension .PPG.

Target Window (automatic and on-the-fly): For automatic and on-the-fly measurements, being within this value of the target position allows the software to take data.

Trigger dwell (automatic only): For automatic measurements, the settling time of the machine (typically 3-5 seconds) is entered here. Choose a value of at least 2 seconds less than the programmed machine dwell time. This allows the computer to finish the data collection before the machine start to move again.

Vel Threshold (automatic only): This is the threshold that the velocity of the retroreflector must drop underneath so that a data point can be taken.

Backlash (automatic only): If the box has an X, backlash at the end and beginning of each run (other than the first point) will be taken. The distance necessary to remove the backlash and allow the software to re-trigger is twice the target window.

New Configuration: You may load a previous configuration file if you have one for this particular machine.

Save Configuration: This updates the LDDM.CFG file so that the data seen on the screen will appear each time LDDM for Windows is run.

Cancel: Cancel the above changes and revert to the previous values.

Ok: Settings are ok for this measurement. If you saved this setup as the default, it will come up first every time, otherwise the previous setup will re-appear next time the program is run.

C. Example of a Linear Measurement

Linear Measurement Main Display (See Fig. 7-3):
1) Check your units in middle right hand side. If it is not the correct type, click on the **inch/mm** icon.

2) Align the laser head visually according to the user's guide. Click the **intensity** button on the middle left hand side and check to see if the laser is aligned over the whole travel. After alignment, click off the **intensity**.

3) Click once on the **setup** icon on the bottom row of Icons.

Linear Measurement Setup Screen (See Fig. 7-4):

4) Setup your system information on the upper right hand side of the machine. Input the **identification** of the machine you are calibrating. To type the text, please move the arrow of the mouse pointer until it turns into a text cursor (an up and down line). Or please hit the tab key until one of the text boxes is highlighted. Type your machine data in.

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5) Enter the axis of measurement (or the diagonal) by clicking the appropriate box on the bottom left graph (**X**, **Y**, **Z** or **OTHER** for diagonal)

6) Enter the **machine coordinates** that you wish to calibrate in the upper right corner.

7) Enter the **number of points**, including zero, that you wish to calibrate. E.g. For a ten inch run, with 2 inch increments, enter 6.

8) Enter the **number of runs** (typically 7 for NMTBA, or 5 or VDI, ISO and at least 3 for B5)

9) Press the **Verify/Edit** button to see the increments. You may manually change these increments if you would like to.

10) If you are manually changing the values, make sure that the **Positions Equally Divided box** is clicked off to show: **Positions As Shown Below**.

11) Change the # of points as necessary to achieve the correct increment that You desire (Press **Verify/Edit** to check again).

12) Choose **Forward Only** or **Bi-Directional** runs.

13) Click on the **ATC board** if you have one.

14) Choose your type of measurement:

Manual

> you may: 1) Hit the **enter key** at each point, or
> 2) Click the mouse on **Take** at each point

Automatic

To take data automatically, you will have to program the machine controller to do 2 or 3 things: to move in a certain increment with a delay time in-between movements (3-5 seconds recommended), and add a backlash movement that is greater than double the target window at each end (backlash is optional).

The following information will be necessary for Automatic measurements:

Target Window: This tells the computer a distance window around the target position where the computer is allowed to take data. This value is related to the

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backlash needed (see below). A typical value is .001 inch or .02 mm, depending how tight your machine is. The backlash movement of the machine must be at least double this value.

Trigger Dwell: Set this value for two seconds less than the machine delay time for each point.

Velocity Threshold: This value keeps the risk of false triggering down. A good value to use is 0.01 for inches, 0.1 for metric.

Backlash: Check here if you want to account for backlash. The backlash at the beginning and end of each forward/backward run has to be at least TWICE the target window value.

16) Saving the Configuration File:

Save this configuration file by clicking the **Save Config File** Icon. Type the name of the file which you would like the setup saved to (usually the name of the machine). Press **Enter** or **OK** after typing it in.

The program will ask you if you would like to save the file, press **Yes**.

The program will then ask if you want to use this file as your default. If **Yes** is clicked, this setup will be loaded every time that the Linear Measurement Module is loaded.
To load a configuration file next time, click on **New Config File**. You may either:

1) Click on the file name and press **OK**

2) Double click on the file name

3) Type the name of the file name, example: **LDDM.1CF** and hit enter.
The extension .1CF indicates a configuration file.

17) Press **OK** to get back to the main screen.

Taking Data Points for a Linear Measurement (Fig. 7-6)

19) Input the **Humidity Value**.

