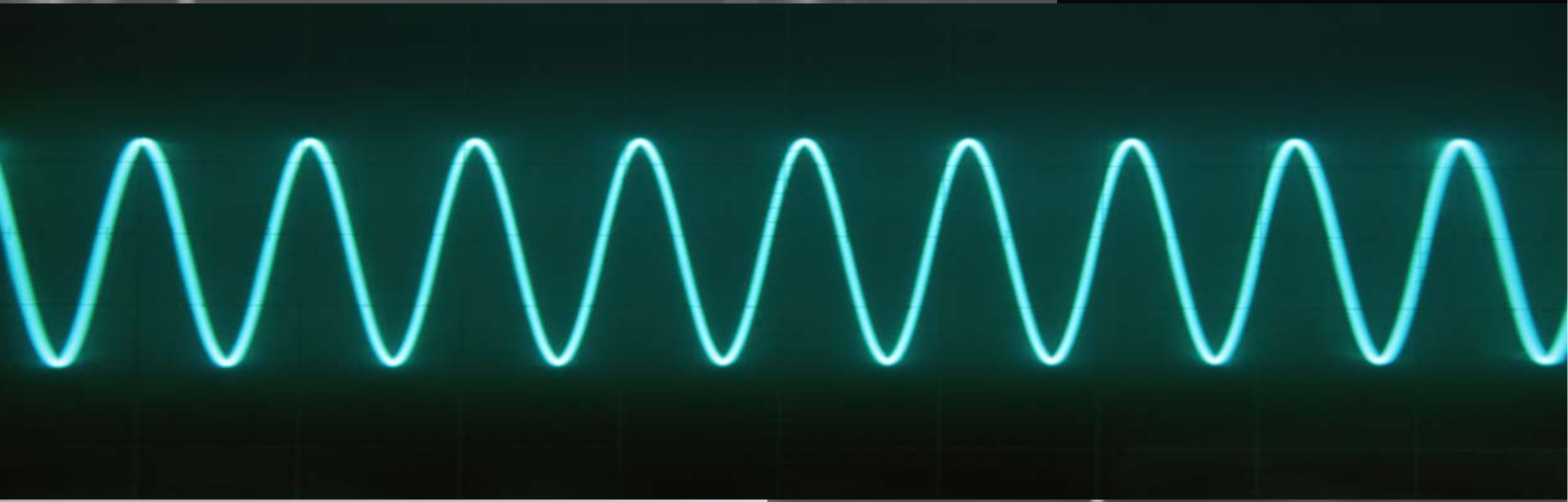
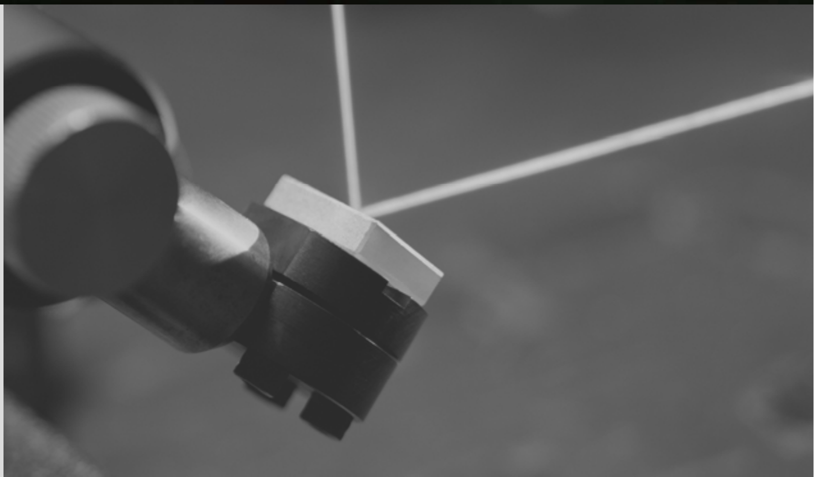
# MotionX

## Distance
## Measuring
## Laser
## Interferometer
## System
## Components





# MotionX Distance Measuring Laser Interferometer Configurations

MotionX, Inc. offers a wide range of laser designs to meet the needs of OEM customers.

## Single-Axis Laser Interferometers

Distance measuring, single-axis laser interferometers have four major elements

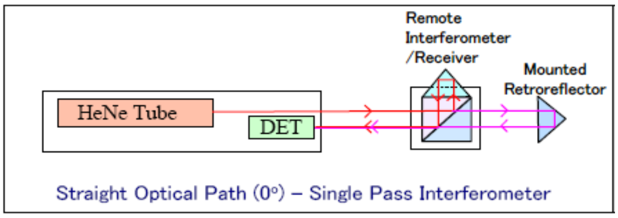
1. Stabilized Helium-Neon (He-Ne) Source
2. Optical Interferometer
3. Electronic Detection and Counting Circuitry
4. Retro-reflector or Plane Mirror

in 18 different configurations.

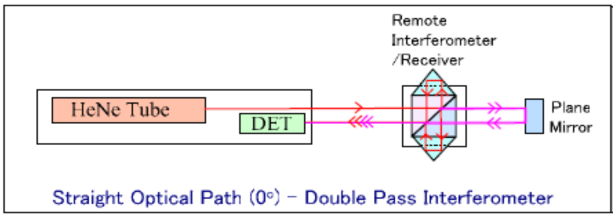
### Configurations

| Optical Path | Straight Single | Left Single | Right Single | Up Single | Down Single | Straight Double | Left Double | Right Double | Up Double | Down Double |
|---|---|---|---|---|---|---|---|---|---|---|
| Straight | X | | | | | X | | | | |
| $90^0$ | | X | X | X | X | | X | X | X | X |
| $180^0$ | | X | X | X | X | | X | X | X | X |

### Straight Optical Path ( 0 degrees)



Straight Optical Path (0°) – Single Pass Interferometer

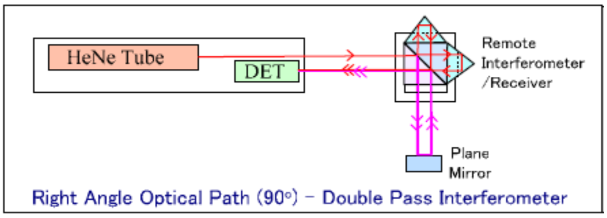


Straight Optical Path (0°) – Double Pass Interferometer

A **single pass configuration** uses a retroreflector, which provides easy alignment. Laser beams entering the reflector are returned along the same path to the detector. The technician installing and aligning the system must still ensure that the retroreflector travels parallel to the incident laser beam to minimize cosine error.

**Double pass configuration** substitutes a plane mirror for the retroreflector. In a single axis application, the benefit of using a plane mirror is doubling the optical resolution of the system by having the laser beam make two trips between the interferometer and the reflector.

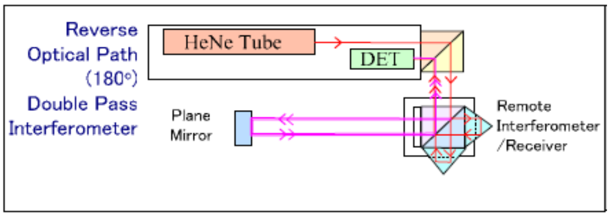
### Right Angle Optical Path (90 degrees)



Right Angle Optical Path (90°) – Double Pass Interferometer

A $90^0$ fold can be added to the optical path in the interferometer module. The path can either be folded to the **left**, the **right**, **up** or **down**, **single** or **double** pass configurations.
"Left" or "right" are from the point of view of an observer standing at the rear of the HeNe source.

### Reversed Optical Path (180 degrees)



Reverse Optical Path (180°) Double Pass Interferometer

By placing an additional fold at the output end of the HeNe source, a $180^0$ fold can be added to the optical path in the interferometer module. Together with the **left**, the **right**, **up** or **down** fold, and the **single** and **double** pass configurations, there are 8 possible configurations.

## Dual-Axis Laser Interferometers

The four elements of a single-axis interferometer are augmented by beam splitters and beam benders.

