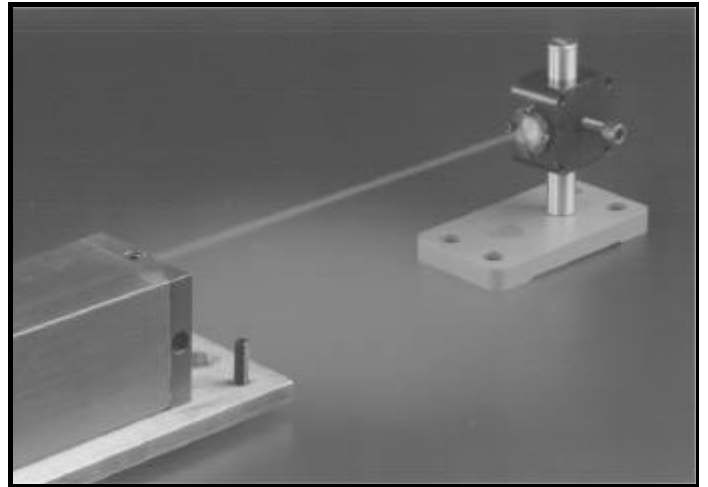


# Laser Doppler Displacement Meter Laser Doppler Scale



## User's Guide



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## 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 FDA Radiological Performance Standard 21 CFR, subchapter J.

**Warning:** This equipment generates, uses, and can radiate radio frequency energy and if not installed and used in accordance with the instructions for 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 (also CISPR 22, Class A), 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:** There is high voltage in the Laser Head Module. When the cover of the module is removed, the operator is exposed to high voltage. Make sure that all cables are firmly connected to both modules before turning on the laser power switch.

## 1.2 Patent

This device is patented- U.S. Patents 4,715,706, 5,116,126, 5,394,233 and 5,471,304 with other patents pending.

## 2.0 General Information

### 2.1 Introduction

There are several methods of measuring position, such as with inductive scales, magnetic scales, glass scales and laser interferometers. Inductive scales are known for ruggedness. Made of metal, they can withstand greater vibration and speed, and are perceived to be more reliable. Magnetic scales have the reputation for being less sensitive to contamination. Glass scales with higher resolution are more sensitive to hostile environmental conditions. Laser interferometers have the highest accuracy and resolution.

In general, encoder makers often process output signals through a special kind of circuitry known as interpolation electronics. This circuitry takes the two output sinusoidal signals from encoder and produces output signals of a higher frequency. These output signals can be used to measure distance traveled with more resolution than available from a non-interpolated encoder output.

However, imperfections in the scanning signals produce measuring errors on the order of 1% to a fraction of 1%, hence, the smaller the distance between encoder gratings or pitches, the smaller the interpolation error. Typical pitches,  $P$  for inductive scales is  $P=2$  mm; for magnetic scales,  $P=200$   $\mu\text{m}$ , for glass scales,  $P=20$   $\mu\text{m}$ , and for laser interferometers a pitch of  $0.6$   $\mu\text{m}$  is typical. Interferometers are the most expensive and difficult to use.

For more than two decades, traditional users of linear scales or transducers have had to settle for moderately accurate, glass or magnetic scales, or expensive and complex laser interferometers. As a result, the precision positioning industry has been locked behind a price/precision barrier.

Optodyne's innovative Dopplometry™ technology has broken through the technological barrier of bulky, cumbersome interferometer laser heads, time-consuming installation and alignment, and costly measurement methods. Optodyne has set a new industry standard for precision positioning and measurement equipment--a durable, compact, simple, and economical precise laser-based linear scale.

The Optodyne Laser Doppler Scales (LDS) are based on the firm's patented LDDM™ (Laser Doppler Displacement Meter). The LDS measures displacement by monitoring the phase shift of a laser beam reflected from a target. Recent progress in microelectronics, electro-optics, and computer and communication technologies, makes it possible to produce the surprisingly compact LDS with stunning performance at a very low cost.

The Laser Doppler Scale provides speed, high accuracy and long range positioning for 1, 2 and 3-axis applications, such as Linear Motors, CNC machine tools, CMM's, precision stages, supermicrometers and other linear measurement devices.

Major features of the LDS are:

- Inherent high accuracy and high resolution

## 3.0 Operation

### 3.1 General Applications

Optodyne's LDS is designed for applications requiring high accuracy, high speed, long range in NC machine tools, X-Y stages, automatic equipment and positions where maximum performance is vital. The LDS has the advantage of small size, weight and easy installation. The standard TTL output and the selectable incremental provide direct interface to motion controllers. Because of the new technology breakthrough, the LDS provides laser interferometer performance, glass scale and linear transducer size. The LDS is designed for OEM applications. The electronics board may be installed in the controller. Engineering support is available to help you design the LDS into your machine. If your needs are accuracy, high resolution, high speed or long range, an LDS system will meet requirements.

Compared to other position transducers such as glass or Inductosyn scales and frequency laser interferometers, the LDS requires less setup time and is less complicated. Also, the total system accuracy is significantly better and considered more stable. For example, in the LDS, alignment shifts do not usually result in periodic errors. If an alignment shift is so severe that a measurement is no longer possible, the user will be alerted with an error signal. In contrast, glass and Inductosyn scales are prone to alignment shifts inducing positioning errors which may remain undetected until either a recalibration is performed or improperly fabricated parts are discovered.

The LDS system is easily adapted to one, two, three, or multi-axis systems. The benefits of the LDS for major areas of application are described below.

Major features for linear motor applications are:

1. Higher attainable stiffness because of the LDS's inherent mechanical stability.
2. High slew rate (160 ips) does not limit linear motor control.
3. Isolates orthogonal disturbance to minimize axis cross coupling (for multi-axis applications).
4. High device bandwidth.
5. High resolution (25  $\mu$ m) promotes servo stiffness.
6. Axis thrust centerline mounting capability.

Major features for 2-axis applications, such as X-Y stages, PC board drilling, grinders, IC fabrication and projector include:

1. Accuracy is independent of the X-Y stage for a low-cost, high-precision system.
2. Center-mount reduces Abbé error, saves space.
3. Measurement scales are independent of ways for increased accuracy.
4. Detects and compensates for wobble along the X-axis.

Major Features for 3-axis applications, such as precision machine center and C are:

1. Centerline mounting improves accuracy by minimizing Abbé error.
2. Compensates for temperature to reduce effects of thermal expansion.
3. Electrical noise has minimal effect.
4. Increased servo stiffness for smooth cutting.
5. LDS characteristics minimize pitch error compensation.
6. Increase tool path and material removal accuracy.
7. Precision-machined surface not required for installation.
8. Wiring required for laser head only.
9. Minimal installation and alignment time.

### 3.2 Installation and Checkout

A properly installed LDS results in high accuracy and resolution, increased reliability and less maintenance and calibration than other types of positioning transducers. However, as with any measuring device, improper installation or operation degrade the performance. Prior to installation of the equipment, it is important to understand the basic measurement capabilities of the LDS along with considerations of relevant sources of errors.

The LDS is extremely easy to set up and operate. The laser head, placed on the object of interest, is mounted in a fixed position. The retroreflector should be rigidly mounted on the moving objective or target. The final position of these two components is determined by targeting the laser beam while moving the objective. There are no limitations on the location of the processor module within the limits of its interconnecting cables; one to the laser head, the other to the controller on the machine and its AC power cord.

Mount the laser head by means of the two mounting holes on the front and back of the unit. This base plate may be secured to a work surface in any fashion that will not generate and transmit excessive mechanical stresses to the laser head.

After the retroreflector is mounted onto the target, and the laser head is in position, attach the cables between the laser head and processor module. Connect the processor module to a DC power source.

**Caution!** Do not look directly into the beam aperture on the laser head face. Eye damage can result.

The laser light beam is most easily detected by holding a piece of white paper in the path of the beam so that the beam forms a visible spot on it. If the laser does not start, turn the power switch off and then on again. Adjust the positions of the laser head and retroreflector so that the return beam is visible on the laser head face. Continue

adjust these two components until the spot of the return beam enters the rec aperture.

The outputs on the processor board are:

J3:	PIN 1	INT	SIGNAL STRENGTH	J4:	PIN 1	INT	SIGNAL STRENGTH
	PIN 3	ERR	ERROR		PIN 3	ERR	ERROR
	PIN 5	UP	UP PULSE		PIN 5	A	SQUARE WAVE
	PIN 7	DN	DOWN PULSE		PIN 7	-B	SQUARE WAVE
	PIN 9	HR	ANALOG PHASE		PIN 9	-B	SQUARE WAVE
	PIN 2		REFERENCE		PIN 2	A	SQUARE WAVE
	PIN 4		GROUND		PIN 4	-HR	N/C ANALOG PHA
	PIN 6		GROUND		PIN 6	I	HOME POSITION
	PIN 8		GROUND		PIN 8	I	HOME POSITION
	PIN 10		GROUND		PIN 10	GND	GROUND

For LDS systems with more options, such as reference mark (IHS), autor pressure and temperature compensation and AC power feed and enclosur interconnecting wire diagram is shown in APPENDIX E.

After all interconnecting cables are connected, turn on the DC power, and then the laser beam parallel to the linear motion of the retroreflector over the displacement range of interest.

The system will function immediately after turning power on, however, ultimate accuracy is achieved only after a warm-up period of 20-30 minutes during which the laser has a chance to reach its operating equilibrium. In a constant temperature environment, drift is negligible after the laser reaches equilibrium. In an environment having an ambient temperature variation of 5°C over 8 hours, system drift will be in the range of 1 to 2 counts per hour. When the retroreflector moves away from the laser head the output pulses are "up" pulses and when the retroreflector moves toward the laser head the output pulses are "down" pulses.

For more specific installation instruction or trouble shooting, see **Install Instruction** shipped with the hardware.

### 3.3 Accuracy Considerations

The LDS system accuracy is determined by the accuracy of the instrument, environmental effects, and the optical installation effects. The instrument accuracy is determined by the laser head frequency stability, the electronic accuracy and sensitivity of the automatic compensation (if needed). The environmental effects are changes in atmospheric pressure, air temperature and material temperature. The optical installation effects are dead path errors, cosine error and Abbé error.

#### 3.3.1 Instrument Accuracy

The laser head accuracy is determined by the frequency stability of the laser. The LDS uses an active frequency stabilization technique. Typical laser frequency stability is better than 0.005 ppm (see NIST Test Report No. 821/25461).

November 14, 1994). The electronic accuracy is determined by the detector signal-to-noise ratio, which is much smaller than the smallest resolution increment. Hence, the electronic accuracy is determined by the resolution used. Since the laser beam is polarized, there is no interferometer non-linearity. If the automatic temperature and pressure compensation option is used, the accuracy of the compensation is determined by the accuracy of the temperature and pressure sensors.

Without considering the material thermal expansion, typical system accuracy is better than 1 ppm.

### 3.3.2 Environmental Effects

Laser measurements may be corrected for the two potential sources of measurement errors when the highest accuracy is desired: the effect of atmosphere on the wavelength (or speed of light) and the effect of temperature on the material expansion. Usually, the effect due to material thermal expansion is much larger than the effect due to laser wavelength change. For example, a 1°C change in air temperature causes a correction factor of 1 ppm, while a 1°C change in material temperature causes a correction factor of 12 ppm for steel and 22 ppm for aluminum. Specifically, for a measured distance of 10 meters, a 1°C material temperature change will cause an error of 120 μm. However, a 1°C air temperature change will cause an error of only 10 μm.

Hence, for most machine tool applications, it is not necessary to compensate for atmospheric pressure and air temperature change, and material thermal expansion can be compensated through the controller scale factor. A more detailed discussion of automatic temperature and pressure compensation is in Appendix F.

### 3.3.3 Optical Installation Effects

When planning the installation of the laser head and optics on a specific machine, a number of factors must be considered to maintain the system accuracy. The important points to consider are:

1. Installing the laser and retroreflector to minimize deadpath errors.
2. Align the laser beam path parallel to the axis of motion to minimize cosine errors.
3. Selecting the measurement paths to minimize Abbé error.
4. Both the laser head and the retroreflector should be solidly mounted to increase the stiffness.

In many cases, it may not be possible to completely eliminate these sources of error, but every effort should be made to minimize them. The following paragraphs describe methods of installing and compensating for these errors.

### *Deadpath Errors*

A deadpath error is an error introduced due to an unnecessary length of travel of light between the laser head and the retroreflector when the machine is at its position. To reduce the deadpath error, make sure the unnecessary length of travel between the laser head and the retroreflector is minimized.

### *Cosine Error*

Misalignment of the laser beam path to the axis of motion of the translation stage results in an error between the measured distance and the actual distance traveled. This is referred to as cosine error because the magnitude of the error is proportional to the cosine of the misalignment angle.

As a rule of thumb, the cosine error is proportional to the square of the misalignment angle. For example, if the misalignment angle is  $0.1^\circ$ , the cosine error is  $(0.1/57.3)^2 = 0.000003$  or 3 ppm.

Cosine error can be reduced by making the laser beam parallel to the actual translation axis.

### *Abbé Error*

Abbé offset error occurs when the measuring point of interest is displaced from the actual measuring scale location and there are angular errors in the positioning system.

A very important advantage of the LDS system is that the Abbé error evident in all positioning systems is very easily reduced.

Abbé offset error will make the indicated position either shorter or longer than the actual position, depending on the angular offset. The amount of measurement error resulting from Abbé offset is:

$$\text{Offset distance} \times \text{tangent of offset angle}$$

To minimize the Abbé error, simply reduce the offset distance by directing the measurement path as close as possible to the actual work area where the measurement process takes place.

## **3.4 Air Turbulence and Thermal Gradient**

Air turbulence and thermal gradients are important considerations when the travel distance is longer than 5 meters. The air turbulence generated by the hot or cold air will deflect the laser beam and cause loss of signal strength. To minimize these effects, shield the laser beam from direct air currents to the laser beam path or protect the laser beam with some type of enclosure.

cover. Since this would normally be done for protection against beam interruption, turbulence effects will usually not be a significant installation factor in typical environments.

For extremely high accuracy applications, thermal gradients created by localizing sources (e.g. motors, electromagnetics, lamps, laser heads, etc.) located on or near the machine will cause air turbulence or beam shift. Care must be taken to minimize these effects.

- No need for periodic recalibration
- No wearing parts for non-contact devices
- Freedom to locate point of measurement close to measured object reduces Abbé error
- Orthogonality of positioning system determined by mirrors, not X-Y stages
- Electronics flexibility with variable increment and automatic temperature compensation
- No mounting stress on scale
- No thermal expansion on scale
- No need for machined flat surface for mounting scale saves installation costs
- Higher loop gain possible for closed loop servo control
- No coupling between X-axis and Y-axis motion
- Optional hermetic seals for hostile environments
- Rejection of vibration in two of three planes reduces structural resonance effects
- Immune to electronic noise and interference makes it suitable for linear servo motor drives

## 2.2 Product Description

Based on Optodyne's patented Laser Doppler Displacement Meter (LDDM™) technology, the LDS reflects a modulated laser beam off of a movable target. The beam is detected and processed for displacement information used by the control to determine position.

Installation is made easy with only three compact, ruggedized and light weight components. The helium neon (HeNe) laser head and retroreflector are installed under the way covers. The standard processor board, with TTL output, is available with either an A Quad B square wave or up/down pulses.

The LDS unit consists of three components; a Laser Head Module, Retroreflector and Processor Module as shown in Fig. 2-1, LDS System Block Diagram.