20) Choose your material from the list given. Press the **Down arrow key** and you will get a list, press the **down arrow key** or **PgDn key** from there to scroll down.

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21) Choose the number of digits on the upper right hand side of the screen you wish the screen to display. Click the **right arrow button** to increase the amount (up to six), or click the **left arrow button** to decrease the amount.

22) Move your retroreflector to the beginning of your run. Click on **Start**.

Manual: If you are manually operating the laser/machine, press the designated key to take data as shown (after you move the machine). Also, if you would like to change the target position, you may do so in the value box located in-between the run information.

Automatic: If you are running the automatic program, you will see a stoplight appear. The red means that the conditions for a measurement have been met (inside the target window, and the velocity is lower than the given one), yellow means that the delay is being counted and the green means that the data has been collected and the program is waiting for you to move to the next point (Fig. 7-5).
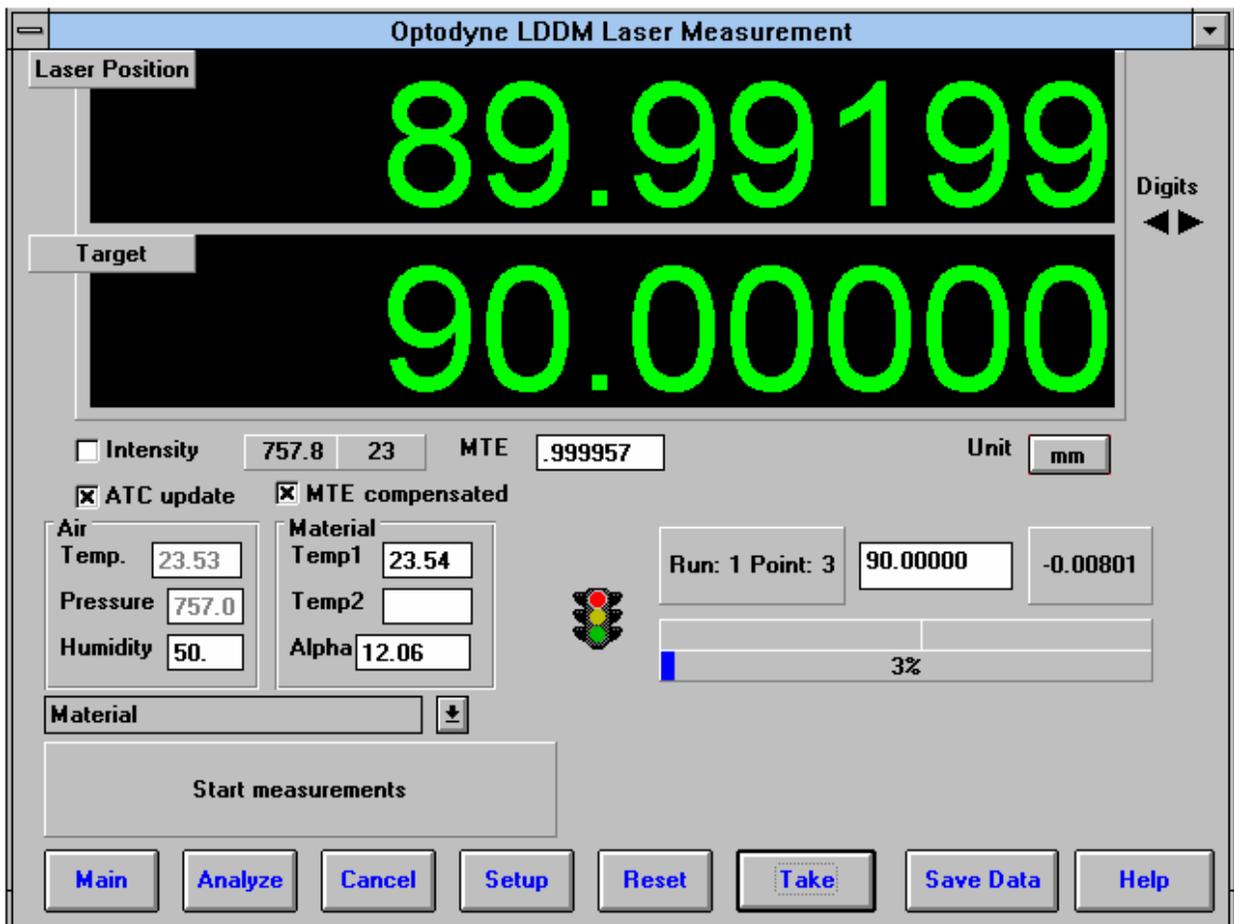
FIG.7-6 AUTOMATIC LINEAR DATA COLLECTION

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23) After all the data is taken, press **OK** to save the data, or **cancel** to not save the data.