1. Stabilized Helium-Neon (He-Ne) Source
2. Optical Interferometer
3. Electronic Detection and Counting Circuitry
4. Plane Mirror Reflector
5. Beam Bender and Beam Splitters

### Major Differences

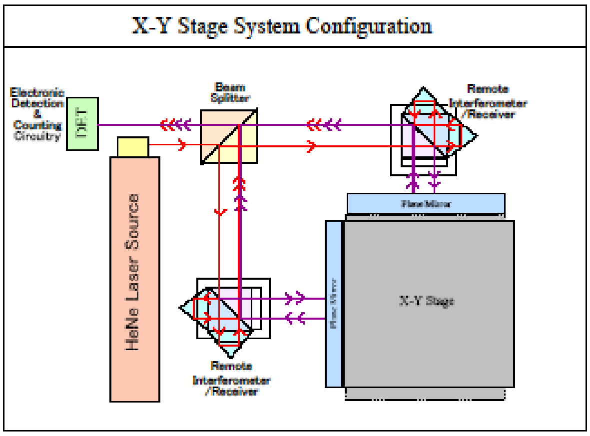
Single- and dual-axis systems are distinguished by the use of a more powerful HeNe source and the inability to use retro-reflectors. Single-axis systems use a 0.4 milli-watt (mW) output source unless the stage travel exceeds 500 mm. Because most dual-axis systems use a single source and split the energy into two paths, the 0.9 mW HeNe source is recommended.

While numerous configurations of dual-axis systems are possible, three representative ones are described here.

### X-Y Stage

The configuration below is the simplest and most common. The laser source has its output bent 90o to allow a compact system. A 50/50 beam splitter sends half of the laser output to one axis and half to the other.

Single Remote Interferometer/Receiver packages direct the beams to two plane mirrors. This configuration has one major deficiency. Stage rotation in the horizontal plane around an axis through the stage center (yaw) will not be detected since each laser beam strikes the mirror on a path coincident with the rotation axis.

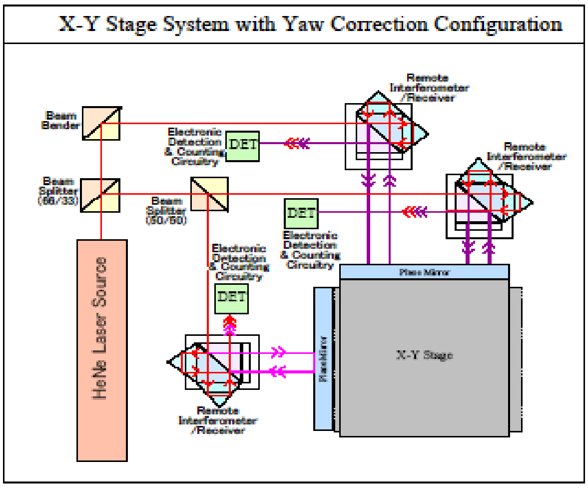

X-Y Stage System Configuration

### X-Y Stage with Yaw correction

The configuration below solves the yaw detection problem by adding a third interferometer/receiver and a second beam splitter.

The beam exiting the HeNe source has 2/3 of its energy split off and then split 50/50 for the two orthogonal elements as before. The remaining 1/3 of the beam is bent 90o and passed to the third interferometer/receiver.

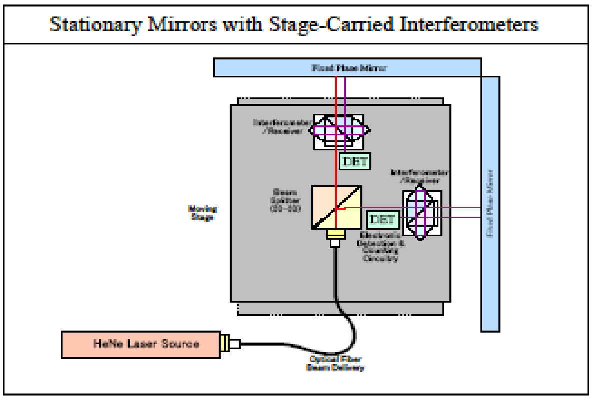
By spacing the two units on the same axis apart, yaw rotation errors will result in a differential number of counts in the two interferometer/receivers.


X-Y Stage System with Yaw Correction Configuration

### Stationary Mirrors with Stage-Carried Interferometers

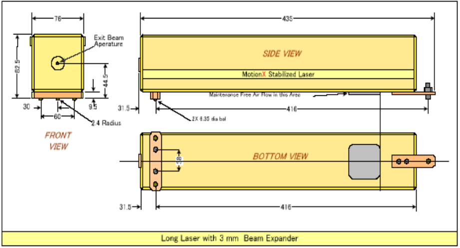
The configuration below is the X-Y Stage configuration inside-out. Laser energy is delivered to the moving stage by means of a flexible, optical fiber.

The advantage of this approach is that the mass of the mirrors does not have to be added to the stage for rapid step-and-settle applications. A third axis for yaw detection can be added, if necessary.

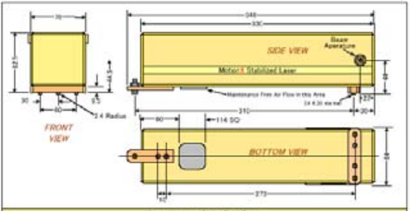

Stationary Mirrors with Stage-Carried Interferometers

# Stabilized HeNe Lasers

MotionX has a series of single frequency, stabilized HeNe lasers. The helium-neon laser tube is stabilized into a single frequency mode by means of a thermal control servo loop. The electronic circuitry detects any deviation in the balance of the S and P modes and an active thermal shunt responds to either heat or cool the laser tube to maintain frequency stability. MotionX lasers are available in several plasma tube types and sizes and a variety of case packages for diverse applications. They are fitted with a variety of beam expanding telescopes, beam benders, receiver optics and electronics, as required by the particular application. The plasma tubes in this series provide high reliability projected at greater than 30,000 hours.



Long Laser with 3 mm Beam Expander



Short Laser - Right Fold Beam

| **Specifications** | | |
|---|---|---|
| | Long | Short |
| Output power (at 632.8 nm cw) | 0.9 mW nominal | 0.35 mW nominal |
| Spatial structure | $TEM_{00}$ | $TEM_{00}$ |
| Mode structure | Single frequency | Single frequency |
| Polarization | Linear | Linear |
| Beam diameter* (at $1/e^2$ points) | 0.59 mm | 0.48 mm |
| Beam divergence* (full angle) | 1.3 mr | 1.7 mr |
| AM Noise (10HZ to 10MHz) | < 0.1% RMS | < 0.1% RMS |
| Frequency stability | < +/- 1 MHz/sec<br>< +/- 3 MHz/min<br>< +/- 10 MHz/24 hrs | < +/- 1 MHz/sec<br>< +/- 3 MHz/min<br>< +/- 10 MHz/24 hrs |
| Warm-up time | Approx 10 min | Approx 10 min |
| Normal environmental Temperature range | $10^0 \sim 37^0$ | $10^0 \sim 37^0$ |
| BRH class | II | II |
| Weight | 3 ~ 5 lbs | 3 ~ 5 lbs |
| Operating voltage | 12 volt DC | 12 volt DC |
| Power consumption (max) | 25 W (warm up)<br>15 W (normal mode) | 25 W (warm up)<br>15 W (normal mode) |

**Tube type** - Use the **SH** (Short) tube for its smaller size and lower heat dissipation (20W) unless higher output power requires the **LG** (Long) option (30W).

**Beam Exit** options allow the system designer flexibility in locating the Laser relative to other system components. The beam usually exits to the left or right in order to provide for a compact layout. It may also exit straight, or be directed up or down. An optional 1-meter optical fiber can be used to guide the laser beam in very tight physical situations.

The **Receiver** is generally not located in the laser; it is mounted remotely with the Interferometer. The Receiver output can be either AQuadB (lower resolution) or Sine/Cosine (higher resolution). If no receiver, **N** is specified.