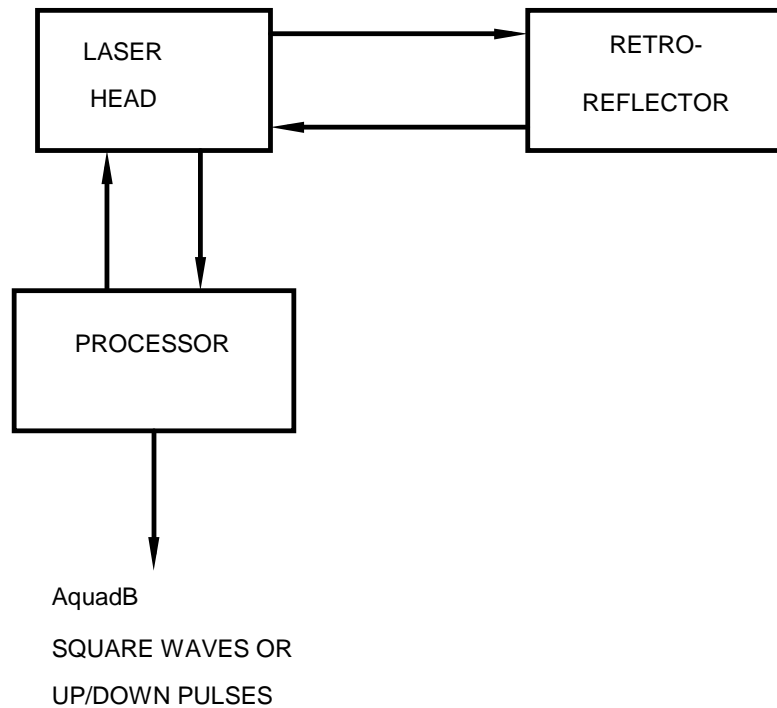


FIG. 2-1 LDS System Block Diagram

The following is a general description of these three components:

#### Laser Head Module

The Laser Head Module houses a stable HeNe laser source and electro-optic assembly and a photodetector which functions as a receiver. In a manner similar to the well known Doppler Radar, the Doppler shift of the return light beam is measured by an optical heterodyne technique. Three types of laser heads, L-109, L-102 and L-101 are shown in Figs. 2.2a, 2.2b and 2.2d. Suggested mounting way illustrated in Fig.2.2c.

#### Retroreflector

The Retroreflector serves as a cooperative target. It is a corner cube, which reflects the laser beam back to the receiving aperture on a path parallel to the input beam, 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. A  $\varnothing 0.5$  in. retroreflector with and without post and base are shown in Fig.2-3.

### Processor Module

The Processor Module consists of a processor board and driver. The signal from the photodetector is processed by the phase-demodulator and converted to standard TTL up/down or AquadB square waves. A processor board and driver are shown in Fig. 2-4.

MOUNTING HOLES  
FOR #1/4-20 SCREW 0.30DP 4PL AT BOTH END  
FROM BOTTOM  
OR FOR #10-24X2" SOCKET HEAD SCREW  
FROM TOP

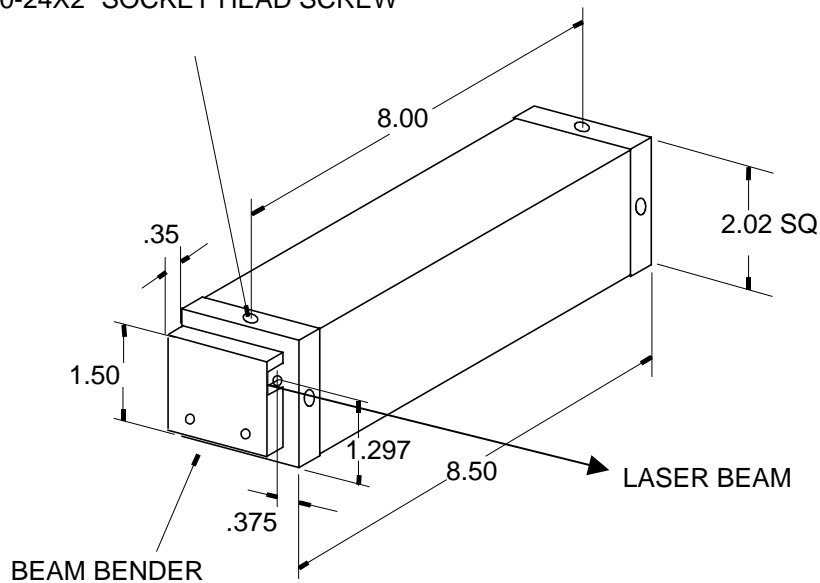
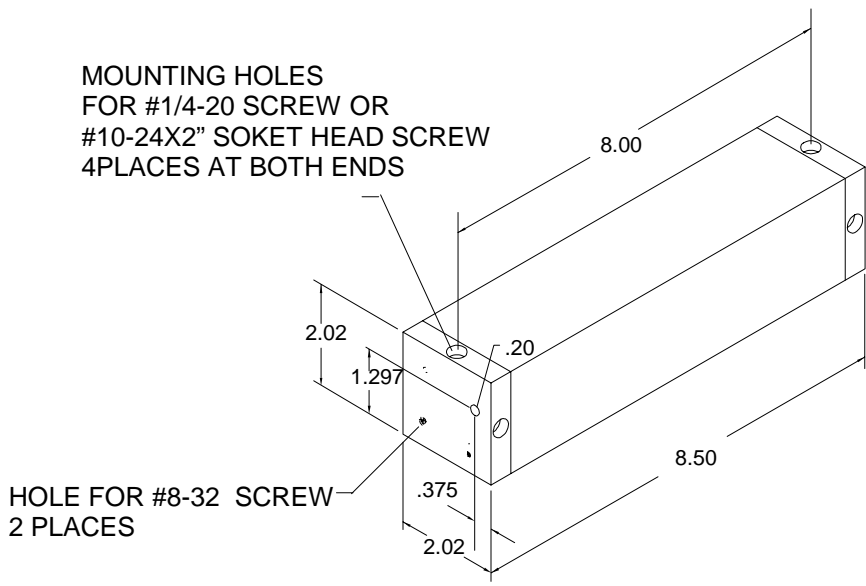
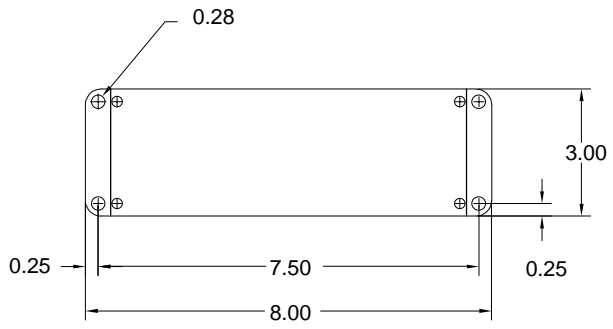
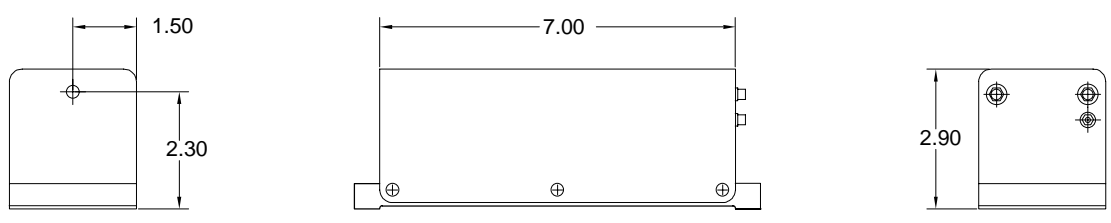


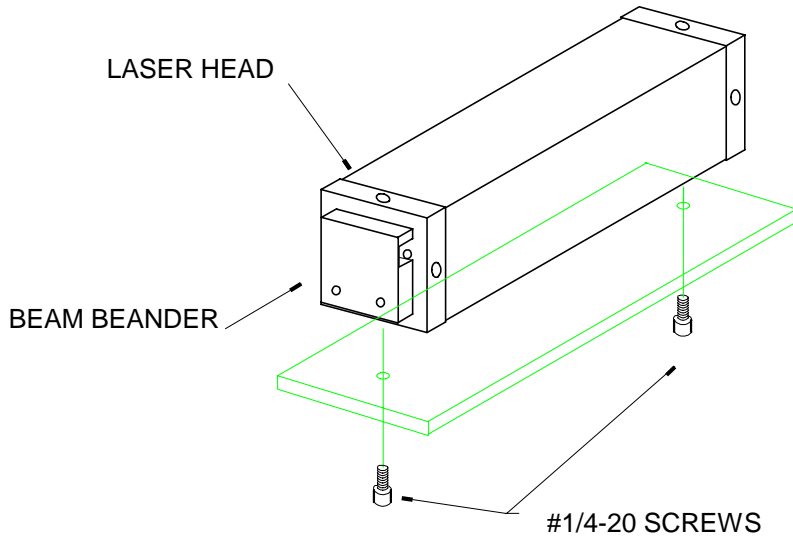
FIG.2.2a LASER HEAD (L-109)  
WITH 90°BEAM BENDER (LD-51S)



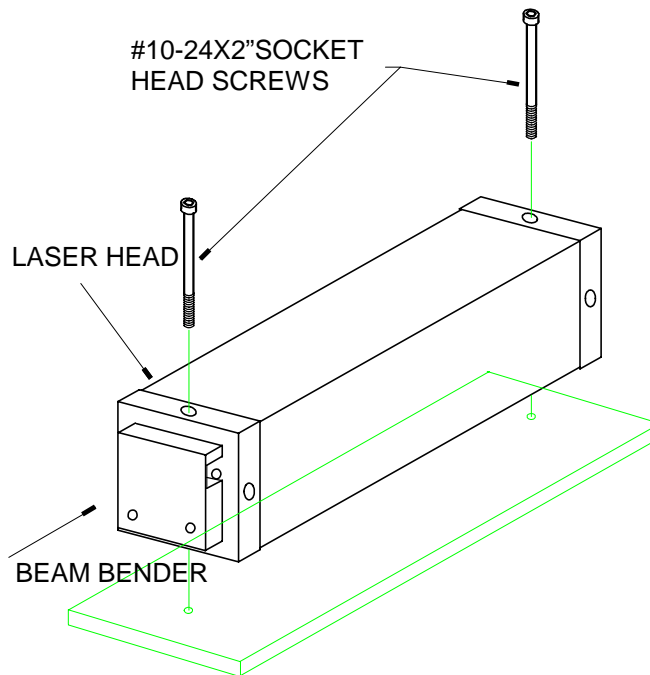
LASER HEAD (L-109)



LASER HEAD (L-102)  
FIG.2.2b STANDARD LASER HEAD (L-109,L-102)

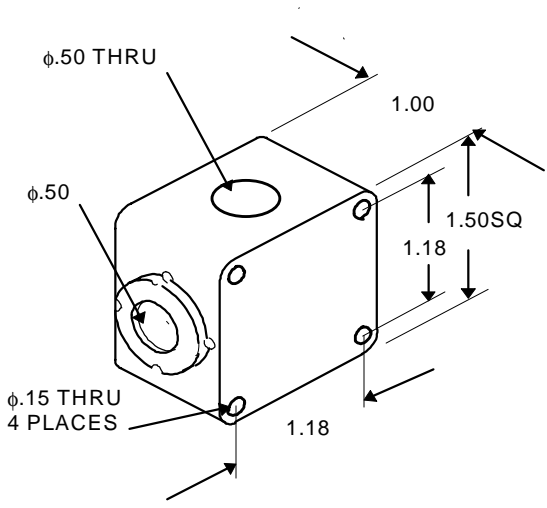


MOUNTING LASER HEAD FROM BOTTOM  
WITH #1/4-20

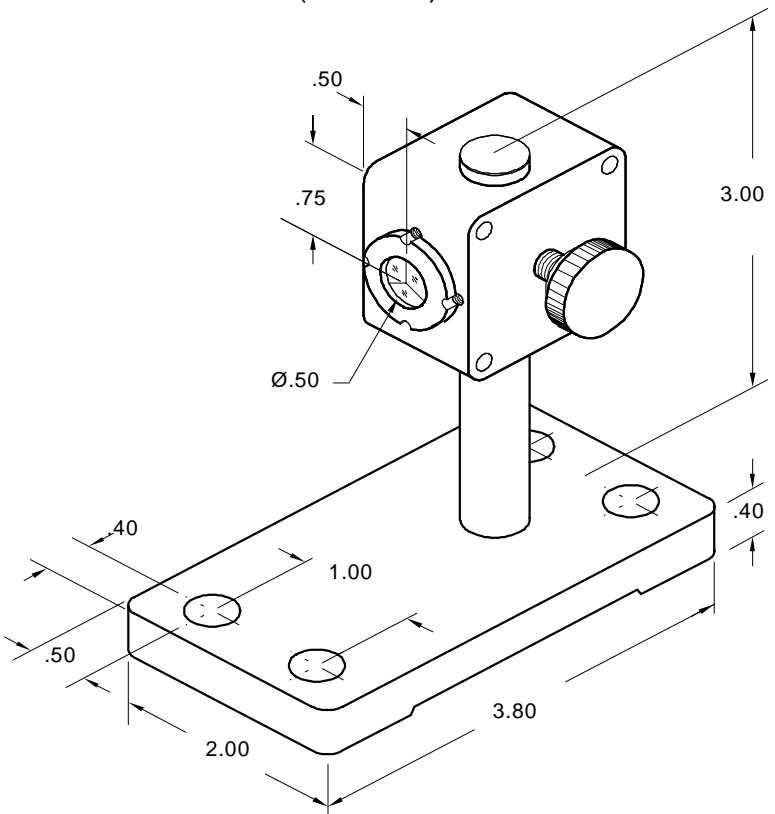


MOUNTING LASER HEAD FROM TOP  
WITH #10-24X2\" SOCKET HEAD SCREWS

FIG.2.2c LASER HEAD MOUNTING



1/2" RETROREFLECTOR  
(R-102A)



Ø1/2" CORNER CUBE WITH POST AND BASE (R- 102)

FIG. 2.3 1/2"RETROREFLECTOR

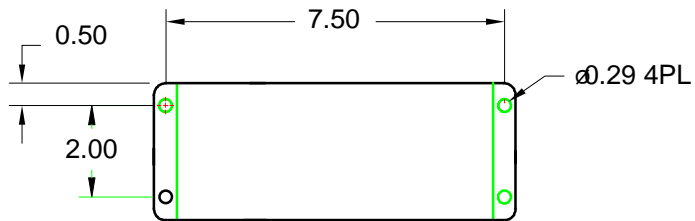
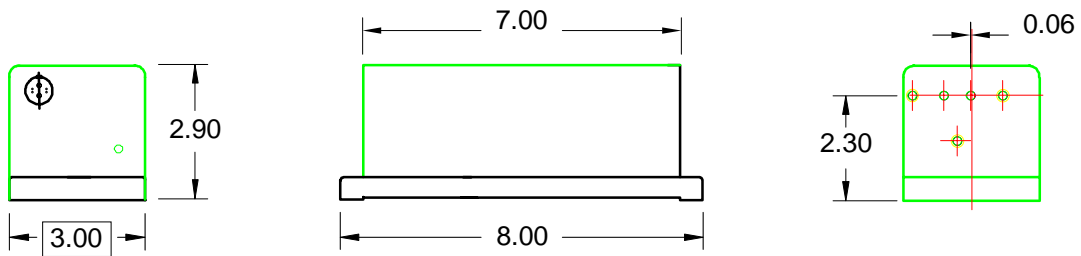
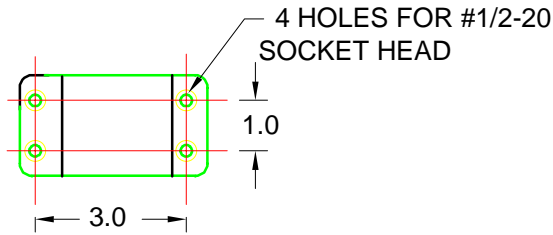
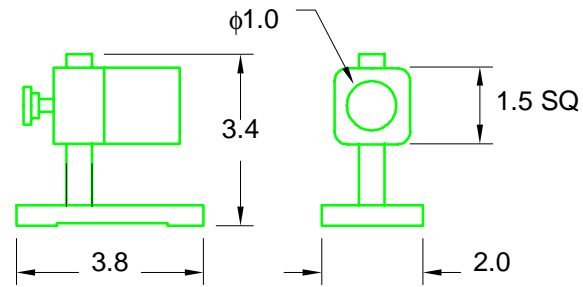


FIG.2.2d LASER HEAD (L-101)  
AND 1" RETROREFLECTOR (R-106)



Fig. 2-4 LDS-1000

### 2.3 Theory of Operation

LDDM™ monitors the displacement of the objective or target, from an initial position, to any final position within the range of the instrument. Displacement is counted continuously as the target moves. Once set up the system operates without further adjustment.