24) To save data, type in the **filename** to save and hit **<Enter>** (the extension is automatically saved as .LIN). You may also save collected data by pressing the **save data button**, and follow the procedure above.

25) To analyze the data click on the **Analyze button**. When it prompts you, unload the module.

D. Linear Data Analysis Menu (Fig. 7-6)

Position Measurement, Error Analysis (mm)   File=C:\LDDM\VICTORX2.LIN   Date :02/24/95
Machine :Victor VMC2615   S/N :5047   By :Rick
Start Position: (10, 0, 0)   End Position: (235, 0, 0)
Total Travel = 225   Points = 6   No of Runs= 5
Pressure: 764.12   Humidity: 0.00   Air Temp: 20.41   Material Temp: 18.31
Max Error: 0.00104   Min Error: -0.00351   Mean: -0.00117

Position,mm	Run #1	Run #2	Run #3	Run #4	Run #5
10.0	0.00040	-0.00036	-0.00111	-0.00145	-0.00272
55.0	0.00022	0.00021	-0.00115	-0.00176	-0.00265
100.0	0.00023	0.00015	-0.00078	-0.00151	-0.00198
145.0	-0.00073	-0.00058	-0.00177	-0.00255	-0.00288
190.0	0.00024	-0.00005	-0.00056	-0.00085	-0.00178
235.0	-0.00085	-0.00181	-0.00111	-0.00223	-0.00244
235.0	-0.00092	-0.00127	-0.00203	-0.00213	-0.00306
190.0	0.00086	0.00043	-0.00002	-0.00114	-0.00112
145.0	-0.00053	-0.00153	-0.00225	-0.00268	-0.00351
100.0	0.00047	-0.00057	-0.00102	-0.00226	-0.00222
55.0	0.00104	-0.00052	-0.00094	-0.00160	-0.00243
10.0	0.00074	-0.00041	-0.00141	-0.00159	-0.00230

FIG.7-6 LINEAR MEASUREMENT DATA ANALYSIS TABLE

Under the **File Menu**, you can open a **new** data file, **save** a data file, set your **printer type**, set your **printer style**, or return to the **main menu**. When loading a file, choose the files with the extension of .LIN for linear. You can only **print data** tables using the print function under this heading.

Under the **Data Selection** heading, you can only choose **Displacement** when looking at a linear (.LIN) file.

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Under **Analysis**, you can choose **Error**, **NMTBA**, **NMTBA with Zero Shift, ISO-230-2(1988), ISO-230-2(1997), VDI 3441**, **ASME B5.54, and ASME B5.57,** for different types of data manipulation. After choosing **Error**, you will be given a choice on what you wish to see, **Runs #1-7**, and **forward** or **backward**. Click with the mouse button on which runs you wish to see.

The following icons have the following function in Analysis:

Open a new data file.

Save a data file.

Graph a data file (After graphing, you may also change the scaling of the graph by checking X on adjust grid).

Print a data graph (for printing data tables, use the Print option under the "File" heading)

Moves to the previous screen.

Moves to the next screen.

Exits the program.