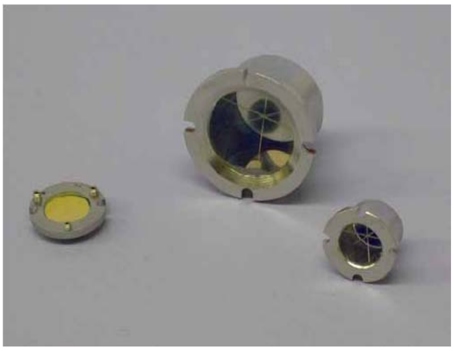
**Beam Size** is determined primarily by maximum measurement length for single axis systems. For measurements < 6 meters, (3mm **SM**) is suggested. For > 6 meters, Large beam systems (7mm **LG**) are usually selected.

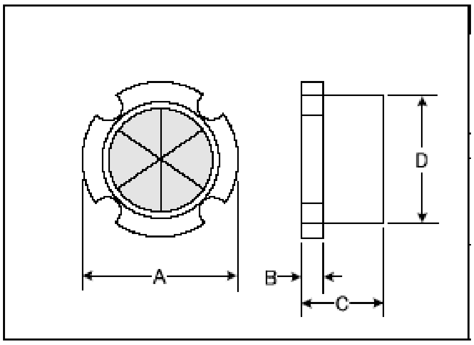
The **Connector** choice will be NON unless the Receiver is mounted internal to the Laser. For an external Receiver, select the No connector option (NON).

The **Power Supply** is 12 voltDC. It can be purchased from MotionX or supplied by the customer. A capacity of 1.8 A is required for the SH tube and 2.5 A for the LG tube. These amperages are valid whether a Receiver is located inside the Laser or not.

| Part Number | Description |
|---|---|
| **Long Tube** | |
| MX-LAS-LG-DN-N-SM-NON-C | Stabilized HeNe Laser, Long Tube, Down, None, 3mm, None, Customer 12V dc |
| MX-LAS-LG-DN-N-SM-NON-M | Stabilized HeNe Laser, Long Tube, Down, None, 3mm, None, MX 12V dc |
| MX-LAS-LG-DN-S-SM-9DC-C | Stabilized HeNe Laser, Long Tube, Down, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-LG-DN-S-SM-9DC-M | Stabilized HeNe Laser, Long Tube, Down, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-LG-LT-N-SM-NON-C | Stabilized HeNe Laser, Long Tube, Left, None, 3mm, None, Customer 12V dc |
| MX-LAS-LG-LT-N-SM-NON-M | Stabilized HeNe Laser, Long Tube, Left, None, 3mm, None, MX 12V dc |
| MX-LAS-LG-LT-S-SM-9DC-C | Stabilized HeNe Laser, Long Tube, Left, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-LG-LT-S-SM-9DC-M | Stabilized HeNe Laser, Long Tube, Left, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-LG-RT-N-SM-NON-C | Stabilized HeNe Laser, Long Tube, Right, None, 3mm, None, Customer 12V dc |
| MX-LAS-LG-RT-N-SM-NON-M | Stabilized HeNe Laser, Long Tube, Right, None, 3mm, None, MX 12V dc |
| MX-LAS-LG-RT-S-SM-9DC-C | Stabilized HeNe Laser, Long Tube, Right, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-LG-RT-S-SM-9DC-M | Stabilized HeNe Laser, Long Tube, Right, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-LG-ST-N-SM-NON-C | Stabilized HeNe Laser, Long Tube, Straight, None, 3mm, None, Customer 12V dc |
| MX-LAS-LG-ST-N-SM-NON-M | Stabilized HeNe Laser, Long Tube, Straight, None, 3mm, None, MX 12V dc |
| MX-LAS-LG-ST-S-SM-9DC-C | Stabilized HeNe Laser, Long Tube, Straight, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-LG-ST-S-SM-9DC-M | Stabilized HeNe Laser, Long Tube, Straight, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-LG-UP-N-SM-NON-C | Stabilized HeNe Laser, Long Tube, Up, None, 3mm, None, Customer 12V dc |
| MX-LAS-LG-UP-N-SM-NON-M | Stabilized HeNe Laser, Long Tube, Up, None, 3mm, None, MX 12V dc |
| MX-LAS-LG-UP-S-SM-9DC-C | Stabilized HeNe Laser, Long Tube, Up, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-LG-UP-S-SM-9DC-M | Stabilized HeNe Laser, Long Tube, Up, None, 3mm, Sine/Cosine, MX 12V dc |
| **Short Tube** | |
| MX-LAS-SH-DN-N-SM-NON-C | Stabilized HeNe Laser, Short Tube, Down, None, 3mm, None, Customer 12V dc |
| MX-LAS-SH-DN-N-SM-NON-M | Stabilized HeNe Laser, Short Tube, Down, None, 3mm, None, MX 12V dc |
| MX-LAS-SH-DN-S-SM-9DC-C | Stabilized HeNe Laser, Short Tube, Down, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-SH-DN-S-SM-9DC-M | Stabilized HeNe Laser, ShortTube, Down, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-SH-LT-N-SM-NON-C | Stabilized HeNe Laser, Short Tube, Left, None, 3mm, None, Customer 12V dc |
| MX-LAS-SH-LT-N-SM-NON-M | Stabilized HeNe Laser, Short Tube, Left, None, 3mm, None, MX 12V dc |
| MX-LAS-SH-LT-S-SM-9DC-C | Stabilized HeNe Laser, Short Tube, Left, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-SH-LT-S-SM-9DC-M | Stabilized HeNe Laser, Short Tube, Left, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-SH-RT-N-SM-NON-C | Stabilized HeNe Laser, Short Tube, Right, None, 3mm, None, Customer 12V dc |
| MX-LAS-SH-RT-N-SM-NON-M | Stabilized HeNe Laser, Short Tube, Right, None, 3mm, None, MX 12V dc |
| MX-LAS-SH-RT-S-SM-9DC-C | Stabilized HeNe Laser, Short Tube, Right, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-SH-RT-S-SM-9DC-M | Stabilized HeNe Laser, Short Tube, Right, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-SH-ST-N-SM-NON-C | Stabilized HeNe Laser, Short Tube, Straight, None, 3mm, None, Customer 12V dc |
| MX-LAS-SH-ST-N-SM-NON-M | Stabilized HeNe Laser, Short Tube, Straight, None, 3mm, None, MX 12V dc |
| MX-LAS-SH-ST-S-SM-9DC-C | Stabilized HeNe Laser, Short Tube, Straight, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-SH-ST-S-SM-9DC-M | Stabilized HeNe Laser, Short Tube, Straight, None, 3mm, Sine/Cosine, MX 12V dc |
| MX-LAS-SH-UP-N-SM-NON-C | Stabilized HeNe Laser, Short Tube, Up, None, 3mm, None, Customer 12V dc |
| MX-LAS-SH-UP-N-SM-NON-M | Stabilized HeNe Laser, Short Tube, Up, None, 3mm, None, MX 12V dc |
| MX-LAS-SH-UP-S-SM-9DC-C | Stabilized HeNe Laser, Short Tube, Up, None, 3mm, Sine/Cosine, Customer 12V dc |
| MX-LAS-SH-UP-S-SM-9DC-M | Stabilized HeNe Laser, Short Tube, Up, None, 3mm, Sine/Cosine, MX 12V dc |

## Mounted Retroreflector





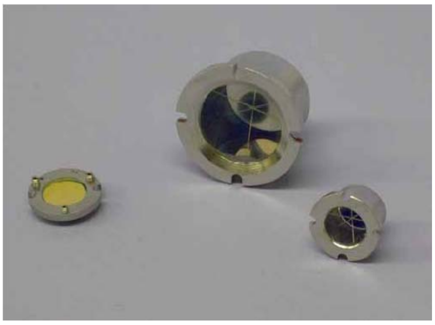
0.45 inch and 0.90 inch Clear Aperture sizes are available.