The 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 tens of 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:

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

Where  $\Delta f$  and  $\Delta \phi$  are the frequency and phase shift and  $\Delta v$  and  $\Delta z$  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. Compensation for changes in the speed of light due to temperature, pressure and humidity variations are available. Compensation for changes in material thermal expansion is also available.

## 2.4 System Description and Options

The basic LDS system, shown in Fig. 2.1, consists of a laser head module (L-109), a processor module (IPS1), a retroreflector (R-102) and a cable set (LD-21R). The inputs to the laser head module are 15V DC and driver signal, and the output is the detector signal. The inputs to the processor module are 15V DC,  $\pm 5V$  DC and the detector signal. The outputs are up/down pulses, AquadB square waves, and error signal. The retroreflector is a  $\text{Ø}1\frac{1}{2}$ in. corner-cube. The cable set is comprised of three 12 ft. long co-axial cables. Accessories and options to the LDS system are described below.

### 2.4.1 Reference Mark (IHS)

The reference mark shown in Fig. 2.5a provides a home position signal. The output is a TTL signal and the position repeatability is better than 1  $\mu\text{m}$ . Figure 2-5b shows the reference mark with cover.

### 2.4.2 High Resolution Output

The standard resolution is 12.45  $\mu\text{m}$  (one-half wavelength,  $\lambda/2$ ) or 24.9  $\mu\text{m}$  (one wavelength,  $\lambda$ ). For a higher resolution output, a divided by 8 board (IPPD2) will provide a resolution of 3.11  $\mu\text{m}$  ( $\lambda/8$ ), or a divided by 64 board (IPPD1) will provide a resolution of 0.39  $\mu\text{m}$  ( $\lambda/64$ ).

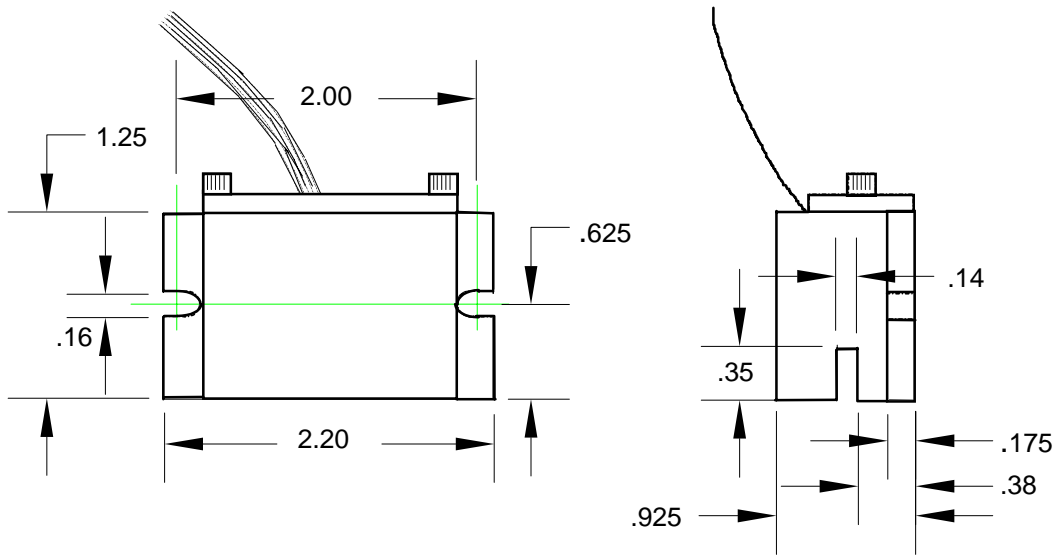
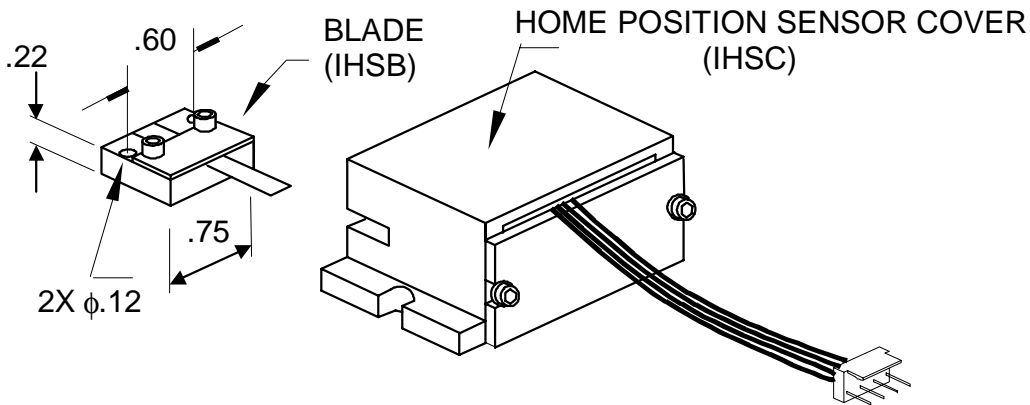


FIG.2.5a HOME POSITION SENSOR WITH COVER

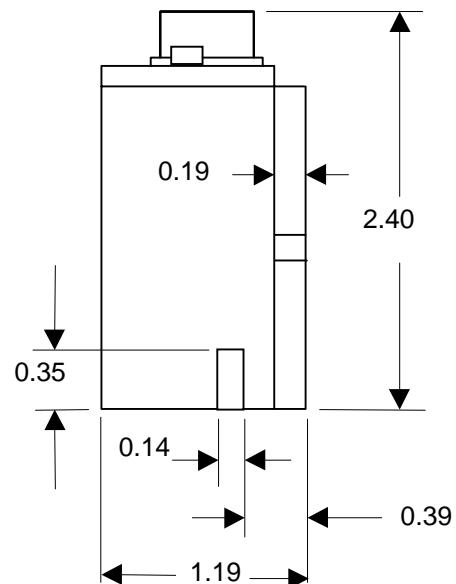
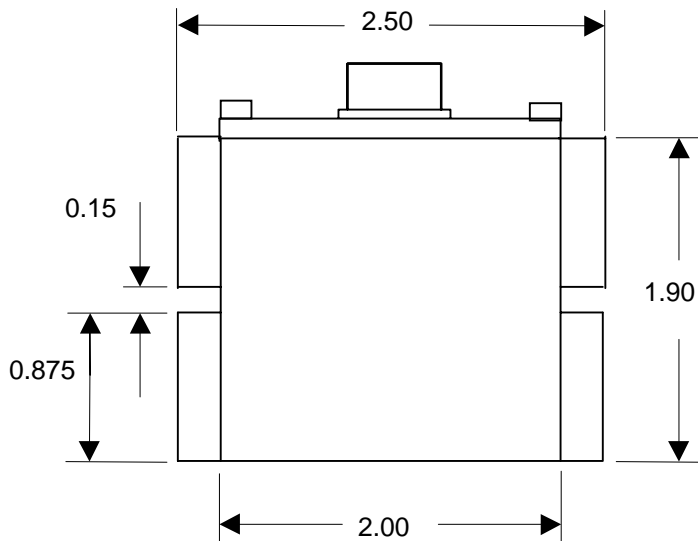
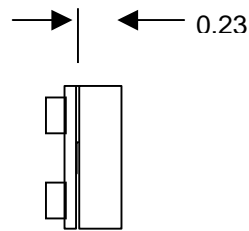
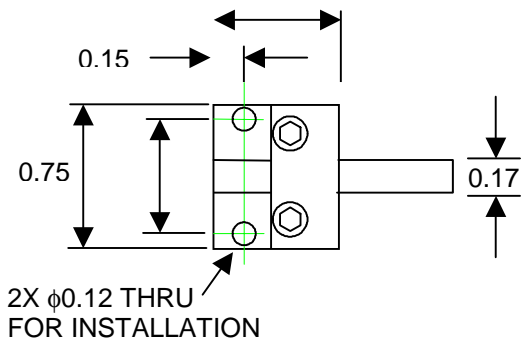
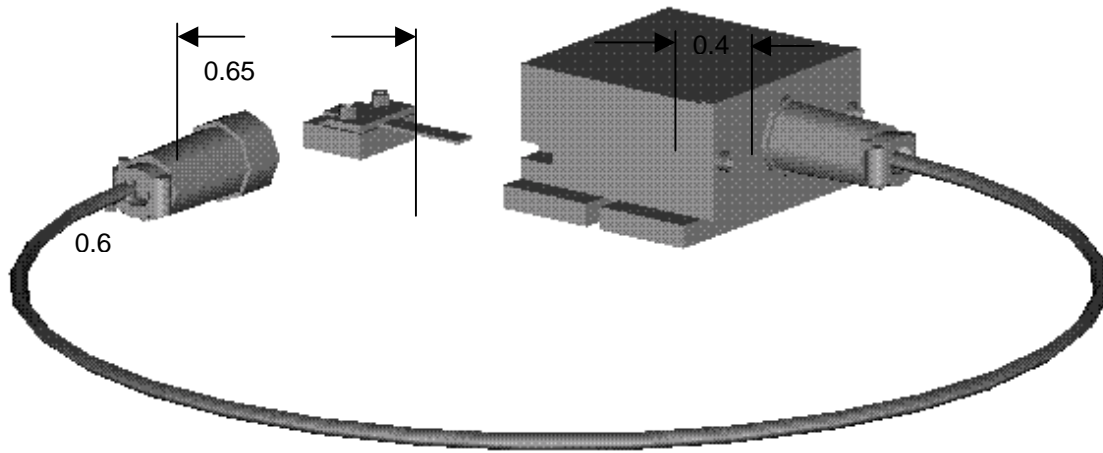


FIG. 2.5b HOME POSITION SENSOR WITH COVER

### 2.4.3 Selectable Increment (IPC3)

For some applications when a specific increment is required, a pulse converter board can be used to meet the requirement. The selectable increment board will provide an increment ranging from 24.9  $\mu\text{in}$  divided by 0.999999 to 0.000001. This selectable increment can also be controlled by an automatic pressure and temperature compensation board.

#### 2.4.4 Automatic Pressure and Temperature Compensation (IPC4)

For automatic compensation of atmospheric pressure, air temperature and material temperature changes, the automatic pressure and temperature compensation option can be added. This addition consists of an atmospheric pressure sensor, an air temperature sensor and a material temperature sensor (ATC, shown in Fig. 2.6), a data processing board and a selectable increment board. For multiple axis machines, only one ATC is needed.

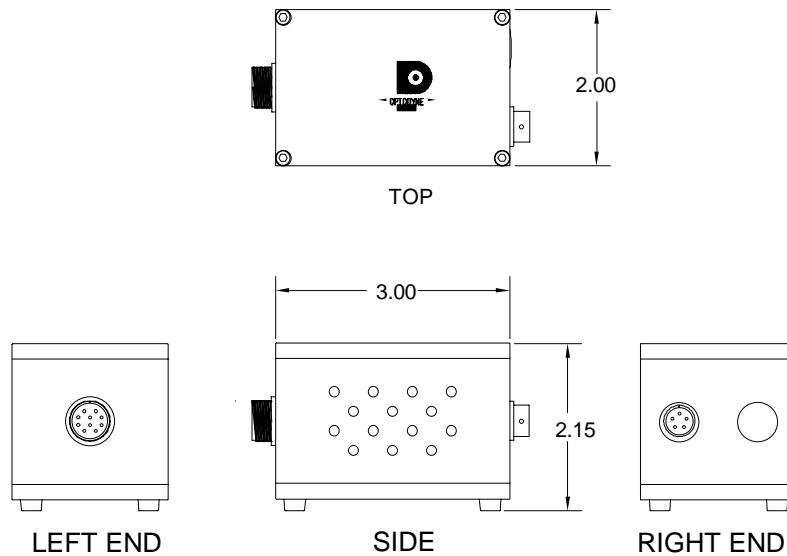


FIG. 2.6 ATC SENSOR

#### 2.4.5 32-bit Parallel Output Board (IPACX)

This is a plug-in board to an IBM PC compatible computer. The board provides a 32-bit position counter with a resolution of 0.1  $\mu\text{in}$  and can be read directly by a PC. It is a standard XT/AT board with 8-bit data transfer compatible to ISA specifications.

#### 2.4.6 AC Power Feed and Enclosure

For stand alone operation, this option will provide a panel-mount enclosure for the processor board and driver, a DC power supply and a terminal strip for the output signals, as shown in Fig. 2.7a and Fig.2.7b.

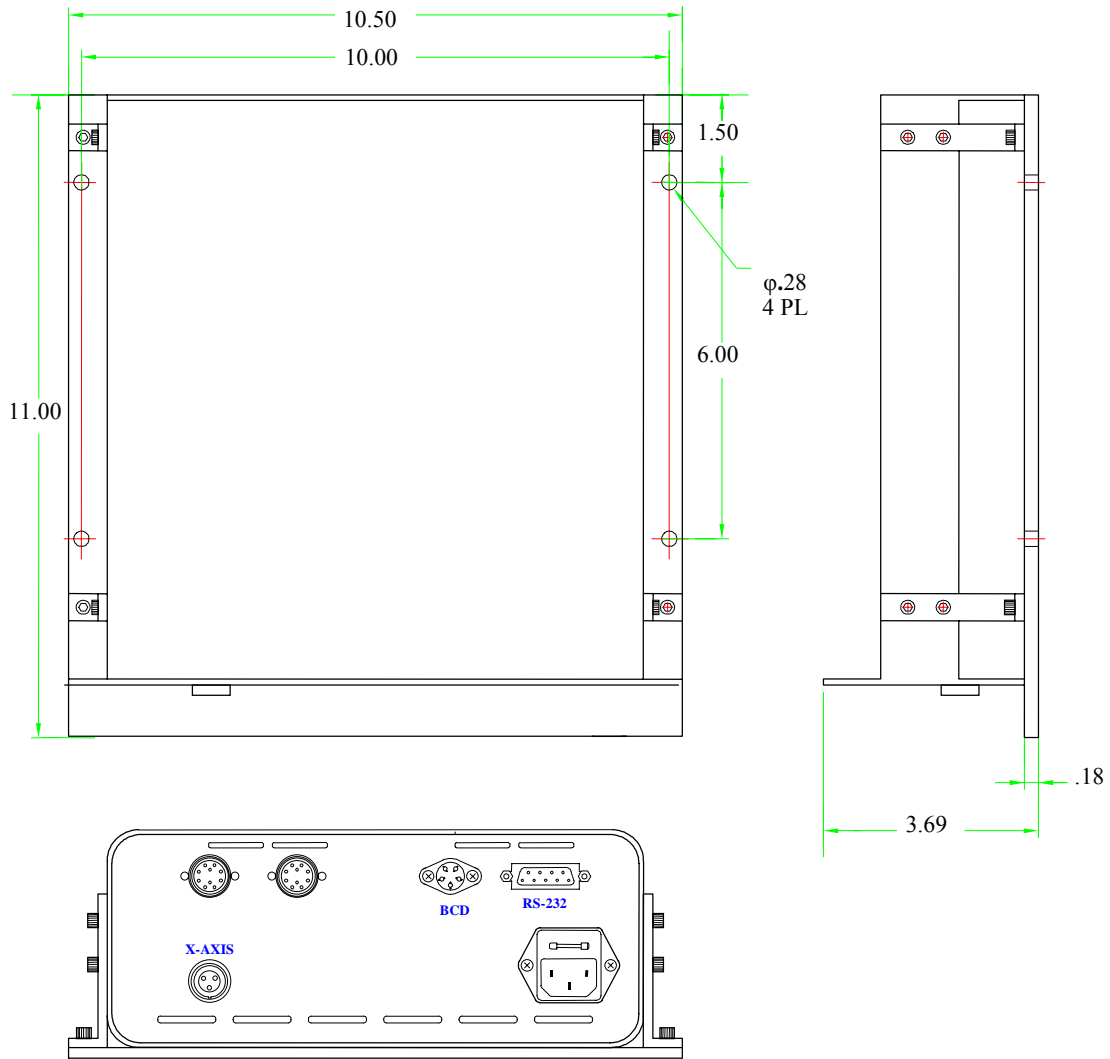


FIG.2.7a PROCESSOR BOX (P-301)