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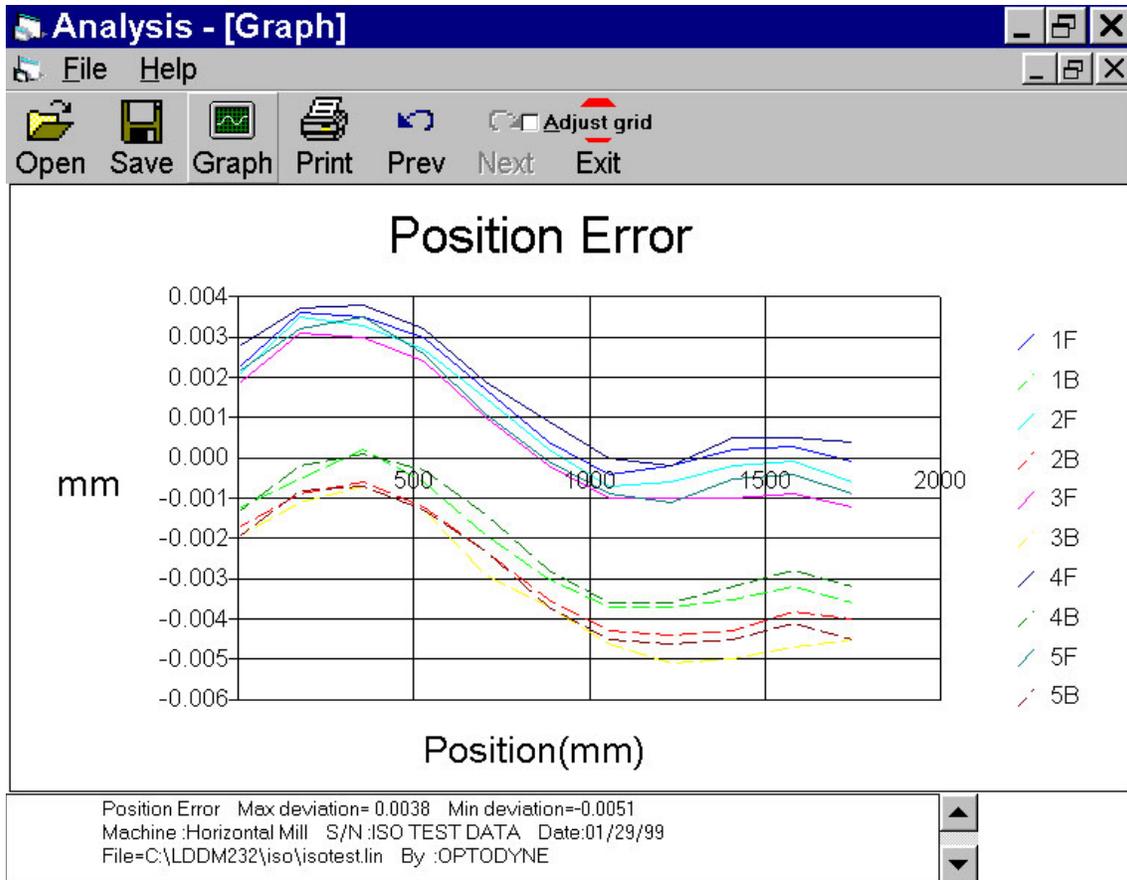
FIG.7-7 LINEAR MEASUREMENT DATA PLOT
(INDIVIDUAL PLOTS TOGETHER)

Pushing the Part program button on the set up screen, you can have the ISO part program to move the machine by sub sequential steps in order to measure positioning error. Load the program in the CNC .

Aligning the laser beam parallel to the X axis movement. Take the first measurement positioning the machine at starting point and collect it pushing START button on the PC screen. Start the positioning program, the machine will move to the next point and stops for few seconds, the point will be collected automatically, the same as the sub sequential points. At the end of the measurement save the data .

7.7 Accuracy and Error Sources

Displacement measurements are accurate within the following tolerances depending on the speed of light compensation and operating temperature. Assume at a standard condition, i.e. 68°F, 29.9 inHg, and 50% relative humidity, the accuracy is ±2 ppm. For example, the error is ±24 μin for a total travel of 12 inches. The LDDM™'s displacement accuracy depends on a

correct system setup and operation combined with accurate utilization of atmospheric pressure, air temperature, humidity and material temperature data.

The following are some potential measurement errors, and how they affect displacement measurements. The LDDM™ has a stability of 0.1 ppm. All of the following measurement errors add to this value. The sources of error in displacement measurement are:

1. Errors in the atmosphere pressure, air temperature and humidity data to determine the speed of light.

2. Errors in the Material temperature data, the material temperature may be higher or lower than the air temperature. The difference may be as large as the actual variation in room temperature.

3. Mis-alignment between machine travel and laser measurement axis. This is the cosine error, which is equal to (1-cos x) where x is the mis-alignment angle.

4. Mechanical vibration and stress of the retroreflector and the laser head.

These errors are common to all laser interferometers. The sum total of all the errors listed above determines the overall accuracy of the laser measurement system in your application. (More details in Appendix J).

7.8 Taking a Measurement

1. Decide which axis you are going to measure, from which starting point to which end point, and the increment per stop. Key in all the variables and pertinent information into the computer.

2. For automatic data collection, program your machine controller with the specific increment per stop, total number of stops (or total travel), and the speed. The dwelling time at each stop should be longer than (6) seconds.

3. Set up the LDDM™ by following the instructions in Section 7.5.

4. Set up computer and load the appropriate software by following the instructions in Section 7.6 or the software manual.

5. Set up the desired configuration or load an existing configuration.

6. Move the machine to the starting point.

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7. Reset the LDDM™ reading, click the start button. Then move the machine to the first stop.

8. For automatic data collection the computer will wait (5) seconds after the machine is stopped and then automatically record the LDDM™ reading. For manual data collection, after the machine is stopped, wait (5) seconds then click the taken button to record the LDDM™ readings.