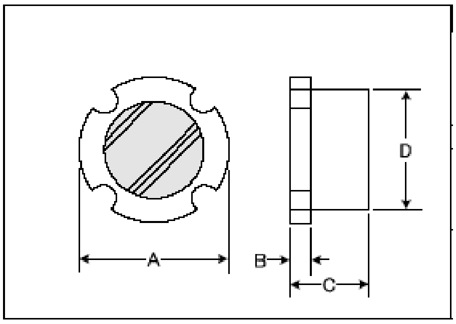
The dimension as shown in the table below are in inches.

| Clear Aperture | Dimension | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 01 | .810 | .100 | .500 | .600 |
| 02 | 1.480 | .125 | .875 | 1.125 |
| | Mounting | | | |
| 01 | 4X Slot Equal Spacing on .75 BC .10 Wide | | | |
| 02 | 4X Slot Equal Spacing on 1.132 BC .125 Wide | | | |

| **Part Number** | **Description** |
|---|---|
| MX-MR-01 | Mounted Retroreflector, 0.450 Clear Aperture |
| MX-MR-02 | Mounted Retroreflector, 0.900 Clear Aperture |

## Mirror (Single Axis)





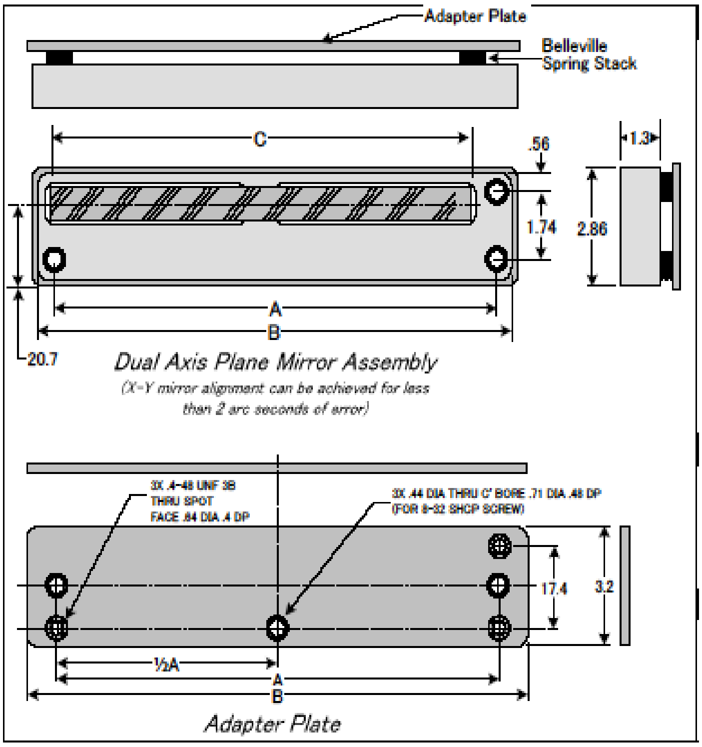
0.45 inch and 0.90 inch Clear Aperture sizes are available.

The dimension as shown in the table below are in inches.

| Clear Aperture | Dimension | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 01 | .810 | .100 | .500 | .600 |
| 02 | 1.480 | .125 | .875 | 1.125 |
| | Mounting | | | |
| 01 | 4X Slot Equal Spacing on .75 BC .10 Wide | | | |
| 02 | 4X Slot Equal Spacing on 1.132 BC .125 Wide | | | |

| **Part Number** | **Description** |
|---|---|
| MX-MS-01 | Plane Mirror, .500 inch Round, 0.450 Clear Aperture, 1/10th Wave Surface Flatness |
| MX-MS-02 | Plane Mirror, 1.00 inch Round, 0.900 Clear Aperture, 1/10th Wave Surface Flatness |

# Mirror (Dual Axis)

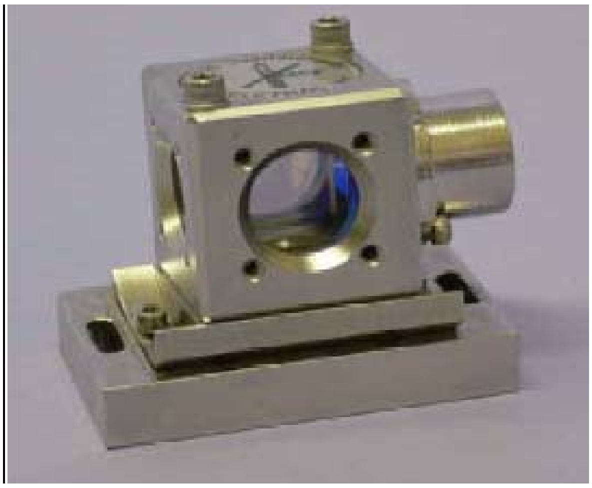


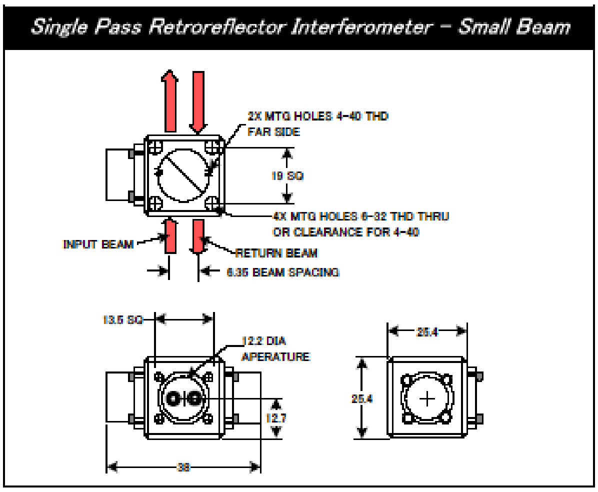
| Travel | Dimension | | |
|---|---|---|---|
| | A | B | C |
| 04 | 5.562 | 6.000 | 5.000 |
| 06 | 7.562 | 8.000 | 7.000 |
| 08 | 9.562 | 10.000 | 9.000 |
| Dimension in inches | | | |

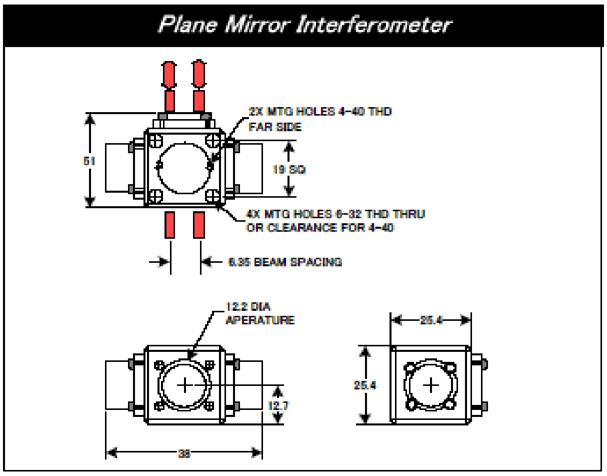
| Travel | Dimension | |
|---|---|---|
| | A | B |
| 04 | 5.562 | 6.125 |
| 06 | 7.562 | 8.125 |
| 08 | 9.562 | 10.125 |
| Dimension in inches | | |