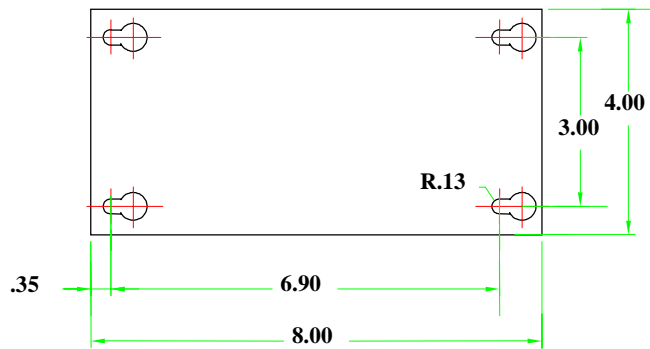
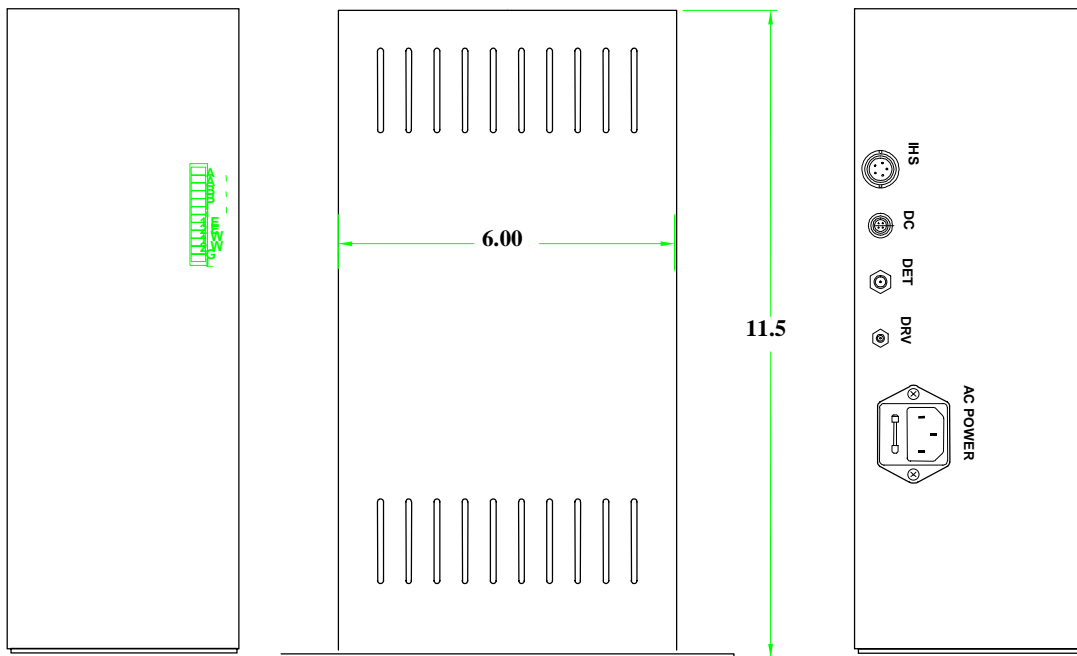
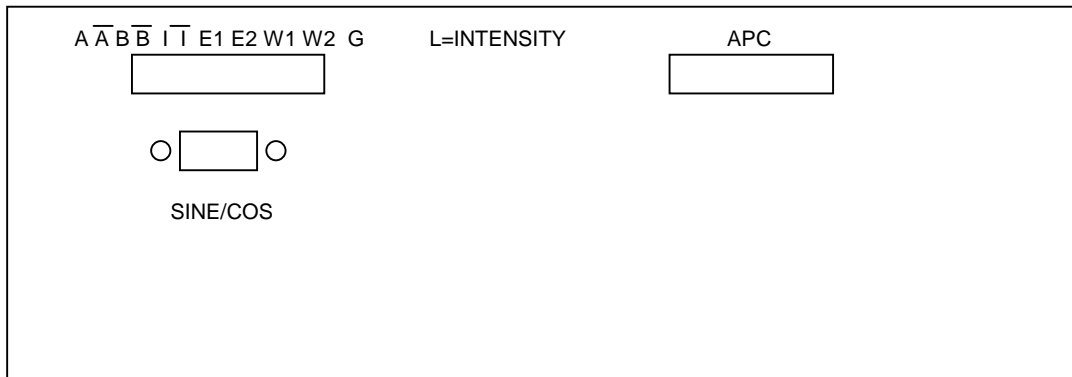
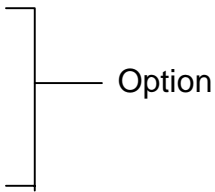


FIG. 2.7b PROCESSOR BOX ( P-108 )

$\overline{A}$  :  $\overline{A}$  quadrature square wave signal  
 $\overline{A}$  :  $\overline{A}$  quadrature square wave signal  
 $\overline{B}$  :  $\overline{B}$  quadrature square wave signal  
 $\overline{B}$  :  $\overline{B}$  quadrature square wave signal  
 $\overline{I}$  : Home position switch  
 $\overline{I}$  :  
 E1: Error relay  
 E2:  
 W1: Warning relay  
 W2:  
 G : Ground  
 L : Intensity



Processor Output Signal

(ICB) and a 10 digit LED display (D-101) to display the position can also be added (optional).

#### 2.4.7 Accessories for Hostile Environments

The laser head can be hermetically sealed (except the connectors) (LHS1). The aperture of the laser head and the retroreflector may be protected by a beam protection gun barrel as

shown in Fig. 2-8. (LD-57). A gun barrel for the retroreflector is also available, as shown in Fig. 2-9. For increased beam protection, the gun barrel can also be air purged. To bend the laser beam 90°, a turret beam bender (LD-15T), as shown in Fig. 2-10, is available.

#### 2.4.8 Cooling Plate for Heat Removal from Laser Head

The Laser head generates 10 to 20 W of heat. This heat is dissipated through the base plate or through the air by convection. For machine tool applications the heat source negligible. This heat source is much smaller than other heat sources, such as the motor drive or spindle. However, for other applications this heat source may generate temperature gradients in the structure and cause positioning errors. For these critical applications, the laser head may be mounted on a cooling plate (liquid coolant or compressed air can be used). This cooling plate will remove the heat generated by the laser head. The dimensions of the cooling plate are 3" x 8" x 0.5" with mounting holes.

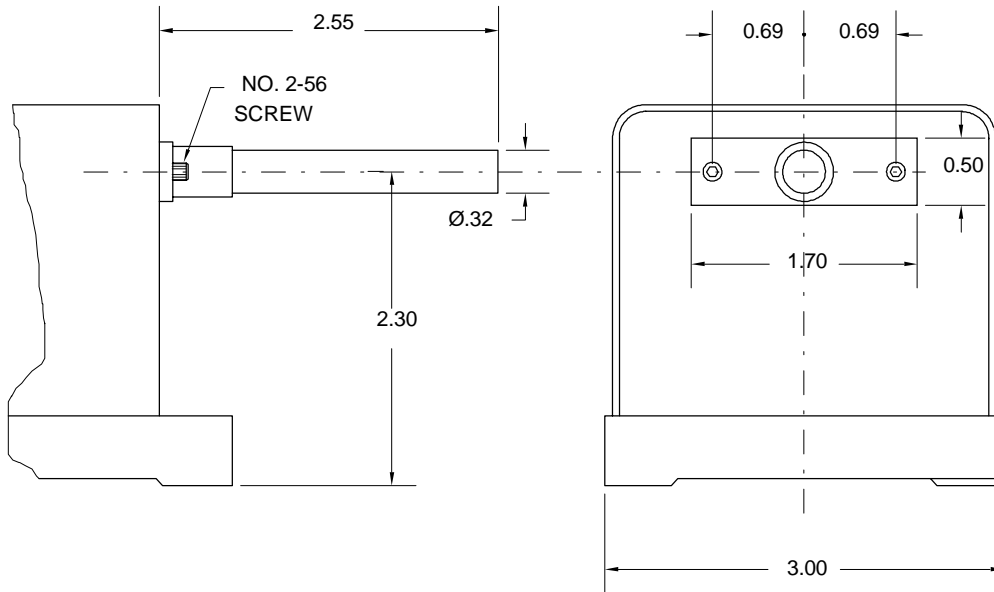


FIG. 2.8 BEAM PROTECTION GUN  
BARREL FOR LASER HEAD

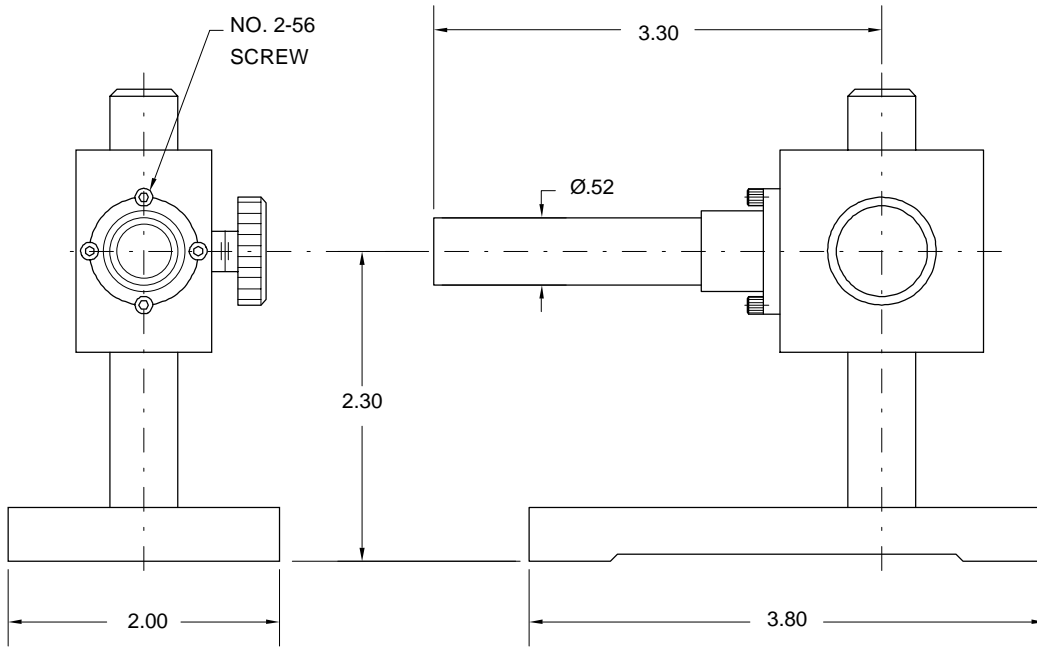


FIG. 2.9 BEAM PROTECTION GUN  
BARREL FOR RETROREFLECTOR

Standard range for the LDS system is 40 inches. The standard range can be extended to 400 inches (ER-400) and 2000 inches (ER-2000) without changes to the overall physical dimensions of the laser head.

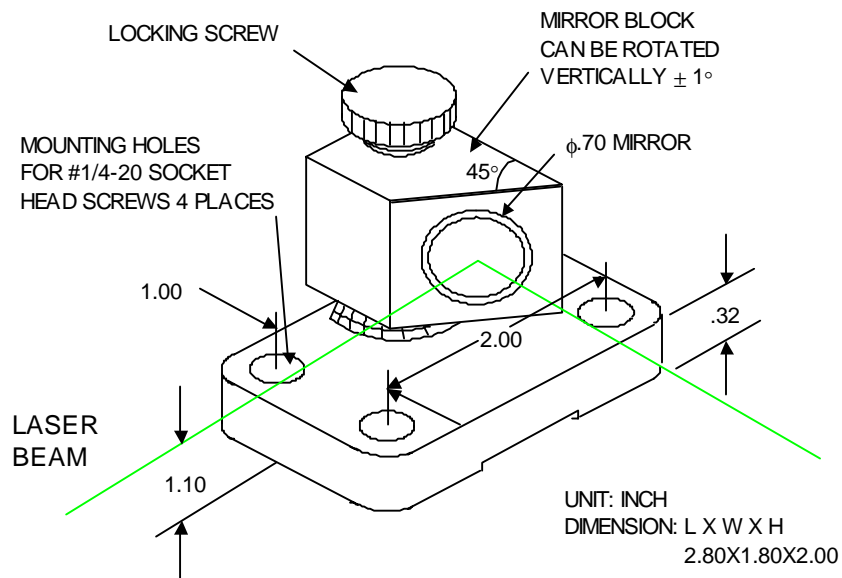


FIG.2-10 90° BEAM BENDER (LD-15TT)

#### 2.4.9 Flat-mirror Target

Since some applications would use a flat mirror as a target, a narrow beam laser head (L-109N) is available. Applications for this option include X-Y stages and servo track writers.

## 2.5 Technical Specifications

### 2.5.1 System Performance

<b>Resolution:</b>	25 $\mu\text{in}$ (24.914155 $\mu\text{in}$ ) 3.1 $\mu\text{in}$ with divided by 8 board 0.38 $\mu\text{in}$ with divided by 64 board 0.1 $\mu\text{in}$ with 32-bit parallel board
<b>Laser Stability:</b>	0.1 ppm
<b>Accuracy:</b>	1 ppm (typical)
<b>Maximum Range:</b>	up to 2,000 inches
<b>Maximum Speed:</b>	up to 160 ips
<b>Maximum Acceleration:</b>	laser head            10g retroreflector    100,000g
<b>Power:</b>	90-230VAC 50-60 Hz
<b>Operating Environment:</b>	Temperature    60 to 90 °F. Altitude        0 to 10,000 ft. Humidity        0 to 95% non-condensing

### 2.5.2 Laser Head p/n L-109 (Fig. 2.2a)

<b>Dimensions:</b>	2 x 2 x 8.5 inches
<b>Weight:</b>	2 lb.
<b>Mounting Holes Separation:</b>	8 inch, 4 sides
<b>Alignment Tolerance:</b>	lateral $\pm 0.05$ inches
<b>Warm-up Time:</b>	20 minutes
<b>Magnetic Field Strength:</b>	no permanent magnetic field
<b>Power Requirement:</b>	15V DC, 2.2A
<b>Laser Type:</b>	HeNe laser, CW
<b>Wavelength:</b>	632.8nm
<b>Output Power:</b>	0.2 to 0.4 mW
<b>Beam Diameter:</b>	$\varnothing 0.2$ inches
<b>Wavelength Stability:</b>	0.1 ppm

**Safety Classification:** Class 2 laser product conforming to US National center for Devices and Radiological Health, Regulations 21 CFR 1040.10, 1040.11

**Lifetime:** 20,000 hours MTBF

**Connectors:** Gold SMA is signal output  
Silver SMA is 15V DC input  
Gold SMB is driver input

### 2.5.3 Retroreflector p/n R-102 (Fig. 2.3)

**Dimensions:** Ø¼inch  
**Weight:** 0.05 oz., (0.4 oz with housing)

### 2.5.4 Processor Board and Driver p/n IPS1, ID1 (Fig. 2.4)

**Dimensions:** Processor Board 0.5 x 4.5 x 8 inches  
Driver 1 x 2 x 4.5 inches  
with mounting plate,  
overall dimensions 2 x 4.5 x 8 inches

**Weight:** 1 lb.  
**Power Required:** (including laser head)  
15V DC at 2.5A  
5V DC at 0.5A  
-5V DC at 0.1A

**Output:** AquadB square waves  
up/down pulses, TTL compatible

**Connectors:** Gold SMA is signal input  
Silver SMA is 15V DC output  
Silver SMA is driver output  
Molex 3-pin is 15V DC input  
Molex 5-pin is ±5V DC input  
DIN 10-pin is AquadB, u/down pulses and error

### 1.3 Unpacking and Inspection

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

1. Processor Module
2. Laser Head Module
3. Retroreflector
4. Cable Assemblies
5. User's Guide
6. Options and Accessories

Please check the condition of all components. Fill out the Warranty Register, Appendix D, 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, page 3.2. 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, copy made available to Optodyne, Inc., Service Department. Optodyne will advise you of the disposition of the equipment and arrange for its repair or replacement. Include model number and serial number when corresponding to this equipment for any reason.

If a warranty claim is necessary, please provide detailed information concerning equipment type, serial number, nature of the problem, etc. Send the claim to Optodyne Service Department on 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 number of the equipment and the values, tolerances, ratings and Optodyne designation of all electrical components required. Please refer to the Part List where applicable.