9. Continue to move the machine to the next stop and repeat step 8.

10. Repeat step 9 until the 'end' point. This is done for single-direction measurement.

11. For bi-directional measurement, move the machine about 0.5 inch (at least 2 x target window) further, stop, wait (6) seconds, then return to the 'end' point, stop, wait (6) seconds and repeat step 8 for the return travel.

12. After all data has been collected, you need to save the data. You may click the analysis button to analyze the data now or save the data now and to analyze the data later.

7.9 Generating a Compensation File

Many machine tool controllers can provide compensations for repeatable position errors on each linear axis of motion. To generate a new compensation file, first set the compensation to zero and set the LDDM™ laser measurement system to measure the position error at an increment corresponding to the compensation file requirement. Second, use the metrology software to collect position error data and to generate a position error table. Third, key in the new compensation file based on the position error table. Finally, use the LDDM™ laser measurement system again to measure the position error with the new compensation file to make sure that the position errors have been compensated. Otherwise, the machine may have large non-repeatability.

For some standard machine tool controllers, software is available to convert the measured error table to a compensation file and load the compensation file.

7.9.1   Comp files for various controllers

A button is added in the analysis program for the generation of compensation files compatible to most of the controllers, such as Fanuc and Siemens. First, open the calibration file of the axis to be compensated by click on "analysis", "open" and enter the file name. Click on "Data Selection", "displacement"' "analysis" and "error", the positioning errors will be displayed on the screen. Click on "Save", a screen will pop up as shown below.

User's Guide

Analysis - [Linear]

File   Data Selection   Analysis   Help

Open   Save   Graph   Print   Prev   Next   Exit

Position Measurement, Error Analysis (in)   File=C:\LDDM232\str-lin\fadal1x.lin   Date :04/21/2000
Machine :Fadal   S/N :1234   By :optodyne
Start Position: (-20, 0, 0)   End Position: (-20, 0, 0)
Total Travel = 40.   Points
Pressure: 30.05   Humidity   Select Save Format   : 66.72 MTE = 1.000009
Max Error: 0.00362   Mean: 0.00176
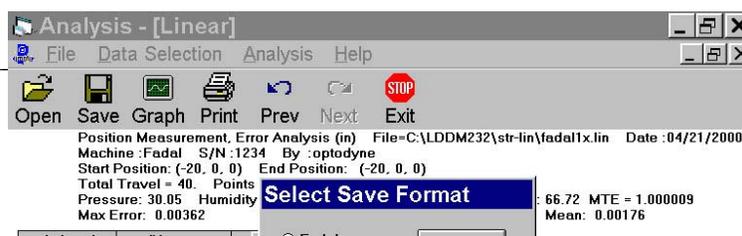
Fig. 7-8 Compensation File Selection Screen

Click on "Fadal", "ok", and enter a filename, a comp file with extension .svx, .svy or svz for fadal machines will be generated. Click on "comp" and "ok", another screen will pop up as shown below.
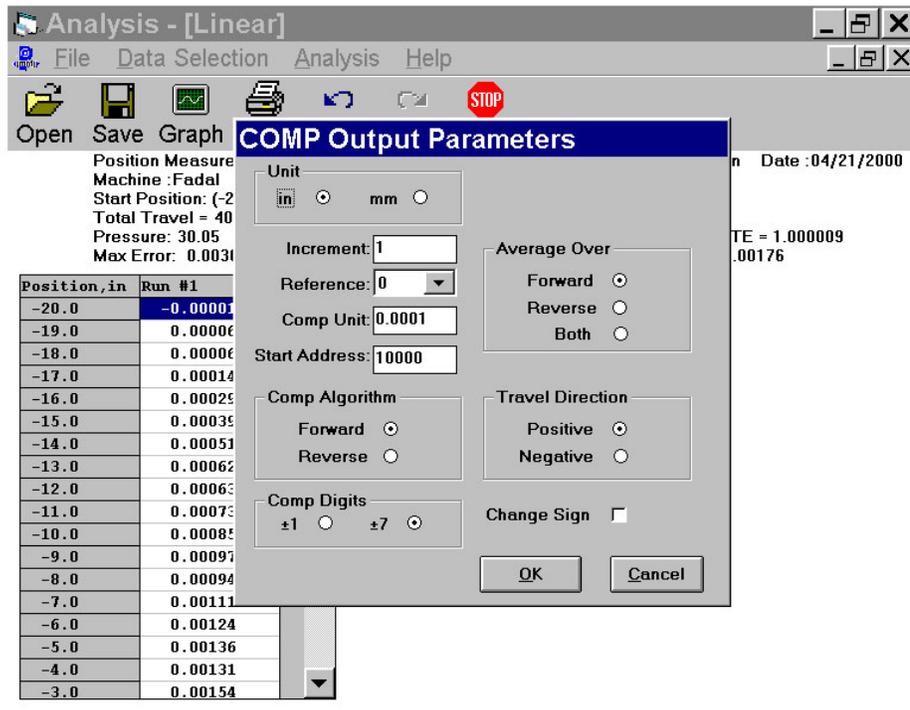
Fig. 7-9 Compensation Input Parameter Screen