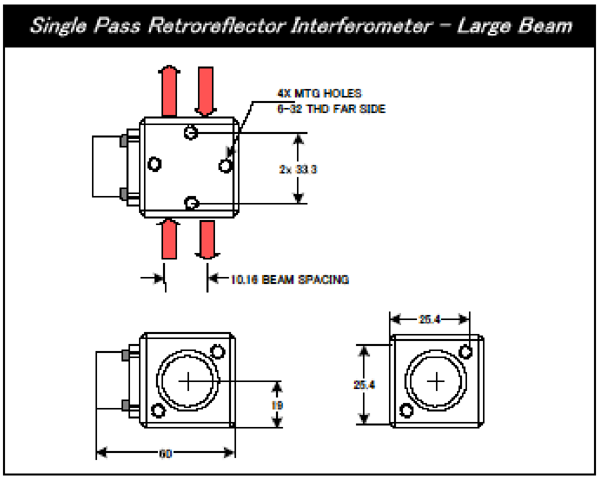
| Part Number | Description |
|---|---|
| MX-MD-01-10-01 | Plane Mirror, 1-inch travel, 1/10th Wave Surface Flatness, Unmounted |
| MX-MD-01-10-02 | Plane Mirror, 1-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted |
| MX-MD-01-10-03 | Plane Mirror, 1-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted w/Adapter Plate |
| MX-MD-02-10-01 | Plane Mirror, 2-inch travel, 1/10th Wave Surface Flatness, Unmounted |
| MX-MD-02-10-02 | Plane Mirror, 2-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted |
| MX-MD-02-10-03 | Plane Mirror, 2-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted w/Adapter Plate |
| MX-MD-04-10-01 | Plane Mirror, 4-inch travel, 1/10th Wave Surface Flatness, Unmounted |
| MX-MD-04-10-02 | Plane Mirror, 4-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted |
| MX-MD-04-10-03 | Plane Mirror, 4-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted w/Adapter Plate |
| MX-MD-06-10-01 | Plane Mirror, 6-inch travel, 1/10th Wave Surface Flatness, Unmounted |
| MX-MD-06-10-02 | Plane Mirror, 6-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted |
| MX-MD-06-10-03 | Plane Mirror, 6-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted w/Adapter Plate |
| MX-MD-08-10-01 | Plane Mirror, 8-inch travel, 1/10th Wave Surface Flatness, Unmounted |
| MX-MD-08-10-02 | Plane Mirror, 8-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted |
| MX-MD-08-10-03 | Plane Mirror, 8-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted w/Adapter Plate |
| MX-MD-10-10-01 | Plane Mirror, 10-inch travel, 1/10th Wave Surface Flatness, Unmounted |
| MX-MD-10-10-02 | Plane Mirror, 10-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted |
| MX-MD-10-10-03 | Plane Mirror, 10-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted w/Adapter Plate |
| MX-MD-12-10-01 | Plane Mirror, 12-inch travel, 1/10th Wave Surface Flatness, Unmounted |
| MX-MD-12-10-02 | Plane Mirror, 12-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted |
| MX-MD-12-10-03 | Plane Mirror, 12-inch travel, 1/10th Wave Surface Flatness, Tangent Bar Mounted w/Adapter Plate |

# Interferometers




Single Pass Retroreflector Interferometer – Small Beam


Plane Mirror Interferometer

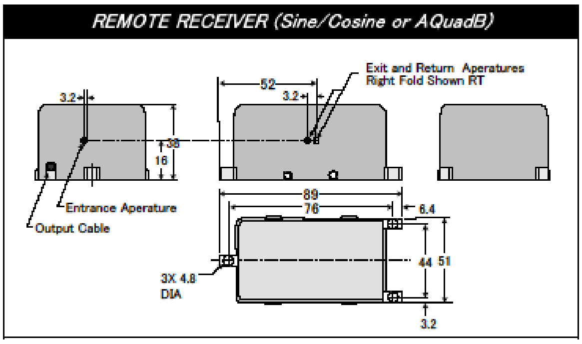

Single Pass Retroreflector Interferometer – Large Beam

| Part Number | Description |
|---|---|
| MX-RIR-10S-MD-NO | Remote Interferometer, 1.0 inch Standard 3mm, Dual Pass, No Mount |
| MX-RIR-10S-MD-SM | Remote Interferometer, 1.0 inch Standard 3mm, Dual Pass, Small Mount |
| MX-RIR-10S-RS-NO | Remote Interferometer, 1.0 inch Standard 3mm, Single Pass, No Mount |
| MX-RIR-10S-RS-SM | Remote Interferometer, 1.0 inch Standard 3mm, Single Pass, Small Mount |
| MX-RIR-15S-MD-NO | Remote Interferometer, 1.5 inch Standard 3mm, Dual Pass, No Mount |
| MX-RIR-15S-MD-SM | Remote Interferometer, 1.5 inch Standard 3mm, Dual Pass, Large Mount |
| MX-RIR-15S-RS-NO | Remote Interferometer, 1.5 inch Standard 3mm, Single Pass, No Mount |
| MX-RIR-15S-RS-SM | Remote Interferometer, 1.5 inch Standard 3mm, Single Pass, Large Mount |

# Receivers and Interferometer Receivers

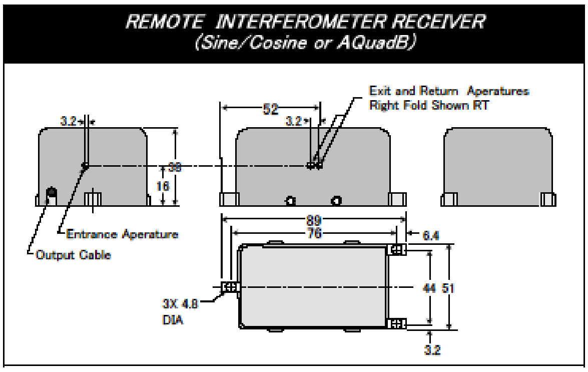
## Remote Receivers

In very specialized cases, the designer may want to separate the Laser, Receiver, and Interferometer. MotionX makes this possible by offering each one as a separate element.



## Remote Interferometer/Receivers

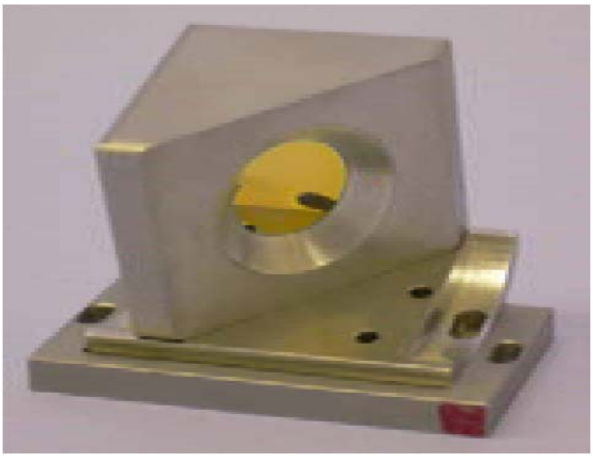
This unit integrates the Remote Interferometer with the Receiver in a single package.

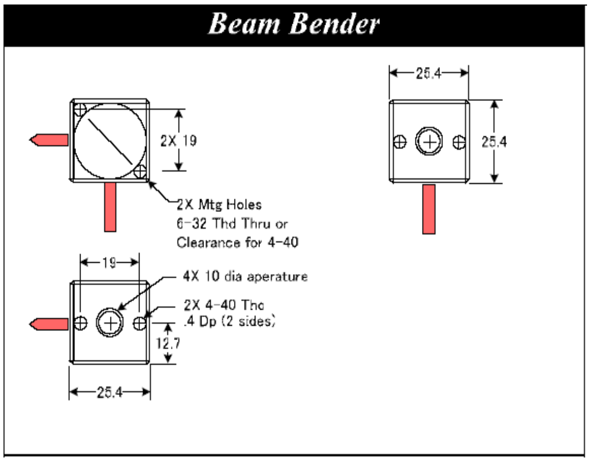


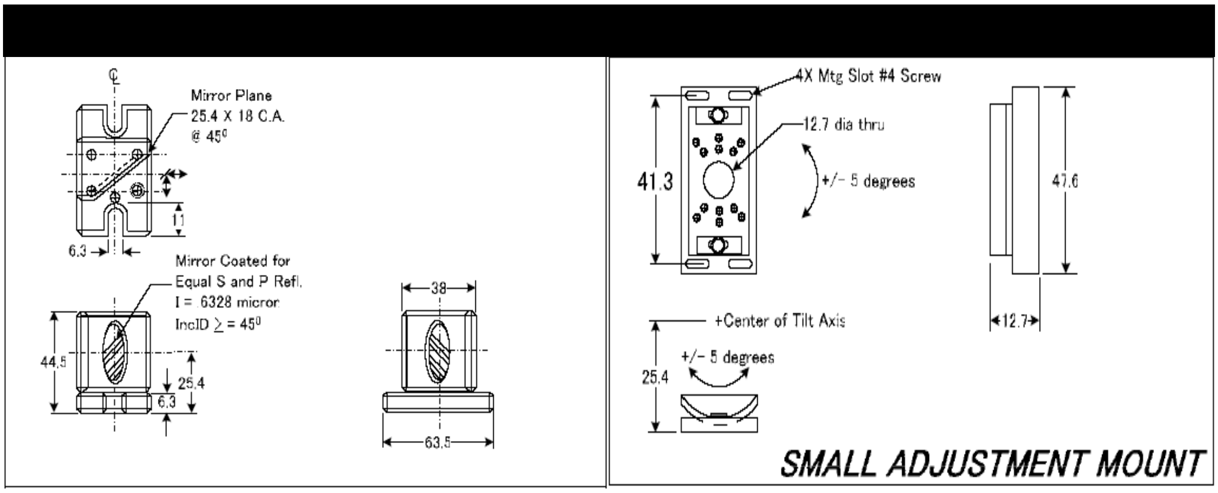
- Interferometer/Receiver: Sine/Cosine current output mates with CIAIP or CMAP, Double Pass flat mirror for X-Y Stage applications, $\lambda/256$ resolution, DB-9 connector.
- Interferometer/Receiver: Sine/Cosine current output mates with CIAIP or CMAP, Single Pass retroreflector for single axis applications, $\lambda/128$ resolution, DB-9 connector.
- $\lambda/16$ Double pass. AQuadB flat mirror interferometer/receiver for X-Y stage applications. Complementary TTL interface to motion control cards.
- $\lambda/8$ Single pass. AQuadB flat mirror interferometer/receiver for single axis application, TTL Complementary, with DB-15 connector.