## 4.0 Maintenance

### 4.1 Trouble Shooting

#### 1. No Laser Beam Output or Weak Beam

Check Connectors. Make sure the laser is connected properly. Check cables and make sure they are in good condition. Check the AC power line into the processor module, and make sure the power is on.

Sometimes when the machine is cold (< 50° F or < 10° C), it may take more than 1 minute before the laser beam is emitted. If the laser still does not come on line, return the laser head to the factory for repair.

#### 2. Error Signal On

- a. Check laser output beam
- b. Check alignment, make sure the return beam enters the receiving aperture
- c. Check signal intensity, it should be more than 3.3V DC. If the intensity is less than 3.3V, check the RF signal, it should be more than 0.8 peak-to-peak. If the RF signal is less than 0.8V, the laser head may be damaged and should be replaced. Return both the laser head and processor for repair.

#### 3. Warning Signal On

- a. The warning signal indicates that the laser is not locked or the signal is weak and the laser needs either realignment or its optics need to be cleaned.
- b. If the light stays on continuously after realignment and cleaning, the laser head should be returned for repair.

### 4.2 Preventive Maintenance

There is no preventive maintenance required for the LDS. 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 either a weak laser beam or a warning signal. The laser head must be returned to the factory for laser tube replacement. Please contact your local sales representative for more information on charges associated with this repair when done out of warranty.

For the duration of the warranty period, repairs must be performed by Optodyne or an authorized service center to maintain the validity of the warranty. The case of the laser head is sealed with foil seals to prevent tampering. **BREAKING OF THESE SEALS VOIDS WARRANTY.** After warranty expiration, Optodyne strongly recommends that defective components be returned to the factory for authorized service. Special tools, test equipment and know-how are required to evaluate the LDS components.

## APPENDIX A. WARRANTY

Optodyne, Inc. warrants that each new instrument which it manufactures and from defects in material and workmanship under recommended use and conditions. Liability under this warranty is limited to servicing or adjustment returned to the factory for that purpose and replacing any defective parts. In the case that a problem is limited to a single module it is preferred that only that module be returned to Optodyne. This warranty is effective for 1 year from delivery to the original purchaser. When the unit is returned (transportation prepaid by original purchaser) and when upon examination, it is disclosed to be then if the fault has been caused by misuse or abnormal conditions of operation will be billed at the then prevailing repair rates and component replacement. In case, an estimate will be submitted before the work is started. Optodyne, Inc. is liable for damages by reason of failure of the instrument to perform proper consequential damage. This warranty does not apply to any unit that has been neglected, accident, misuse, improper operation or that in any way has been tampered, altered or repaired by any person other than an authorized Optodyne person unit whose serial number has been altered, defaced, or removed.

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

This warranty only covers equipment manufactured by Optodyne, Inc. Accessories such as computers, printers, etc. are not covered by this warranty, but by their manufacturer.

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Optodyne, Inc.

## **APPENDIX B. CERTIFICATION**

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

---

**Optodyne, Inc.**

**B**

## APPENDIX C. CALIBRATION

The fundamental accuracy of the LDDM™ is based upon the wavelength of the laser in the system. This wavelength has been measured to  $632.8195 \pm 0.0001$  nm under conditions defined as follows:

<b>Temperature:</b>	20° C
<b>Pressure:</b>	29.92 in Hg
<b>Relative Humidity:</b>	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 NIST, formerly the National Bureau of Standards, is provided upon request.

## APPENDIX D. WARRANTY REGISTRATION

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

<b>End user's name:</b> _____		
<b>Title:</b> _____	<b>Dept.:</b> _____	
<b>Company:</b> _____	<b>Phone Number:</b> (____) _____	<b>ext.:</b> _____
<b>Address:</b> _____		
<b>City:</b> _____	<b>State:</b> ____	<b>ZIP:</b> _____
<b>Date of Purchase:</b> _____		
<b>Model Number:</b> _____		
<b>Laser head</b> S/N: _____	<b>Processor</b> S/N: _____	<b>Display</b> S/N: _____
<b>Description of intended use or application:</b>		
_____		
_____		
_____		
_____		

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

or FAX to 310-635-6301.

## APPENDIX E. DESCRIPTION OF INTERFACES

The LDDM™ Processor Unit can be configured to give the following outputs:

- Up/Down Count pulses
- Analog Phase
- A Quad B Quadrature square wave
- Laser error signal
- BCD

### Up/Down Count

The Up/Down pulses are high going TTL level pulses with a minimum pulse width, and a maximum pulse rate of 10 MHz. The inactive pulse output is held low other is active. The output buffer can source 15 ma (output high current) and sink (output low current). In some configurations an RSV-422 buffer provides single outputs with 50 ma source and sink.

### Analog Phase

The Analog Phase signal is voltage which is used to interpolate values between pulses. With movement in the up direction, this voltage changes from 1.7 to 3.1 volts between two up pulses; with movement in the down direction, the voltage changes from 3.1 to 0.6 volts between down pulses. The voltage ranges are different because the output has hysteresis when the direction changes. The leading edges of the pulses are coincident with the respective extremes of the analog voltage ranges.

### A Quad B

The quadrature square wave signals are at TTL levels. In the normal configuration a 422 buffer provides 50 ma differential outputs. In some configurations the output is a single ended output buffer which can source 15 ma (output high current) and sink (output low current).

### Error Signal

The Error Signal is a TTL level digital output which is LOW to indicate that the laser signal level is too low, and HIGH to indicate that the laser signal level is sufficient. In an error condition, the position pulse outputs should be disabled.

## APPENDIX F. AUTOMATIC TEMPERATURE AND PRESSURE COMPENSATION (ATC)

Accurate measurement is dependent upon the measuring system's ability to adjust to environmental changes and upon the user's/operator's ability to set and operate the system properly.

Environmental changes affect the wavelength of the laser beam and the material's physical properties. 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°C increase in temperature corresponds to an increase in laser beam wavelength of 1 ppm. A 1°C increase in temperature is equivalent to a 3.3 mbar (0.1 in Hg) decrease in pressure, or 60% decrease in relative humidity.

THUS, FOR ACCURATE MEASUREMENTS, AIR TEMPERATURE, PRESSURE AND RELATIVE HUMIDITY SHOULD BE MEASURED AND THEIR EFFECTS COMPENSATED.

Most materials undergo expansion or contraction due to change 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 known. Material temperature and the material's coefficient of expansion will allow determination of the amount of change due to fluctuations in temperature.

THUS, FOR ACCURATE MEASUREMENTS, MATERIAL TEMPERATURE SHOULD BE MEASURED SO THAT THE EFFECT OF EXPANSION OR CONTRACTION CAN BE COMPENSATED.

## APPENDIX G. 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.

The laser output is locked to the gain curve. Thermal expansion and contraction cause the resonant frequency of the cavity to drift through the gain profile and produce peak-to-bottom changes in the laser output. The power generated by the laser head is about 14W at 75°F (21W at 60°F and 7W at 90°F).

When the laser frequency is locked, it is operated at two axial modes. The mode separation is 1085 MHz and one axial mode is always less than 20% the other axial mode.

The short term (less than a few minutes) frequency stability is  $\pm 0.001$  ppm and the long term (more than a few hours) frequency stability is  $\pm 0.004$  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 H. 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 3 $\sigma$  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 known 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  $\pm 1.5$  ppm (See NBS technical note 1248), no calibration is necessary for accuracy less than  $\pm 1.5$  ppm once the repeatability of the instrument is established.

For certain applications, an NIST traceable number is required. An Optodyne LDDM™ system (s/n 9410001252, 9410001039, and 941001) was calibrated by NIST on November 14, 1994, Test # 821/254610-95. A report was issued stating that the laser wavelength stability is  $\pm 0.0049$  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 9410001252) 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 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 errors 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 frequency stability is 0.005 ppm and the wavelength accuracy certified by NIST is better than 0.1 ppm.

## APPENDIX I. USE OF FLAT-MIRROR TARGETS FOR X-Y STAGES

The LDDM™ narrow beam laser head can be used for plane mirror reflection applications. For example, in a two axis system (e.g. an X-Y stage), the reflector can be allowed to move in the Y direction without affecting the signal strength of the X-measurement. Consequently, both reflectors in a 2-axis system can be mounted on the same moving part to minimize Abbé offset error. Defining the measurement as the point where the axis beams intersect, measurement is essentially independent of yaw motion of the moving stage shown in Fig. I-1.

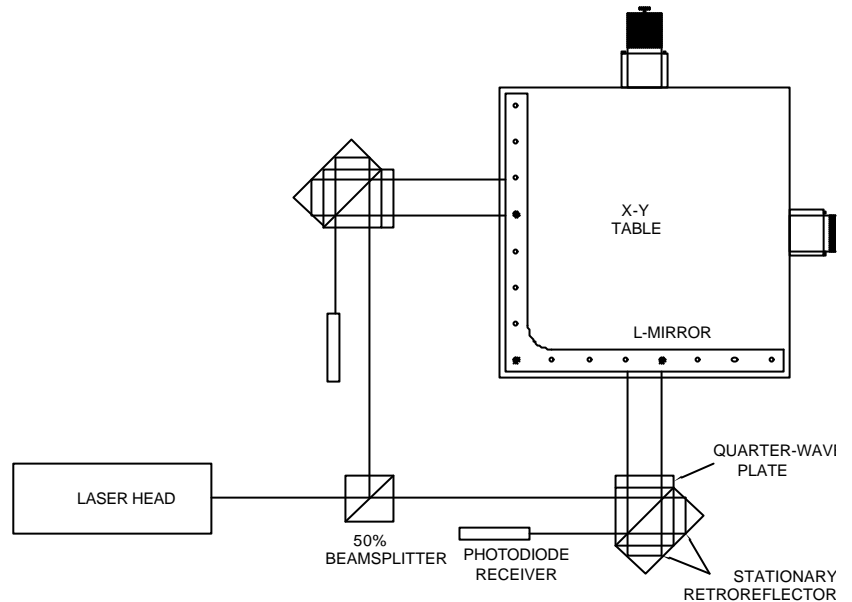


Fig. I-1 X-Y Stage Measurement with Interferometers

Contrast this system to a 2-axis system using retroreflectors. The X-axis retroreflector must be mounted on a part of the stage that moves in the X-direction and not in the Y-direction. The Y-axis retroreflector must also be mounted on a different part of the stage that is allowed to move in the Y-direction and not the X-direction. These constraints prevent 2-axis measurements from

## APPENDIX J. FASTENING, THERMAL AND VIBRATION ISOLATION

The laser head is fastened through two through holes, one in the front and one in the back. The laser output beam is not at the center, hence the output beam location can be changed by rotation of the laser head. A 90° beam bend attached to the laser head is available to bend the output laser beam 90°. There is some heat dissipation (10 to 20W) from the laser head. On smaller, very accurate machines, care must be taken in the selection of a mounting configuration. A cooling plate is available to isolate the heat flux to the machine. A circulatory coolant is needed for this cooling plate.

Vibration of the optics in a direction parallel to the beam can cause the reading to fluctuate rapidly, making it difficult to determine which number indicates the true position of the optics. When vibration occurs in a direction perpendicular to the beam, the beam signal power can fluctuate. If this fluctuation is too great, an insufficient beam signal will result, indicated by an error signal.

Loose mounting can cause the optics to move inappropriately during measurement, causing a measurement error or loss of beam strength.

Elastic mounting can have the same effect as loose mounting. It can also be responsible for a "sag" offset in the optics' positions. If there is vibration in the machine, an elastic mounting can transmit and amplify the vibration to the attached optic, possibly causing additional errors.

## APPENDIX K. LASER BEAM AND OPTICS PROTECTION

For most applications, the laser is inside the way cover or other protective cover of the machine. For some applications, when the laser beam is not covered, protection should be provided to prevent metal chips or cutting fluid from interfering with the measurements. The LDS requires protection against unintentional laser beam blockage and air turbulence problems. Also, the optical components usually require protection to prevent contamination of the optical surfaces by oil or cutting fluid.

If protection of the laser beam and optical components is required, a simple cover can be provided. In many applications, the only moving component is the retroreflector. In this case it is only necessary to provide fixed tubing for the laser beam and some type of sealed enclosure for the optics. Since only one laser beam of approximately  $\text{Ø}5.0$  mm is involved, relatively small diameter tubing (1/4" ID) can be used. There is a wide variety of commercially available protection covers which are suitable for this purpose.

In some applications when the laser beam and optics are already protected by way covers or other means, oil vapor or small metal chips may still leak through the cover. For this environment, usually a dust cover (gun barrel) in front of the laser head and the retroreflector will provide adequate protection.

The laser system has been tested under oil vapor and oil mist conditions for extended periods without the need to clean the optics. This is because the temperature of the laser head is higher than the environment temperature, so the oil vapor will not condense on the laser head. There is some oil condensation on the retroreflector, but it will not interfere with the measurement. Of course, periodic cleaning of the retroreflector may be needed.

In certain environments, where excessive oil vapor and oil mist leaks through the way cover and also with large temperature fluctuations, adding an air purge to the dust cover for the retroreflector, may reduce the frequency of cleaning the optics. For high velocity applications, the protection provided for the linear motors should be more than adequate to protect the laser system.

When using air purge, care must be taken to minimize air turbulence, which may disturb the laser beam.

## APPENDIX L. PARTS LIST

### LDS-1000

1. LDS Laser Head (2"x2")	P/N L-109
2. 0.5"Retroreflector without Base and Post	R-102A
3. Processor Board with Driver	IPS1
4. 12 ft Cable Set, No BNC	LD-21R

#### Options:

1. AC Powerfeed and Enclosure with Terminal Strip(LDS)	P-107
2. AC Powerfeed and Enclosure without Terminal Strip(LDS)	P-107A
3. AC Powerfeed and Enclosure w/Strip, Lemo Connectrs	P-107L
4. AC Powerfeed and Enclosure w/o Strip, Lemo Connectors	P-107L
5. Home Position Transducer	IHS
6. Pulse Convertor	IPC3
7. Automatic ATC Converter Board & C4 Board(w/probes)	IPC4
8. Wavelength Divided by 8 Board	IPPD2
9. Wavelength Divided by 64 Board	IPD1
10. 32-bit Parallel Board (IPCAX)	IPP32
11. LDS Laser Head, Narrow Beam(2"x2")	L-109N
12. Extended Range, 8mm Beam	L-109R
13. Counter Board with Microprocessor	ICB
14. 10 Digit LED Display	D-101
15. Extended Range to 400 in for L-109	ER-400
16. Extended Range to 2000 in for L-109	ER-200C
17. Hermetically Sealed (Except Connectors)	LHS1
18. 90 Degree Beam Bender LDS Model	LD-15C
19. Laser Head Gunbarrel	LD-57P
20. Retroreflector Gunbarrel	LD-57P
21. 90 Degree Beam Bender (Enternal +/- 1 Degree Adjustable)	LD-15T
22. 90 Degree Beam Bender (L-109, Fixed)	LD-51S
23. Sinusoidal Output	IPPS
24. IBM PC Interface	

## APPENDIX M. REPRINTS OF PAPERS

HIGH SPEED AND HIGH ACCURACY MACHINE TOOLS USING  
LASER ENCODER FEEDBACK

Dr. Charles Wang  
President  
Optodyne, Inc.  
and  
Jeff Porter  
Product Line Manager  
Ingersoll Milling

PRESENTED AT: Advances in Precision Machine Design  
September 12, 1994  
Chicago, Illinois

SPONSORED BY: Society of Manufacturing Engineers  
Conferencing Division  
One SME Drive, PO Box 930  
Dearborn, MI 48121-0930  
(313) 271-1500 FAX (313) 271-2861

## I. Introduction

A revolutionary concept in the design of machine tools eliminated the lead screw increase the speed of the machine tool, as well as accuracy and rigidity. The lead screw, as a machine's main source of inertia limits speed, so it has been replaced with a linear motor and motion control servo that uses a laser as feedback. The result is a machine tool that is very fast when performing operations, such as moving between cuts, tool retraction and tool changes. The machine tool's path accuracy and settling time is improved, because of the benefits the laser provides for the machine's servo control system. The speed, power, and rigidity of the system makes both high metal removal rate and high part accuracy possible at the same time. In addition, the high acceleration and deceleration rates provided by this drive system make improved tool life at high feed rate possible because a constant chip load on the cutting tool is maintained at all times.