Select in or mm unit for the comp file while the data file can be either in English or Metric unit. Select a increment for the comp file. The increment may or may not be the same as the data file. Select a reference point, compensation unit,

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start address, comp algorithm and travel direction based on the controller's requirement. For multiple-run data, select the average over forward, reverse or both. After all the parameters are selected, click "ok" and enter a filename, a comp file with extension .CPF will be generated. To view the compensation file, click on "file" and "Start Notepad", then enter the file name. A sample comp file is shown below.

```
               Optodyne Linear Error Compensation Table

    LDDM file: C:\LDDM232\fadal1Y.lin
    First Comp Pt:        0.00      Data:           Avg All Forward Runs
    Last Comp Pt:       20.00      Unit:                          in
    Interval:            1.000     Travel Direction:         Negative
    Comp Unit:           0.0001    Table Start Address:        10000
                                   Comp Algorithm:           Forward

    Machine: Fadal   Serial#: 1234  Axis: Y  04/21/2000
    MTmp: 66.72162  ATmp: 70.32162  Alpha: 6.67  Baro: 30.05  Humid: 50.0
    AxisLen: 20.00   #pts: 21  Runs: 1  MTE: 1  Run by: optodyne
    Reference: 0.0000  # Cmp Pts: 21  AvResEr: 0.0000295  MaxResEr: 0.0000498

     Target    LDDM Avg    Addr    CmpPos     Error    Cmp     CumCmp     CmpdVal
       0.00   -0.0000055  10021     0.00   0.0000000    0     0.00000    0.0000000
       1.00    0.0000500  10020     1.00   0.0000555   -1    -0.00010   -0.0000445
       2.00    0.0000450  10019     2.00   0.0000505    0    -0.00010   -0.0000495
       3.00    0.0001443  10018     3.00   0.0001498    0    -0.00010    0.0000498
       4.00    0.0002889  10017     4.00   0.0002944   -2    -0.00030   -0.0000056
       5.00    0.0003450  10016     5.00   0.0003505   -1    -0.00040   -0.0000495
       6.00    0.0004560  10015     6.00   0.0004615   -1    -0.00050   -0.0000385
       7.00    0.0005640  10014     7.00   0.0005695   -1    -0.00060   -0.0000305
       8.00    0.0006277  10013     8.00   0.0006332    0    -0.00060    0.0000332
       9.00    0.0006540  10012     9.00   0.0006595   -1    -0.00070   -0.0000405
      10.00    0.0007650  10011    10.00   0.0007705   -1    -0.00080   -0.0000295
      11.00    0.0008760  10010    11.00   0.0008815   -1    -0.00090   -0.0000185
      12.00    0.0009442  10009    12.00   0.0009497    0    -0.00090    0.0000497
      13.00    0.0009980  10008    13.00   0.0010035   -1    -0.00100    0.0000035
      14.00    0.0011230  10007    14.00   0.0011285   -1    -0.00110    0.0000285
      15.00    0.0012350  10006    15.00   0.0012405   -1    -0.00120    0.0000405
      16.00    0.0013060  10005    16.00   0.0013115   -1    -0.00130    0.0000115
      17.00    0.0013940  10004    17.00   0.0013995   -1    -0.00140   -0.0000005
      18.00    0.0014560  10003    18.00   0.0014615   -1    -0.00150   -0.0000385
      19.00    0.0015120  10002    19.00   0.0015175    0    -0.00150    0.0000175
      20.00    0.0016549  10001    20.00   0.0016604   -2    -0.00170   -0.0000396
```

The machine information and parameters are shown in the first few lines.
The first column is the target position from data file and the second column is the averaged errors calculated from data file.
The third column is the address number.
The forth column is the comp position, determined by the comp increment for the controller.
The fifth column is the positioning error calculated at the comp position.
The sixth column is the differential comp values. For Siemens controller, it is limited to ± 1 and for Fanuc controller, it is limited to ± 7.
The seventh column is the absolute comp value with the least increment of comp unit.
The eighth column is the remaining error after the compensation.

The AvResEr is the average positioning error after compensation, and the MaxResEr is the maximum positioning error after compensation.