| Part Number | Description |
|---|---|
| MX-RIR-RSP-LT-AB-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Single-Pass, Left-Fold, AQuadB |
| MX-RIR-RSP-LT-SC-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Single-Pass, Left-Fold, Sin/Cosine |
| MX-RIR-RSP-RT-AB-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Single-Pass, Right-Fold, AQuadB |
| MX-RIR-RSP-RT-SC-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Single-Pass, Right-Fold, Sin/Cosine |
| MX-RIR-RSP-ST-AB-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Single-Pass, Straight, AQuadB |
| MX-RIR-RSP-ST-SC-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Single-Pass, Straight, Sin/Cosine |
| | |
| MX-RIR-PMD-LT-AB-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Double-Pass, Left-Fold, AQuadB |
| MX-RIR-PMD-LT-SC-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Double-Pass, Left-Fold, Sin/Cosine |
| MX-RIR-PMD-RT-AB-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Double-Pass, Right-Fold, AQuadB |
| MX-RIR-PMD-RT-SC-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Double-Pass, Right-Fold, Sin/Cosine |
| MX-RIR-PMD-ST-AB-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Double-Pass, Straight, AQuadB |
| MX-RIR-PMD-ST-SC-ST-ST | Remote Interferometer/Receiver, Plane Mirror, Double-Pass, Straight, Sin/Cosine |
| | |
| MX-RIR-ST-SM-AB-ST-ST | Remote Receiver, Standard Case, Small Beam 3mm, AQuadB |
| MX-RIR-ST-SM-SC-ST-ST | Remote Receiver, Standard Case, Small Beam 3mm, Sin/Cosine |

# Beam Benders

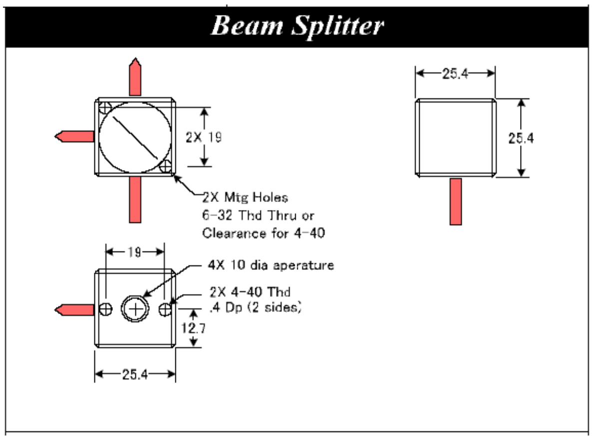


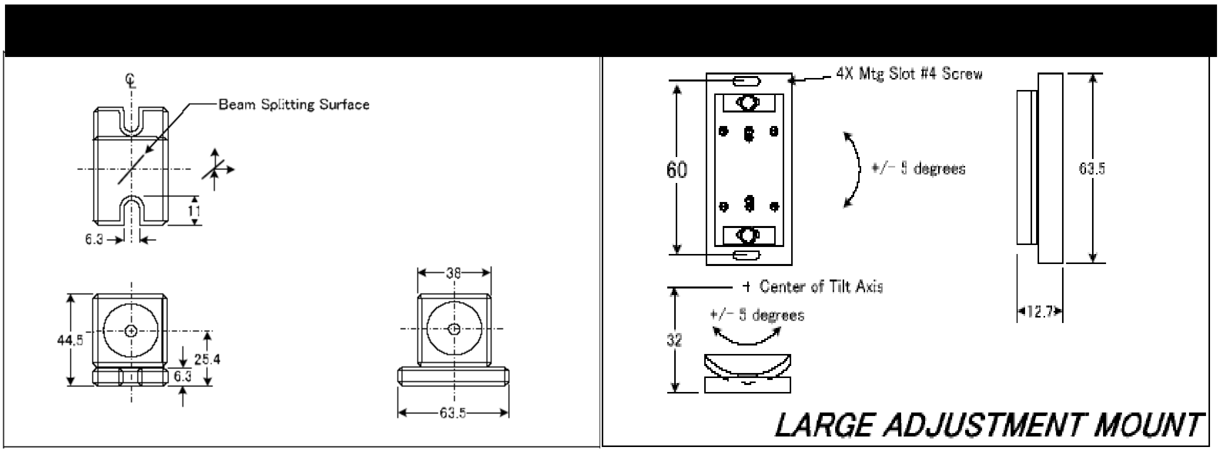




| Part Number | Description |
|---|---|
| MX-BB-MD-MD | Beam Bender, .700-inch Clear Aperture, Medium Adjustment Mount |
| MX-BB-MD-NO | Beam Bender, .700-inch Clear Aperture, No Adjustment Mount |
| MX-BB-SM-NO | Beam Bender, .500-inch Clear Aperture, No Adjustment Mount |
| MX-BB-SM-SM | Beam Bender, .500-inch Clear Aperture, Small Adjustment Mount |

## Beam Splitters





| Part Number | Description |
|---|---|
| MX-BS-10-33-NO | Beam Splitter, 1.0-inch, 34% Transmissive / 66% Reflective, No Adjustment Mount |
| MX-BS-10-33-SM | Beam Splitter, 1.0-inch, 34% Transmissive / 66% Reflective, Small Adjustment Mount |
| | |
| MX-BS-10-50-NO | Beam Splitter, 1.0-inch, 50% Transmissive / 50% Reflective, No Adjustment Mount |
| MX-BS-10-50-SM | Beam Splitter, 1.0-inch, 50% Transmissive / 50% Reflective, No Adjustment Mount |
| | |
| MX-BS-10-66-NO | Beam Splitter, 1.0-inch, 66% Transmissive / 34% Reflective, No Adjustment Mount |
| MX-BS-10-66-SM | Beam Splitter, 1.0-inch, 66% Transmissive / 34% Reflective, No Adjustment Mount |
| | |
| MX-BS-15-33-LG | Beam Splitter, 1.5-inch, 34% Transmissive / 66% Reflective, Large Adjustment Mount |
| MX-BS-15-33-NO | Beam Splitter, 1.5-inch, 34% Transmissive / 66% Reflective, No Adjustment Mount |
| | |
| MX-BS-15-50-LG | Beam Splitter, 1.5-inch, 50% Transmissive / 50% Reflective, Large Adjustment Mount |
| MX-BS-15-50-NO | Beam Splitter, 1.5-inch, 50% Transmissive / 50% Reflective, No Adjustment Mount |
| | |
| MX-BS-15-66-LG | Beam Splitter, 1.5-inch, 66% Transmissive / 34% Reflective, Large Adjustment Mount |
| MX-BS-15-66-NO | Beam Splitter, 1.5-inch, 66% Transmissive / 34% Reflective, No Adjustment Mount |

# *Laser Interferometer Theory*

## *INTRODUCTION*

This section provides an overview of laser interferometers. For purposes of discussion, a number of simplifying assumptions have been made.