## II. High Velocity Manufacturing

Starting in 1985, Ingersoll Milling Machine Company, in conjunction with Ford Motor Company, began the development of a radically new machine tool technology which utilized high thrust linear motors to drive the machine's linear axis. These linear motors replace the ball screws, ball nuts, gearboxes, servo motors, encoders, and end bearings traditionally used in a machine tool axis drive system. Magnetic force alone is used to drive the machine axis and hold them in position. The objective of this development was to produce a machine which would be several times more productive than conventional machining centers with superior accuracy and reliability. Ultimately, flexible systems of these machines would be used to replace transfer lines for mid-to-high volume production applications.

The result of this effort was the development of machines with the following characteristics:

- Acceleration and deceleration rate which are 10 - 15 times higher than conventional machining centers (1-1.5 g).
- Rapid traverse and feed rates that are 3 - 4 times higher than conventional machining centers (3,000 IPM, 76 m/min).
- A very stiff, stable machine platform capable of supporting new spindle technology also developed by Ingersoll - high speed, high power, hydrodynamic bearing motorized spindles.

In order to achieve these results, every area of machine design needed to be rethought. A rigid machine structure with a first order resonant frequency three times higher than a conventional structure was required, but the structure had to weigh less than half that of a conventional steel or iron structure. Very high position and velocity loop gains were required for the machine's control system in order to maintain high path accuracy.

at high acceleration and feed rates. A photo of the Ingersoll high Velocity Machining Center is shown in Fig. 1. Ingersoll experimented with three different kinds of feedback systems and concluded that only one had all the capabilities needed for the demanding application - laser encoder feedback.

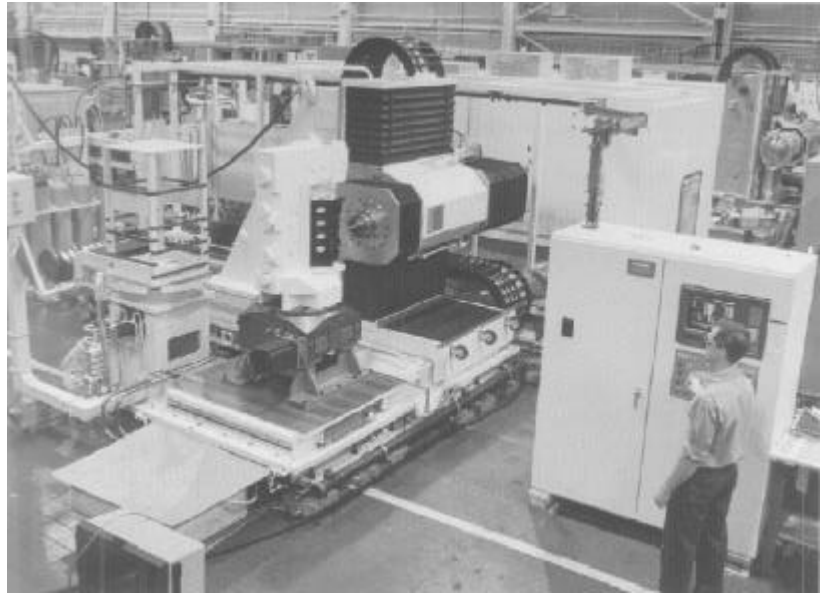


Fig. 1 Ingersoll High Speed Milling Center

### III. Laser Doppler Displacement Technology

As described in Ref. 1, the LDDM™ is based on the principles of radar, the Doppler effect and optical heterodyne. Basically a target or retroreflector is illuminated by a laser beam. The laser beam reflected by the retroreflector is frequency shifted by the motion of the retroreflector and the phase of the reflected laser beam is proportional to the position of the retroreflector. That is

$$x = \frac{c}{2f} \cdot \left( N + \frac{f}{2 \cdot p} \right) \quad (1)$$

Where  $x$  is the position of the retroreflector,  $c$  is the speed of light,  $f$  is the laser frequency,  $N$  is the number of  $2\pi$ 's and  $f$  is the phase angle. For a typical output,  $N$  is expressed as quadrature square waves and  $f$  is expressed as analog signal. The maximum speed for the phase detection is 8 MHz which corresponds to 2.5 m/s (96 in/s) and the resolution per pulse is 0.63 micrometer (0.000012 inch). An LDDM™ laser encoder is shown in Fig. 2.



Fig. 2 LDS Laser Head

Briefly, a laser beam is directed to a retroreflector. The retroreflector will reflect the laser beam back parallel to the output beam, and its position will be determined by the Doppler Shift. There are a number of advantages to working with a laser beam for precise positioning. The inherent accuracy of using a laser beam from a stabilized laser as the measurement ruler is achieved with no periodic re-calibration. The measurement is non-contact eliminating mechanical linkages with the stage. One important advantage is the freedom to locate the point of measurement close to the measured object. The retroreflector can be mounted closely in line with the location to be measured reducing or eliminating the Abbé offset, (Ref. 2) or increasing the tightness of the servo control. LDDM™ requires very little maintenance. There are no moving parts subject to wear. All machine mounted parts are of rugged design that insures long life. The laser tube is small and rugged it can withstand 8 g of force and its laser beam never needs re-calibration. When repairs are required, the modular design of the LDDM allows for rapid replacement of the defective module, thus minimizing down-time.

#### IV. Application of Laser Feedback to the High Velocity Module

##### A. Primary Drivers

1. Capable of high resolution feedback at high data rates. The ability of system to provide 0.000012" positional resolution at velocities of 50"/second was a benefit of this design.
2. Rejection of vibration in two of three planes reduced the effect of structural resonances. A linear motor (Ref. 3) machine must close the velocity feedback loop through the position feedback system since no rotating encoder or tachometer is available. This introduces the machine structure into the velocity loop. In order to achieve high servo stiffness and high acceleration and deceleration rates, high velocity loop gains are required. The laser systems rejection of resonance in two planes makes it possible to have high velocity loop gains without exciting the machine structure. A block diagram of the servo control is shown in Fig. 3.

3. Immune to electric noise or interference. Linear servo motors do not contain electrical noise or interference as well as rotary motors. The immunity of the laser feedback system to the electrical noise created by a linear motor drive system contributed to a clean feedback signal and stable machine control system.

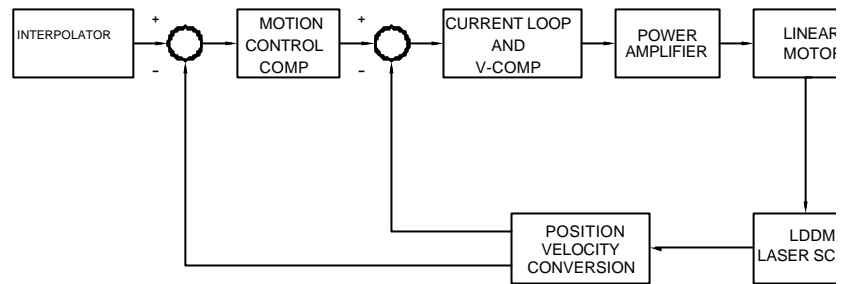


FIG. 3 BLOCK DIAGRAM OF A DIRECT DRIVE AND LASER FEEDBACK SYSTEM

#### B. Secondary Benefits

1. Compensation for temperature related growth in the machine structure. When properly applied, a laser feedback system can provide compensation for thermal growth in a machine structure because of its low coefficient of expansion compared with other scale designs (Ref. 4). The laser coefficient of expansion of 0.2 parts/million is approximately one-eighth the coefficient for glass scales and one-eleventh the coefficient of steel scales. As a result, the laser system is capable of maintaining axis position despite growth of the machine structure.
2. Ease of installation and calibration. No precision machined surfaces are required to mount the laser scale system. No time-consuming alignment and calibration procedure is required. Wiring is required only for the laser head itself. The laser retroreflector is a passive device. If the laser head is mounted to an adjustment mechanism, the alignment procedure consists of reading a beam strength signal off a test point on the laser controller card and adjusting the laser position to maximize the beam strength signal. No additional calibration or alignment is required.

#### V. Conclusion

While it would have been possible for High Velocity Machines to achieve the productivity and quality objectives using more conventional linear scales, our testing shows that the use of a laser feedback system materially improved machine stiffness and accuracy due to the benefits this system offers the machine's servo control system. The High Velocity Machines' combination of direct axis drive system and high controller gains for the position and velocity loops results in improved dynamic stiffness, acceleration/deceleration, and path accuracy. The use of laser feedback system improved the servo system performance and thus the overall level of machine performance and accuracy.

References:

1. Wang, "Laser Doppler Displacement Measurement", *Lasers and Optics*, 4 (No. 9), pp. 69-71, Sept 1987.
2. Wang, "Abbé Error and Its Effect on Position Accuracy of an XY-Table", *Motion Control*, 5, (No. 6) pp. 19-22, Nov/Dec 1989.
3. Chris Koepfer, "Linear Motor Drive--- A Fast Track for Machine Tools", *Modern Machine Shop*, 67 (No. 2), pp. 64-70, July 1994.
4. Rick Korte, "High-Tech Sensors Bring New Precision to Machine", *American Machinist*, 138, (No. 2) pp. 46-49, Feb 1994.

Figure Captions:

1. Photo of the Ingersoll High Velocity Machining Center
2. Photo of the LDDM™ laser encoder
3. Block diagram of the servo control loop



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being made on the same part of the stage. Furthermore, there will be so geometry error inherent to the system if it is not perfectly rigid.

However, the flat mirror arrangement needs a large space for the two laser heads. The laser beams are also exposed making laser beam paths vulnerable.

The LDS laser head can be incorporated in a new design with the two laser heads mounted underneath the X-Y stage (Fig. I-2). This laser head configuration allows measurement of the two flat mirrors from inside the stage rather than from outside as in the conventional flat mirror/laser head configuration.

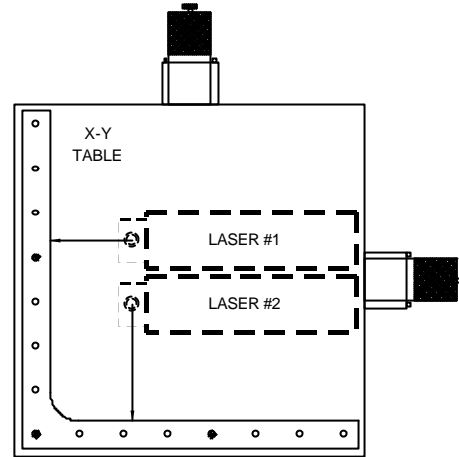


Fig I-2. X-Y Stage Measurement with LDS Narrow Beam Laser Beneath Stage.

This arrangement has all of the advantages of flat-mirror reflector but without disadvantages of the large external space requirement and beam vulnerability.

The laser head does produce heat (typically 10-20W), which may cause thermal distortion of the stage. Care must be taken to either properly isolate the heat source or allowance for the system to reach thermal equilibrium after power-

## 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  $\lambda_V$  and  $\lambda_A$  by

$$n = \lambda_V / \lambda_A$$

where  $\lambda_V$  and  $\lambda_A$  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 air composition, 1 ppm error results from any one of the following conditions:

- a. 1°C change in air temperature
- b. 2.5 mm Hg change in air pressure
- c. 60% 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 known. This correction or compensation term is known as Material Thermal Expansion Compensation (MTE) and is defined as:

$$MTE = 1 - \alpha \Delta t$$

where

$$\alpha = \text{thermal expansion coefficient}$$
$$\Delta t = T - 68^\circ\text{F}$$

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 cause a change in optical path length which appears as an apparent distance change. A typical thermal drift is about  $0.2\mu\text{m}/^\circ\text{C}$ . 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,  $\phi$ .

#### 9. Cosine Error

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

$$\text{Cosine Error} = 1 - \cos\theta$$

where

$\theta$  is the misalignment angle.

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

For example, with the following variables:

controlled environment	$T = \pm 0.5^\circ\text{C}$
total machine travel	$L = 50$ in.

dead-path	D = 3 in.
misalignment angle	$\theta = 1$ mrad
machine guideway pitch angle	$\phi = 25$ $\mu$ rad
Abbé offset	s = 1 in.
material thermal expansion coefficient	$\alpha = 6.5$ ppm
laser wavelength error	1 $\mu$ in

The following errors would result:

The atmospheric compensation error:	1 ppm x 50 in x 0.5°C = 25 $\mu$ in
The material thermal expansion:	6.5 x 50 in x 0.5°C = 162.5 $\mu$ in
The dead-path error:	1 ppm x 3 in x 0.5°C = 1.5 $\mu$ in.
The Abbé error:	1 in x 25 $\mu$ rad = 25 $\mu$ in.
The cosine error:	(1 mrad) <sup>2</sup> /2 x 50 in = 25 $\mu$ rad.

The total error, E would then be:

$$E = \sqrt{50^2 + 1^2 + 25^2 + 162.5^2 + 1.5^2 + 25^2 + 25^2}$$

$$\cong 175 \mu\text{in.}$$

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.

Setup and measurement error is due to misalignment of the machine tray along the laser measurement axis (cosine error). For an accuracy of 1 ppm, the misalignment angle should be less than 1 mrad. There is also error due to uncompensated measurement path length (dead path error).

In order to accurately correct the effects of environmental changes and material temperature on the LDS output, the Automatic Temperature Compensation Factor and Material Thermal Expansion Coefficient should be keyed in. This can be done manually if you can measure the temperatures and feed in the data. If your system has the ATC option, the ATC will automatically compensate for the environmental changes.

The ATC package comes with an ATC board, air pressure and temperature sensor and material temperature sensor. In order to compensate for temperature change, you must place the sensors where they can monitor the conditions that would influence the laser. The air sensor (continuously monitors the atmospheric conditions) should be kept as close as possible to the actual measurement path, so that it can monitor the conditions the laser beam experiences. The material temperature sensor should be placed on the part of the machine closest to its displacement measurement system. Do not place the air sensor on top of the processor box during a measurement. The processor box heats up due to its power supply, and placing the air sensor on top of the processor could alter the air reading.

**Important:** Note that when you are using Optodyne's ATC package, you do not have to key-in air temperature; it will be compensated for automatically. But, for the material thermal expansion, the material thermal expansion coefficient must be loaded into the ATC board.

ATC Specifications:

**Temperature:**

Range: 60-90°F (15-32°C)  
Accuracy: 0.18°F (0.1°C) for both air temperature and material temperature sensor

**Pressure:**

Range: 25-32 in Hg (635-813 mm Hg)  
Accuracy: 0.05 in Hg (1.3 mm Hg)

**Cable:**

4 ft., standard (1.25m)  
12, 36 ft available (3.5, 11 m)

## BCD

The BCD output is a bi-directional clocked serial port. The output data is in format for the LDDM™ BCD display unit. The port also accepts input data from buttons on the LDDM™ display unit.

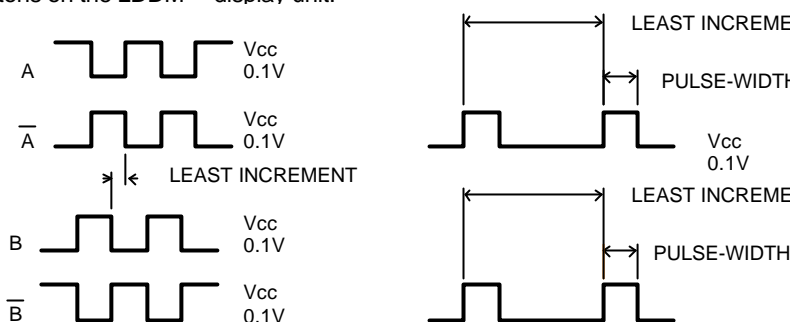


FIG. E-1 PROCESSOR OUTPUT SIGNALS

## Output Signals

As shown in Fig. E-1, the output signals are up and down pulses, and Aquad waves. Each up/down pulse or leading edge of an AquadB square wave corre: the resolution or least increment.