Please consult the controller manual to determine the Pre amble, the prefix, the start address, the reference position, increment or absolute, comp algorithm, travel direction, comp interval and unit. We can provide a customer button to generate the comp file per your specification.

Part III. APPENDIX

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APPENDIX H. MANUAL TEMPERATURE COMPENSATION

Environmental changes affect the <u>wavelength of the laser beam</u> and the material's <u>physical properties</u>. The wavelength of the laser beam is the standard for distance measurements and is proportional to the velocity of light in air.

The velocity of light in air changes due to varying air temperature, pressure and relative humidity.

As a rule of thumb, a 1°K increase in temperature corresponds to an increase in laser beam wavelength of 1 ppm. A 1°K increase in temperature is equivalent to a 3.3 mbar decrease in pressure, or 25% decrease in relative humidity.

Most materials undergo expansion or contraction due to changes in temperature. If a part is measured at two different temperatures, two different values will result. Sometimes this difference can be as great as 100 ppm and can be the most significant source of error in distance measurements.

Ideally a distance measurement made with the LDDM™ should be done in a temperature controlled room held at the standard temperature of 68°F (20°C). Then all parts will be at their "true" size as defined by the International Committee on Weights and Measures.

Since a temperature controlled room is not always available, there should be a compensation factor (Material Thermal Expansion Coefficient) to compensate for the amount of change due to temperature variations. At the time of the measurement, the temperature of the material must be entered. Material temperature and the material's coefficient of expansion will allow you to determine the amount of change due to temperature change. The material thermal expansion coefficient depends on the type of material. A list of materials and their thermal expansion coefficient is provided in the software.

Setup and measurement error is due to misalignment of the machine travel along the laser measurement axis (cosine error). For an accuracy of 2 ppm, the misalignment angle should be less than 1.4 mrad. There is also error due to uncompensated measurement path length (dead path error).

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APPENDIX I. STABILITY OF LASERS

The amplitude and frequency fluctuations of an internal mirror HeNe laser are attributed to variations in the laser tube length due to thermal expansion. The standard LDDM™ laser heads are stabilized by controlling the tube temperature to a constant value. Usually, it takes about 15 minutes to reach within 1% of the final tube temperature and another 10 to 15 minutes to reach within 0.1% of the final tube temperature. To keep the laser tube at a constant temperature, the power generated by the laser head is about 14W at 75°F (21W at 60°F and 7W at 90°F).

The laser frequency stabilized by employing a linear portion of the laser output power as the feedback signal to control the laser cavity length. When the laser frequency is locked, it is operated at two axial modes with linear polarization. The mode separation is 1085 MHz and the horizontal polarized axial mode is always less than 20% of the vertically polarized axial mode.

The short term (less than a few minutes) frequency stability is ±0.004 ppm and the long term (more than a few hours) frequency stability is ±0.01 ppm. Furthermore, there is no permanent magnetic field inside the laser head and the frequency stability is not affected by any magnetic field near the laser head. The reflected light back to the laser resonator will not affect the frequency stability.

APPENDIX J. MEASUREMENT ACCURACY

The repeatability is defined as the maximum deviation between measurements under the same conditions and with the same instrument. The repeatability of the LDDM™ can be checked by repeatedly moving the target between two fixed stops. The 2σ distribution of the readings at each stop is a good indication of how repeatable the instrument is.

The accuracy is defined as the maximum deviation of a measurement from a know standard or true value. Hence, accuracy is the repeatability plus calibration. Since the wavelength of all HeNe lasers is certified by NIST to be accurate to within ±1.5 ppm (See NBS technical note 1248), no calibration is necessary for accuracy less than ±1.5 ppm once the repeatability of the instrument is established.

For certain applications, an NIST traceable number is required. An Optodyne LDDM™ system (s/n 9010000401) was calibrated by NIST on July 17, 1991, Test # 821/248196-91. A report was issued stating that the laser wavelength stability is ±0.004 ppm, while the system accuracy is less than 0.2 ppm without automatic temperature and pressure compensation, and is less than 0.8 ppm with automatic temperature and pressure compensation. For those who have the need, Optodyne, can provide a certificate that the LDDM™ system has been calibrated against the LDDM™ system (s/n 9010000401) and a copy of the test data.

The instrument accuracy is only part of the measurement accuracy. The measurement accuracy is determined by the vector sum (root sum of the square of the individual components) of the error components in the system's error budgets. There are three types of error sources, namely, measurement instrument, environmental changes and installation. Some of the errors are proportional to the measurement length and some of the errors are fixed quantities.