## *INVENTION*

In 1880 at the age of 28, the American physicist, Albert A. Michelson invented the interferometer. The discovery is considered to have been a pivotal event in modern physics. It came only two years after Michelson's pioneering measurement of the speed of light. Over the next 30 years, Michelson used the interferometer to prove the wave theory of light and provide the first experimental confirmation of Einstein's theory of relativity. For his work, Michelson was the first American awarded the Nobel Prize in Physics.

## *BASIC CONCEPTS*

The wave theory of light states that light travels as a sinusoidal wave (Figure 1).

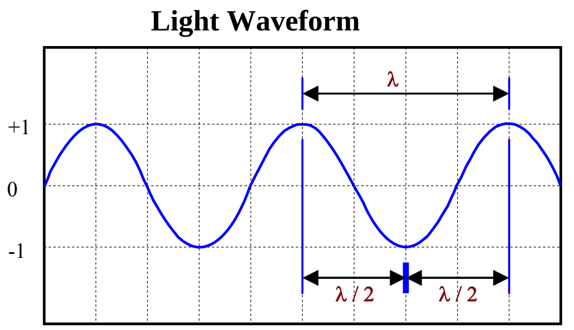


**Figure 1**

The wavelength (l) is the distance between two peaks (or troughs) in the wave. For visible light, the peak to peak distance in microns is approximately 0.7 (red) to 0.3 (violet): in nanometers this is 700 to 300 and in Angstroms, 7000 to 3000 A.

Interferometers are elegant and simple in concept and execution (Figure 2).

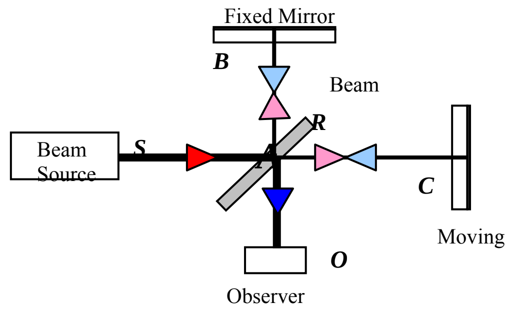


**Figure 2**

A beam of light is emitted from ***S***. About half the light is reflected to mirror ***B*** by the partially silvered surface ***R*** on the glass plate ***A***. The remainder of the light strikes mirror ***C***. An observer at ***O*** sees the combined beams from ***B*** and ***C***. The observer sees light and dark bands. These bands are caused by the constructive and destructive combination (or interference) of the peaks and valleys of the two light waves (Figure 3).

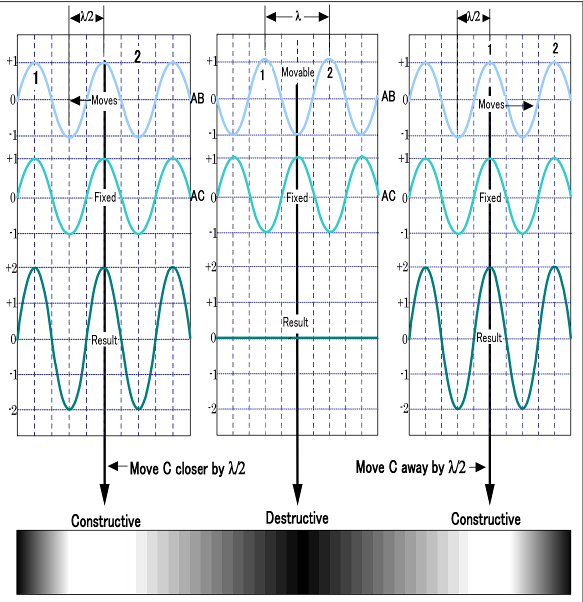


Figure 3

The combination is brightest when the peaks of each beam overlap exactly or *interfere constructively*. Peaks in one beam can be cancelled by valleys in the other resulting in dark bands or *destructive interference* (Figure 3). Changing the length ***AB*** or ***AC*** by one half of a wavelength causes a shift from a light to a dark band (or dark to light). Thus, if ***B*** is fixed and only ***C*** is moved, the relative distance moved by ***C*** can be measured with a resolution of half the wavelength of the source (l/2).

There are three key concepts:

1. The interferometer measures *changes* in path length, i.e. how far either mirror ***B*** or mirror ***C*** has moved. It cannot measure the absolute distance from say mirror ***A*** to mirror ***C***.

2. The interferometer measures the sum of ***AB*** and ***AC***. In order to determine the change in ***AC***, ***AB*** must be held absolutely stationary.

3. Interferometer accuracy is dependent on the frequency stability of the light source. Any change in frequency will cause an apparent change in the length of the path.

Figure 4 shows the schematic of a modern instrument. There is little similarity between the Michelson and the modern design except in concept. The sodium vapor light source (S) in Michelson's design is replaced with a frequency stabilized Helium Neon (HeNe) laser, and the observer's eye with a pair of photo detectors and computer counters.

In the modern instrument, beams AB and AC are returned by two retroreflector mirrors (three surfaces at $90^0$ angles like the corner of a room). Retroreflectors, unlike flat mirrors are insensitive to small angular deviation from being normal to the laser beam. Also, point O is placed in line with path AC. This does not affect the principle, but produces a more compact instrument.

Since the length AB is not critical, beam splitter A and mirror B may be combined into a single optical element, commonly called the "interferometer element" or confusingly enough simply "the interferometer".

## *LASER IMPROVEMENTS*

The laser is pivotal to the modern interferometers. It works by exciting electron transitions in an optical oscillator cavity. This cavity is formed by mirrors at both ends of a glass tube. The distance between these mirrors must be precisely adjusted to the intended laser frequency. When activated, the laser either produces light of a highly stable frequency, or does not produce any light at all.

Lasing action depends on quantum energy transitions occurring in the Helium-Neon gas, which must resonate within the precisely tuned oscillator cavity. If lasing does occur, the laser produces light with an inherent frequency stability of one part per million (1 ppm or $10^6$).

NIST (formerly the National Bureau of Standards) accepts the output of the HeNe laser in a vacuum as a *priori* traceable and not requiring calibration. While the inherent stability of the HeNe is 1 ppm, the stabilization techniques (page 33) can improve this performance to one part in one hundred million ($10^6$).

In actual use, either C moves while the interferometer remains stationary or *vice versa*. If C and the interferometer element move simultaneously, one cannot compute how far each one moved because there is no longer a stationary reference.

## *SINGLE FREQUENCY*

Comparing the single frequency interferometer to the Michelson design reveals more differences than similarities, except in concept. The Michelson design cannot determine the direction of motion, only the change in path length. Imagine the mirror ***C*** moving away from the interferometer and vibrating as it moves. Significant inaccuracies can be introduced in such a situation since light/dark changes would be counted by the computerized counter both while ***C*** is moving away and as ***C*** moves infinitesimally *toward* the interferometer, due to vibration. In order to make a practical instrument, the laser light is polarized by the beam splitter into its vertical and horizontal components. At the receiver (***O***), two detectors view the reflected beam; one through a $0^0$ polarizer, the other a $45^0$ polarizer. The $0^0$ detector is called the "sine detector", the $45^0$ the "cosine detector". The quarter wave plate ($\lambda/4$) provides an additional $45^0$ of rotation for both a $0^0$ and a $90^0$ output. By comparing the phase relationship between the waveforms, the receiver electronics can tell whether a fringe shift was caused by mirror ***C*** moving *towards* or *away* from the interferometer. An added benefit of this method is that it boasts the inherent resolution of the single frequency interferometer to *one eighth* of a wavelength of light. There are two fringes per wavelength and four counts per fringe. Two counts are generated by the sine and two by the cosine detector as each crosses zero (Figure 4).