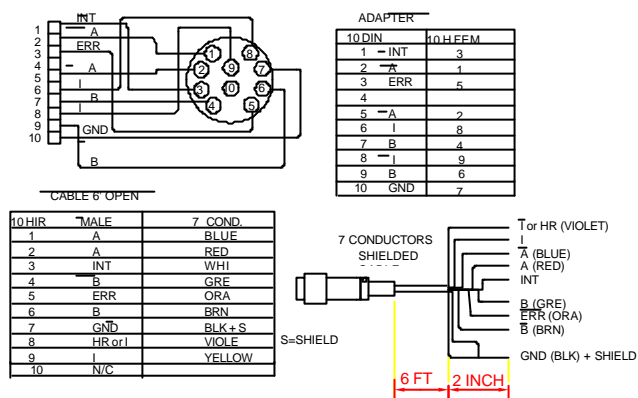
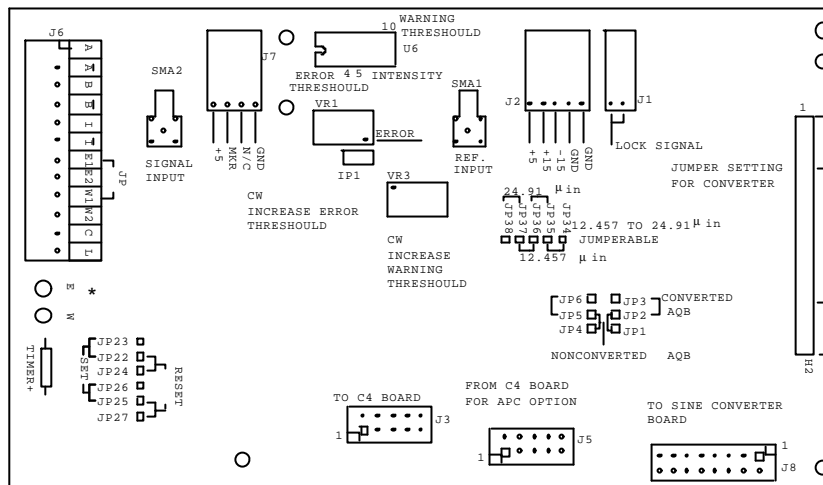


FIG. E-1A P4A/AQB, I/I ADAPTER AND CABLE

## Interconnecting Wiring Diagram

The connectors on the processor board are shown in Figs. E-2a, single axis board. Fig.E-2b, P4ACVZ board and Fig.E-2c, SC4 board. The standard interconnect wiring diagrams are shown in Figs. E-3a and E-3b. The cable set connecting head and processor is shown in Fig. E-4, and the cable connecting the home sensor with pin-outs to the power feed enclosure is shown in Fig. E-5. Please your latest drawings. These connectors may be changed without notice.



\* Error relay indicator: LED ON = Laser signal low or out of alignment.

\* Warning relay indicator: LED ON = Laser signal low or unlock.

FIG.E-2a SCHEMATIC OF P3BCV BOARD CONNECTORS



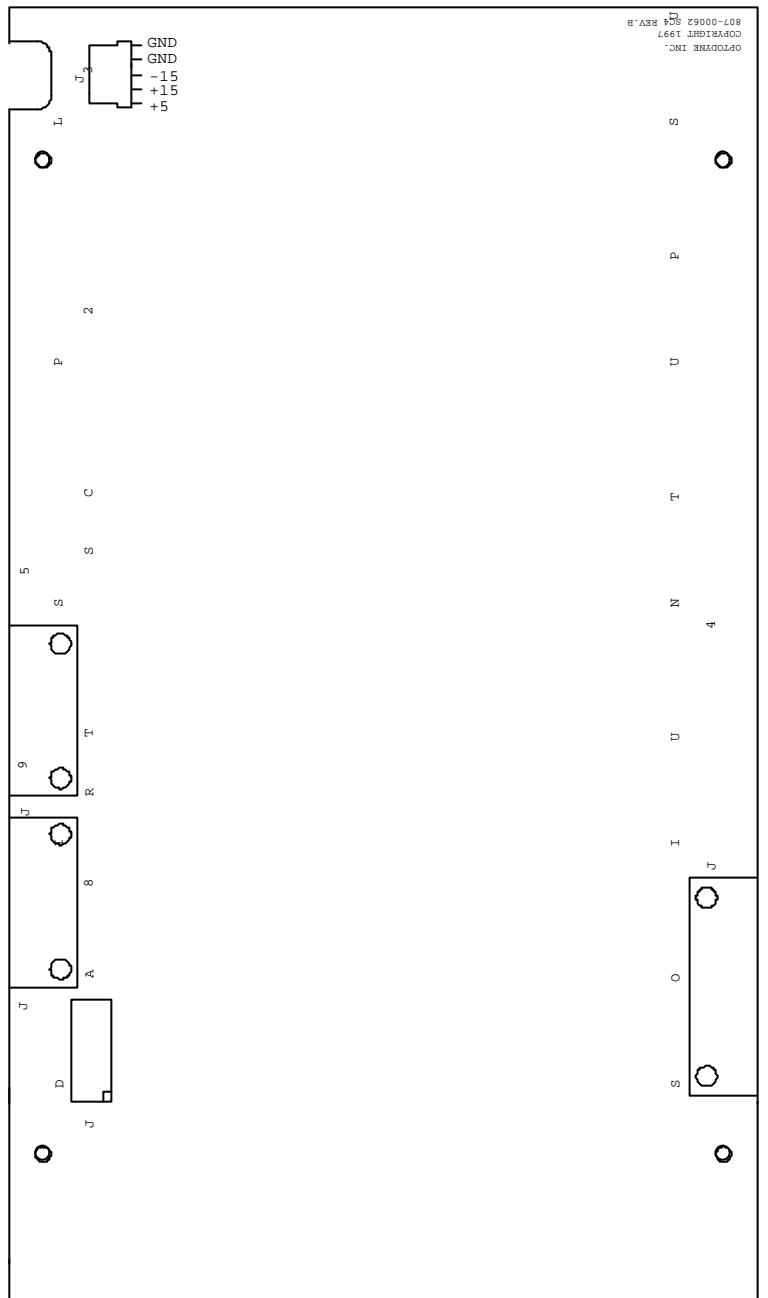
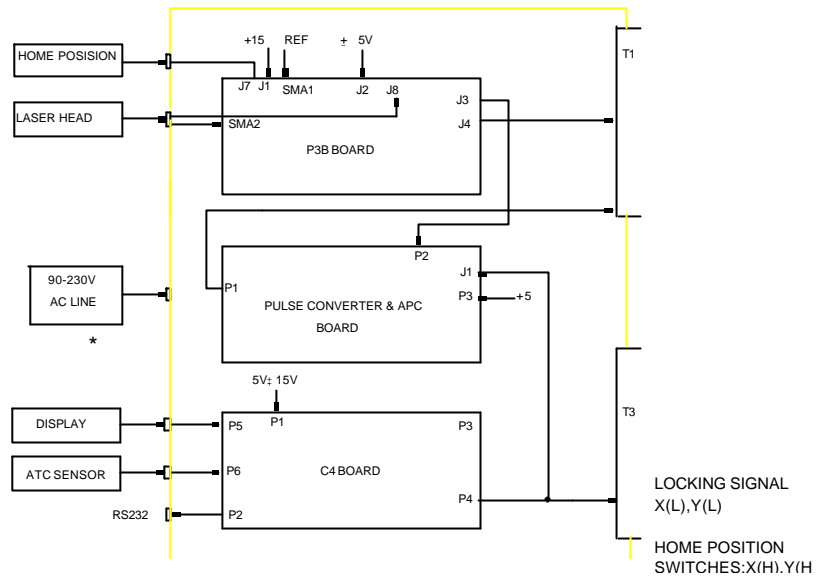
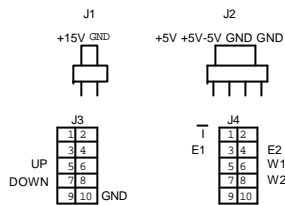


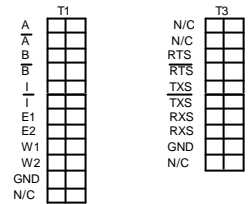
FIG. E-2c SCHEMATIC OF SC4 REB.B



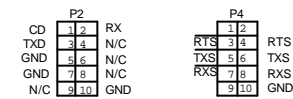
**P3B BOARD(1-AXIS)**



**TERMINAL STRIPS**



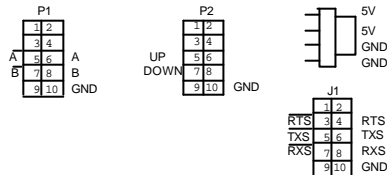
**C4 BOARD**



**CAUTION:**

ANY WIRE CONNECTED TO THE TERMINAL STRIP SHOULD NOT HAVE ACTIVE VOLTAGE MORE THAN 5V. IC MAY BE DAMAGED BY ESD. TOUCHING THE CIRCUIT BOARD OR ANY OPEN TERMINAL.

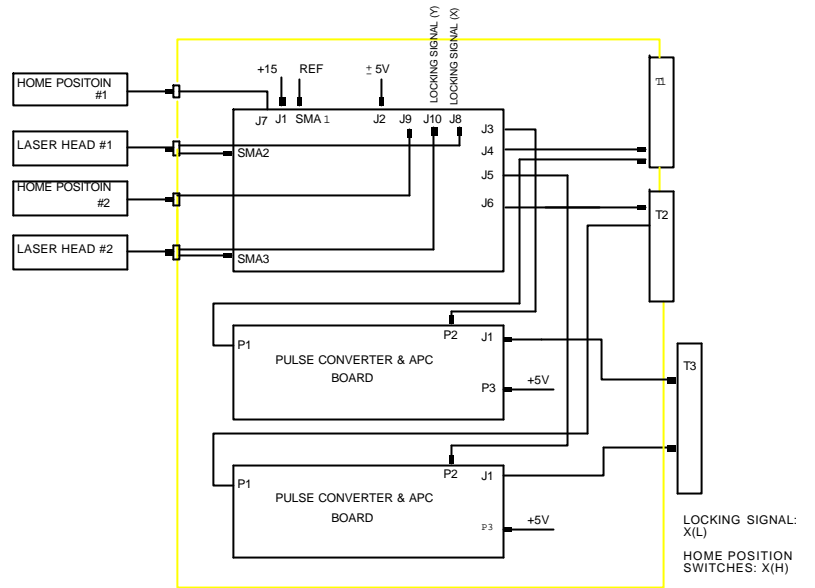
**PULSE CONVERTER & APC BOARD**



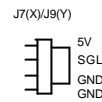
**NOTE:**

ALL OUTPUT SIGNAL ARE TTL STANDARD EXCEPT E1/E2 AND W1/W2 WHICH ARE NORMALLY CLOSED. E1 AND W1 ARE COMMON.

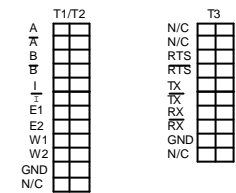
**FIG.E-3a INTERCONNECTING WIRING DIAGRAM WITH AC POWER FEED, ENCLOSURE AND ATC**



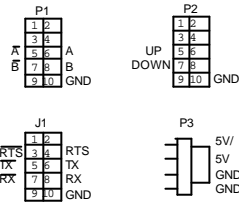
**P3B BOARD(2-AXIS)**



**TERMINAL STRIPS**



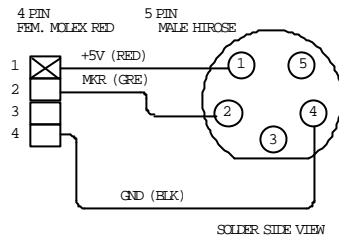
**PULSE CONVERTER & APC BOARD**



CAUTION:  
ANY WIRE CONNECTED TO THE TERMINAL STRIP SHOULD NOT HAVE ACTIVE VOLTAGE MORE THAN 5V.  
IC MAY BE DAMAGED BY ESD.  
TOUCHING THE CIRCUIT BOARD OR ANY OPEN TERMINAL.

NOTE:  
ALL OUTPUT SIGNAL ARE TTL STANDARD EXCEPT E1/E2 AND W1/W2 WHICH ARE NORMALLY CLOSED. E1 AND W1 ARE COMMON.

FIG.E-3b 2-AXIS INTERCONNECTING WIRING DIAGRAM WITH AC POWER FEED, ENCLOSURE AND ATC



CABLE :

5 PIN HIROSE FEMALE	4 PIN MOLEX RED
1. +5V (RED)	1. +5V (RED)
2. MKR (GRE)	2. MKR (GRE)
3. GND(BLK)	4. GND(BLK)

SOLDER SIDE VIEW

USE 3 CONDUCTORS SHIELDED CABLE

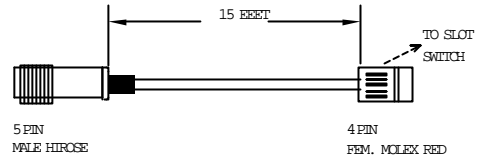
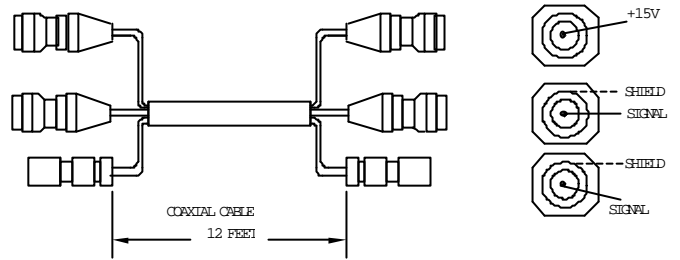


FIG. E-4 CABLE BETWEEN HOME POSITION SENSOR AND POWER FEED ENCLOSURE



NOTES:

- P1 = NICKEL SMA MALE
- P2 = GOLD SMA MALE
- P3 = NICKEL SMB FEMALE

FIG. E-5 CABLE SET BETWEEN LASER HEAD AND PROCESSOR MODULE



USE 3 PAIRED, TWISTED, INDIVIDUALLY SHIELDED CABLE

DB9 MALE CONNECTOR

- 1. GND
- 2. SINE +
- 3. SINE -
- 4. COS +
- 5. COS -
- 6. I -
- 7. I +

HIROSE 12 PLUG

- 11. GND (ALL SHIELD)
- 5. SINE + (RED)
- 6. SINE - (BLK)
- 7. COS + (GRN)
- 8. COS - (BLK)
- 10. I - (BLK)
- 9. I + (WHT)

NOTE: PINS ARE NOT SHOWN, NOT CONNECTED

FIG. E-5a HIROSE TO DB SINE CABLE

*Reference Mark, IHS*

The reference mark is an electro-optic device used to determine home position. The reference mark is provided with an IR light beam and a knife edge or razor-blade. As the razor-blade passes through the IR light beam, an output pulse is generated. The reference mark's receiver detects a drop in IR intensity by one-half. Repeatability of the reference mark is better than 1  $\mu\text{m}$ .

*Divided by 8 Board, IPPD2 and Divided by 64 board, IPPD1*

The standard increment of up/down pulses is 24.9  $\mu\text{in}$ . For higher resolution increments, a divided by 8 board and divided by 64 board are available. The divided by 8 board generates 8 additional output pulses based on the voltage of the analog signal. The divided by 8 board reduces the standard increment of 24.9  $\mu\text{in}$  per pulse to 3.11  $\mu\text{in}$  per pulse. The maximum velocity is 10 ips. The maximum error is one count. This error count is not accumulative and is corrected after each input pulse.

Similarly, the divided by 64 board will reduce the increment of each 24.9  $\mu\text{in}$  width pulse to 0.39  $\mu\text{in}$ . The maximum pulse rate for the divided by 64 board is 10 MHz or a maximum velocity of 3.9 ips.

### *Selectable Increment Board, IPC3*

The selectable increment board is used to change the least input increment to a value larger than the input increment. The selectable increment board can be used to convert the least increment to an integer value, such as 25.00000  $\mu\text{in}$  or 1  $\mu\text{m}$ , or to compensate for temperature variations. The output increment divided by  $F$ , where  $F$  is a constant from 0.000001 to 0.999999. The constant  $F$  is set by 22 jumpers (or 22-bit). Simply specify the desired resolution when the board is ordered, and Optodyne will set the board to the desired resolution at the factory. For different  $F$  values, call the Optodyne Service Department, and the 22 jumper position settings will be supplied. Software may also be ordered (\$50.00 per copy) which will aid in calculation of the jumper positions which correspond to the desired  $F$  value.