Typical instrument errors are laser wavelength variation, electronic error and optical non-linearity. Typical error due to environmental changes are atmospheric compensation error, material thermal expansion compensation error and optics thermal drift error. Typical error caused by improper installation are dead-path error, Abbé error and cosine error. The following is a more detailed description of these error sources.

1. Laser Wavelength

   A laser system's accuracy is based on the laser's wavelength accuracy. For a standard LDDM™, the laser's wavelength is 1 ppm. For the precision laser head the stability is 0.002 ppm and the wavelength accuracy certified by NIST is better than 0.1 ppm.

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2. Electronic Error

The electronic error is a fixed error and is equal to the least resolution of the system. For a standard LDDM™, the resolution is 1 μin (0.01 μm).

3. Optical Non-linearity

This error is referred to as optics non-linearity and occurs solely as a result of the optical leakage of one polarization into the other polarization.   For LDDM™, the laser beam is not polarized, hence there is no optical non-linearity error.

4. Atmospheric Compensation Error

The magnitude of this error depends on the accuracy of the air temperature and pressure sensor and how the atmospheric conditions change during the measurement. The index of refraction, n, of air is related to λ_V and λ_A by:

$$n = \frac{\lambda_V}{\lambda_A}$$

where λ_V and λ_A are wavelength in vacuum and air, respectively. Change in air density, which is a function of air temperature, pressure, humidity, and composition, affect the index of refraction.   Assuming a standard and homogeneous air composition, 1 ppm error results from any one of the following conditions:

a 1°C change in air temperature
a 2.5 mm Hg change in air pressure
an 80% change in relative humidity.

5. Material Thermal Expansion

Since the machine's dimensions are a function of temperature, a correction for expansion or contraction may be required. This correction relates the distance measurement back to a standard temperature of 20°C (68°F). To achieve this correction, the temperature expansion coefficient must be know. This correction or compensation term is know as Material Thermal Expansion Compensation (MTE) and is defined as:

MTE = 1 - $\alpha\Delta t$

where

α = thermal expansion coefficient
Δt = T - 68°F

The magnitude of this error is a function of the object's temperature and the temperature sensor's measurement accuracy.

6. Optics Thermal Drift

Changes in temperature of the retroreflector during the measurement can cause a change in optical path length which appears as an apparent distance change. A typical thermal drift is about 0.2 μm/°C. To eliminate this optical thermal drift, you may use a mirror-type retroreflector.

7. Dead-path Error

Dead-path Error is caused by an uncompensated length, D, of the laser beam between the laser head and the retroreflector, with the positioning stage at the zero position. In most applications, the dead-path errors can be minimized by reducing the dead-path distance, D. The dead-path error can be added to the atmospheric compensation error by adding D to the measurement length, L. That is, the effective length is D + L.

8. Abbé Error

The Abbé Error occurs when the measuring point of interest is displaced from the actual measuring scale location, and when angular error exists in the positioning system. The Abbé error is equal to the offset distance, s, times the tangent of the offset angle, ϕ.

9. Cosine Error

Misalignment of the laser beam to the mechanical axis of motion results in an error between the measured distance and the actual distance traveled. This is called Cosine Error. The cosine error is:

Cosine Error = 1 - $\cos\theta$

where

θ is the misalignment angle.

For small θ, the cosine error is approximately equal to $\theta^2/2$. For example, when θ = 1 mrad (3 arcmin), the cosine error is 0.5 ppm.

For example, with the following variables:

controlled environment   T = ±0.5°C
total machine travel   L = 50 in.
dead-path   D = 3 in.
misalignment angle   θ = 1 mrad
machine guideway pitch angle   φ = 25 μrad
Abbé offset   s = 1 in.
material thermal expansion coefficient   α = 6.5 ppm
laser wavelength error   1 μin

The following errors would result:

The atmospheric compensation error: 1ppm x 50 in x 0.5°C = 25 μin.
The material thermal expansion: 6.5ppm x 50in x 0.5°C=162.5 μin.
The dead-path error: 1ppm x 3 in x 0.5°C = 1.5 μin.
The Abbé error: 1 in x 25 μrad = 25 μin.
The cosine error: (1 mrad)^2/2 x 50 in = 25 μrad.

The total error, E would then be:

$$E = \sqrt{50^2 + 1^2 + 25^2 + 162.5^2 + 1.5^2 + 25^2 + 25^2}$$
$$\cong 175 \ \mu in.$$

To achieve optimum measurement accuracy it is recommended that:

1. Whenever possible make the measurement in a tightly controlled environment and use appropriate compensation method to correct for atmospheric and material effects.

2. Position the laser head such that both the dead-path and Abbé offset are minimized.