The constant,  $F$  can also be controlled by an automatic pressure and temperature compensation board.

### *Sinusoidal Output Board, IPPS*

For controllers that require a sinusoidal feedback signal, a sinusoidal output board can be purchased. Figure E-7 shows the signal voltage requirements, output frequency, and output period. Also shown is the reference or "Z-pulse" which is TTL compatible.

### *Automatic Pressure and Temperature Compensation, IPC4*

The automatic pressure and temperature compensation consists of an air pressure sensor, an air temperature sensor, a material temperature sensor, and a CPU controller. The measured air pressure, air temperature and material temperature are used to calculate the compensation factor and convert to a 22-bit number to the selectable increment board (not included in the IPC4 package). The material thermal expansion coefficient in parts-per-million (ppm) per  $^{\circ}\text{C}$  is loaded into the CPU through an RS-232C interface by a notebook PC compatible computer. Software is provided to change the expansion coefficient which corresponds to the machine's material composition. A material sensor is available for the temperature and pressure compensation package as an option. Each automatic pressure and temperature compensation package can support up to 5 selectable incremental boards. The maximum cable length is 100 ft. For cable lengths greater than 100 ft, additional drivers are needed. Consult your authorized Optodyne representative for details.

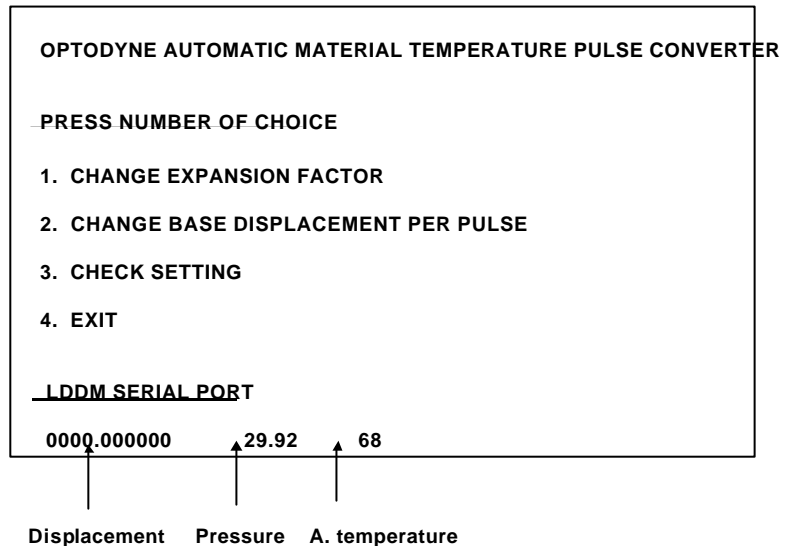
**AUTOMATIC MATERIAL TEMPERATURE PULSE  
CONVERTER UTILITY SOFTWARE**

*Description*

SAPCGP4C is a utility program that use to view and change the setting of material expansion factor (ppm°C) and base displacement per pulse (µinch/pulse)

*Installation and Operation*

1. Connect an RS232 cable from the processor box to the computer. Make sure an APC cable is connected at all times.
2. At DOS prompt A> or C>, type SAPCGP4C \* and press ENTER. It will prompt you to select communication port. Press 1 for COM1 or 2 for COM2. The screen will be shown as follow :



\* Make sure this software matches with your firmware. If not sure, check the Installation Instruction shipped with the hardware.

Press 1 to change the material expansion factor in ppm°C ( e.g. Aluminum =25ppm°C ), (Manufacture default setting = 0 ppm°C) . Press ENTER after new value is selected.

Press 2 to change the base displacement per pulse.  
(factor default setting = 25 µinch.)

Press 3 to view the setting.

Press 4 to exit.

The bottom left corner is LDDM serial reading coming from the processor box. After power on, the serial reading will show laser wavelength and signal intensity. Modes can be toggled pressing Y key. (Fig. E-6).

Press R to reset displacement.

#### *Counter Board, ICB*

The LDS can output displacement readings on a 10 digit LED display (D-101 Optodyne counter board). The counter board converts the up/down pulses and phase data to inches or mm, and gives a BCD output for the digital display. The push-buttons on the display can be used to reset the inch or mm reading displacement units between inch and metric units, and select other functions such as temperature, pressure, and material temperature(s) readouts.

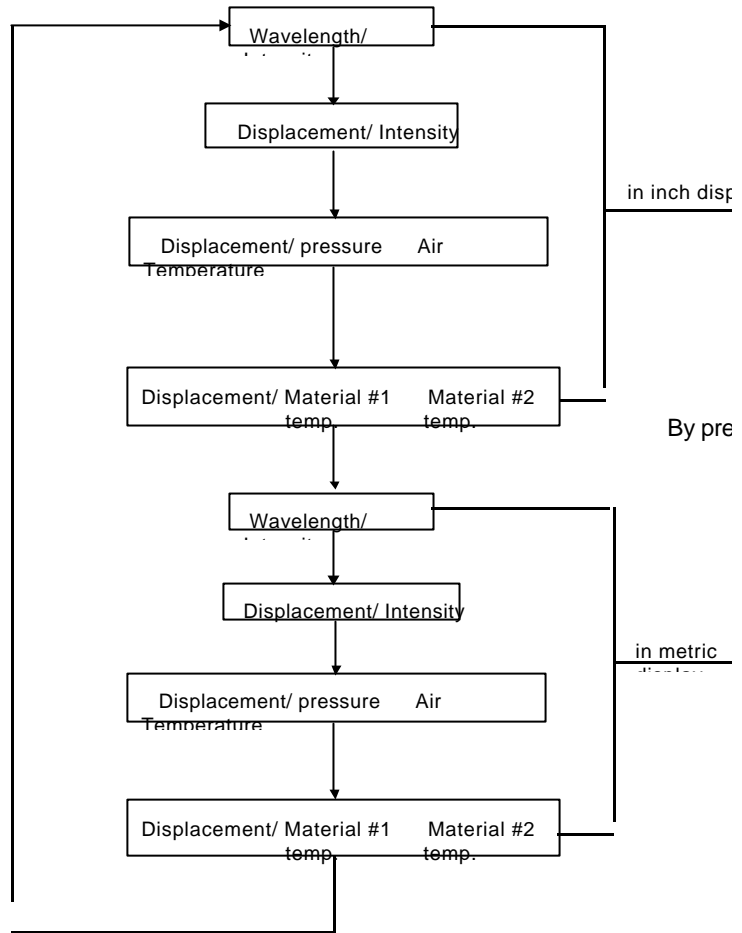
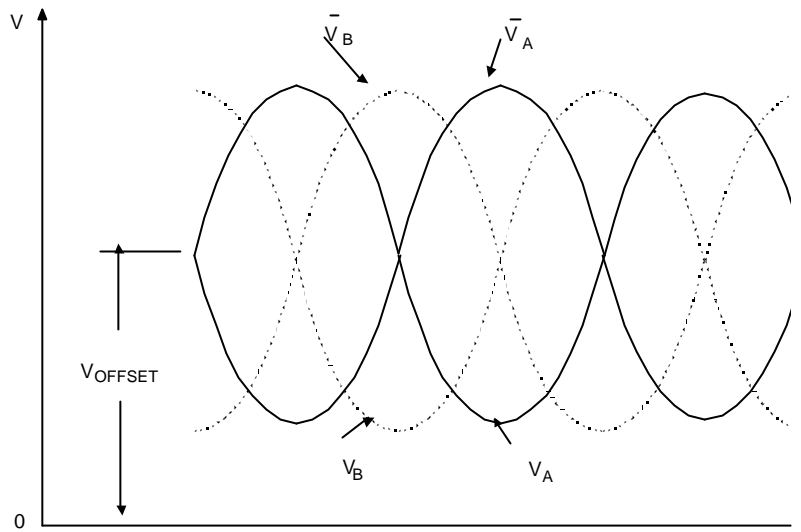


FIG. E-6 DISPLAY MODES BLOCK DIAGRAM

Sinusoidal signals



Amplitude:  $V_A - \bar{V}_A, 1V \pm 0.2V$   
 $V_B - \bar{V}_B$ , peak to peak

Output Frequency: 100 KHz

Offset:  $V_A - \bar{V}_A, V_B - \bar{V}_B, 2.5V \pm 0.2V$   
 $V_A - V_A, V_B - V_B, < 0.1V$

Output Period:  $40.513167\mu m$   
 (compatible to Fanuc's detector for linear motors)

Noise Level: 50 Mhz-100 Mhz,  $< 30 mV$   
 10 ns spikes,  $< 0.2V$

Z-pulse (TTL)

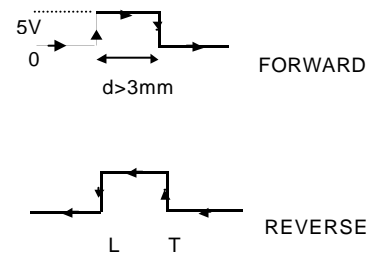


FIG. E-7 SINUSOIDAL OUTPUT SIGNAL

### 32-Bit Parallel Output Board (32BPO), p/n IPCAX

The Optodyne Model 32BPO PC Axis Board is a printed circuit board which fits into one slot on a PC-compatible I/O bus. The board digitizes the output of an LDDM™ and outputs the target position in units of  $\lambda/512$ , or about  $0.05 \mu\text{in}$  ( $1.27 \mu\text{m}$ ). The current position is maintained in a 32-bit counter which may be read over the PC bus and/or output to the Position Error Connector on the top of the board (Fig. E-8).

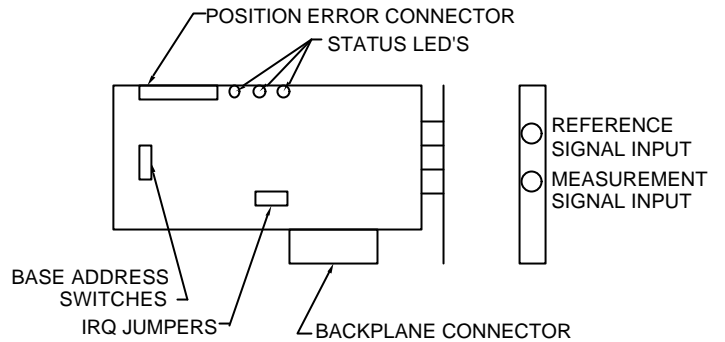


FIG. E-8 MODEL 32BPO PRINTED CIRCUIT BOARD

The Model 32BPO contains several command and status registers through which board operation may be controlled and interrogated. It is also capable of generating requests based on internal and external events.

The Model 32BPO provides an Offset Register which may be written by the host. This register may be used to set the position counter to a predetermined value to establish a reference for the position error output which then functions as the error input to an external servo loop.

The Optodyne Model 32BPO is designed for compatibility with the ISA specification, making it suitable for use with almost all PC-compatible platforms.

The 32BPO employs 8-bit data transfers so that it may be used with XT-type and AT-type computers. The board uses standard +5V, +12V and -12V power connections to the backplane.

The base address is  $\&H210$  with DIP switches 3 and 8 ON and the rest OFF. The data consists of four 8-bit (1 byte) words. The addresses of these 4 bytes are:

$$b_0 = \&H212$$

```
b1 = &H612
b2 = &HA12
b3 = &HE12
```

A sample basic program is listed below.

```
CLS
begin:
OUT &AHA10, 1
‘OUT &AHA10, 0
b0 = INP(&H212)
b1 = INP(&H612)
b2 = INP(&HA12)
b3 = INP(&HE12) AND &H7F
LOCATE 10, 10: PRINT “Byte 0 = “; : PRINT USING “###”; b0
LOCATE 12, 10: PRINT “Byte 1 = “; : PRINT USING “###”; b1
LOCATE 14, 10: PRINT “Byte 2 = “; : PRINT USING “###”; b2
LOCATE 16, 10: PRINT “Byte 3 = “; : PRINT USING “###”; b3
IF INKEY$ = CHR$(27) THEN END
GOTO begin
```

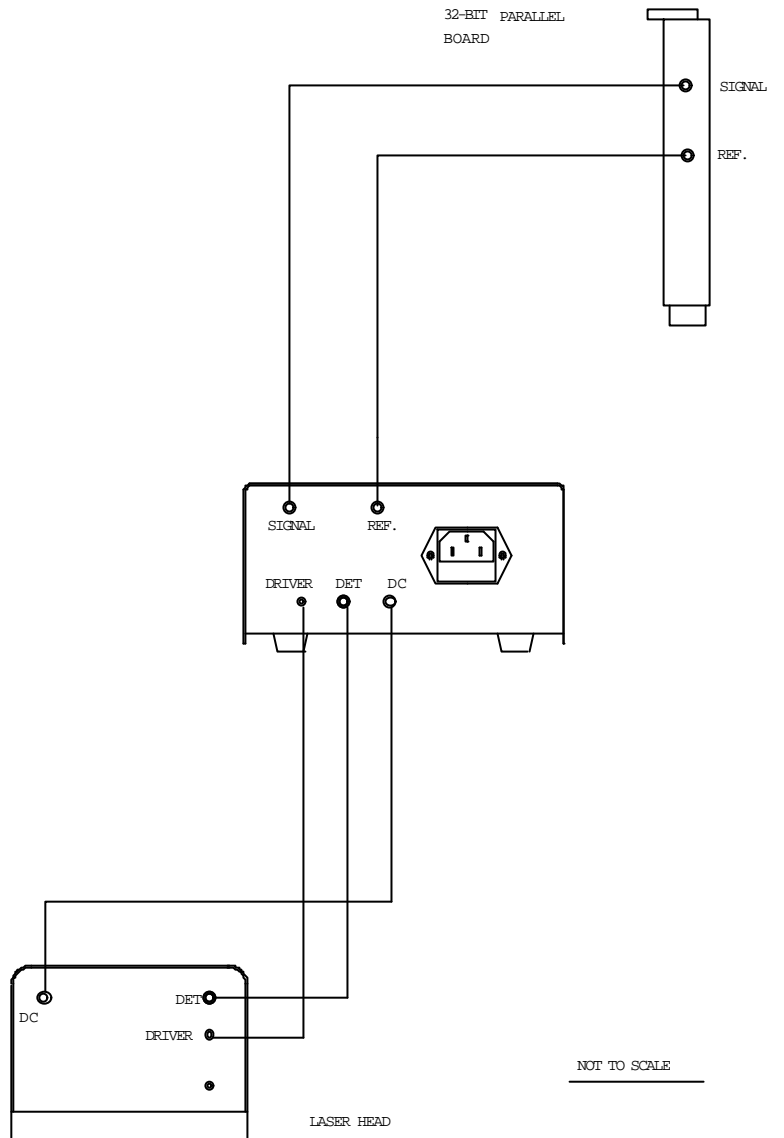


FIG. E-9 POWER SUPPLY AND DRIVER FOR THE 32-BIT

PARALLEL BOARD

Position Error Connector Pinouts

Pin	Signal Name	Pin	Signal Name
1	(none)	33	GND
2	(none)	34	GND
3	FAULT/	35	GND
4	MEASUREMENT FAULT	36	REFERENCE FAULT
5	(none)	37	OVERFLOW
6	FORCE ZERO/	38	GND
7	POSITION RESET/	39	EXTERNAL SAMPLE/
8	OUTPUT ENABLE/	40	OUTPUT HOLD/
9	ERROR CLOCK	41	GND
10	(none)	42	GND
11	(none)	43	(none)
12	P1	44	P0
13	P3	45	P2
14	GND	46	P4
15	P6	47	P5
16	P8	48	P7
17	P10	49	P9
18	P12	50	P11
19	P13	51	GND
20	P15	52	P14
21	P17	53	P16
22	P19	54	P18
23	GND	55	P20
24	P22	56	P21
25	P24	57	P23
26	P26	58	P25
27	P28	59	P27
28	P29	60	GND
29	P31	61	P30
30	(none)	62	(none)
31	(none)	63	(none)
32	GND	64	GND

performance and to match replacement parts in order to achieve sy  
performance per specification.