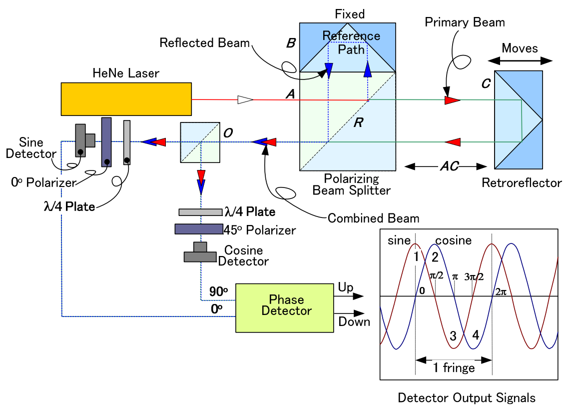


Figure 4

## *HETERODYNE (DUAL FREQUENCY)*

Dual frequency or *heterodyne* interferometers use a special variant of the single frequency HeNe laser employing the Zeeman split. Two frequencies components are generated by the Zeeman HeNe laser separated by approximately 1.8 MHz. Each component has an opposing circular polarization. This allows each frequency to be separated by polarization techniques. The operation of a heterodyne interferometer is more complex than that of the single frequency type. While the single frequency model looks at interference fringes resulting from different *lengths* of *AC* and *AB*, the heterodyne interferometer relies on Doppler shifts caused by *movement* of *C* to generate interference fringes.

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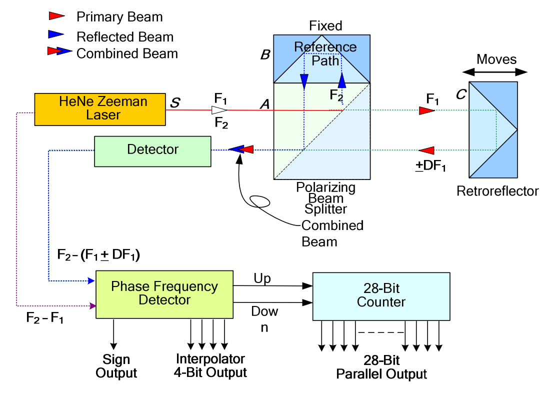


Figure 5

Figure 5 shows a typical heterodyne interferometer. The laser emits a beam of light which contains two separate frequencies, $F_1$ and $F_2$. They are polarized at right angles to one another. As the beam containing $F_1$ and $F_2$ passes through the interferometer module, $F_2$ is directed to B while $F_1$ passes through the polarizing beam splitter to C. As C moves, the frequency, $F_1$, will appear to shift based on the Doppler principle. As the mirror moves *toward* the interferometer module, $F_1$, will *increase*, yielding a *positive* change in $F_1$ ($\Delta F_1$). Think of the train whose whistle apparently increases in pitch as the train approaches. Movement of C *away* from A will cause $F_1$ to decrease, causing $\Delta F_1$ to be a *negative* number.

In the heterodyne system, $F_1$ and $F_2$ are recombined at the interferometer module to give the measurement signal: $F_2 - (F1 \pm \Delta F_1)$. Optics and electronics in the laser head create a reference signal equal to $F_2$-$F_1$. The measurement and the reference signals are combined, leaving only $\Delta F_1$, the rate of change of position C. This velocity (dx/dt) data can then be integrated to yield the position of C.

## *SINGLE FREQUENCY VS HETERODYNE INTERFEROMETERS*

Much has been said about the superiority of one type of interferometer over the other. If an application requires precise servo control of *final position*, the single frequency model, with its higher special resolution, will be preferred. Applications using interferometry for precise servo control of *position and velocity* generally favored the heterodyne approach, in the past. With the advent of newer high speed electronics, velocity is no longer a problem for single frequency interferometers.

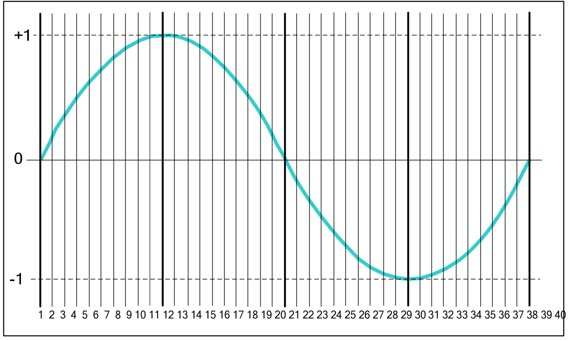
| *Single Pass* | *Single Frequency* | *Heterodyne* |
|---|---|---|
| Inherent Resolution | l/8<br>0.08 microns<br>3.11 minches | l/4<br>0.16 microns<br>6.22 minches |

Table 1

## *EXPANDED RESOLUTION*

Since sine and cosine detector output follows a predictable sinusoidal curve, intermediate distance values may be interpolated electronically (Figure 6). Resolution interpolations of 16X, 32X, 64X and much more are common.

Figure 6



While not required in most applications, the resolution of the interferometer may be increased optically. The optical path length *AC* is multiplied by folding the light beam back and forth 2 or 4 times with mirrors. With each folding, the resolution doubles because the number of “trips” taken by the light beam along the path *AC* has been doubled. Four back and forth passes is usually a practical limit for this technique. With each doubling, the maximum velocity of *C* which the interferometer can measure without “missing” counts is halved. Appendix B shows the combination of both optical and electronic resolution expansions.

### *VACUUM SPECIFICATION*

The performance parameters for laser interferometers are generally specified for vacuum operation. Air temperature, pressure, and humidity are all variables which can change the wavelength of the laser light (see Table 2).

*Table 2*

***To change Laser Wavelength By 1 part per million***

| *Change* | *By* |
|---|---|
| Temperature | 1°C<br>-2°C |
| Barometric Pressure | 2.5 mm Hg<br>0.1 in Hg |
| Relative Humidity | 30% |

Elaborate algorithms are available to correct for these effects. A common "specmanship" ploy in laser interferometry is to quote vacuum specifications as if they referred to operation in air. A string of disclaimers about the accuracy of the environmental sensors is then added.

### *GEOMETRIC ERRORS*

Laser interferometers are the preferred method for the precise control of motion. An ideal linear stage has only one degree of freedom. A real linear stage has six degrees off freedom (3 linear and 3 rotary). The challenge is to control the deviations from the ideal caused by the 5 unwanted degrees of freedom. Since the interferometer modules are mounted rigidly to the granite plate supporting the stage, they form an external frame of reference for measuring stage deviations. Rotary and linear encoders have a much more limited capability to measure and correct for stage errors. Frame of Reference which follows has a more detailed discussion.

### *ORTHOGONALITY ERROR*

X-Y stages are typically two single-axis stages stacked one on top of the other. The first problem presented by this arrangement is the degree to which the two stage halves can be made orthogonal. The mechanical standards and methods for performing this alignment generally limit its accuracy to ± 5 arc-seconds. For many applications, this single error exceeds the entire system error budget. For a 12 x 12 inch travel stage system, an orthogonality error of ± 5 arc seconds translates to 290.9 micro-inches or nearly 3 tenths of a thousandths (0.0003 inches or 7.39 microns).

In an interferometer-based system, ultimate accuracy is determined by the flatness of the mirrors (typically l/8) and the squareness of the X to the Y mirrors.

Careful alignment techniques can achieve mirror squareness of 1 to 2 arc-seconds. To reach nearly perfect orthogonality of ± 0.1 arc-seconds requires a very expensive optical part called an L-mirror.

Laser interferometers are particularly well suited for X-Y stage applications because of their ability to compensate for the mechanical inaccuracies of the stages, while also avoiding the Abbe' Errors introduced with the linear scales.

### *ABBE' ERRORS*

Ernst Abbe' (1840 – 1905), was a pioneer in optical and microscope design. "Abbe' Error" results if the object being measured is at an angle to and/or is displaced from the axis of measurement. Linear encoders by their design are always lower than the plane of measurement. The beams of a laser interferometer, however, can be made to coincide with the plane of measurement. On an X-Y stage, it is not uncommon for there to be a Abbe' Errors of 3 to 6 microns.

### *DEADPATH ERROR*

When laser interferometers are used on limited-travel mechanisms, it is good design practice to place the mirror or retroreflector as close to the interferometer module as possible. If a gap is always present, this excess measurement length is referred to as the "dead path", and will increase errors caused by environmental changes during a measurement.

### *COSINE ERRORS*

If the part or mechanism being measured does not travel parallel to the axis of the laser beam, an error is introduced which is proportional to the cosine of the induced angle, Q (Figure 7). An error of 0.08 degrees (4'48", or 0.013 radians) is equivalent to 1 ppm. Alignment to this degree of accuracy is attainable with careful technique.

**Cosine Errors in Laser Alignment**

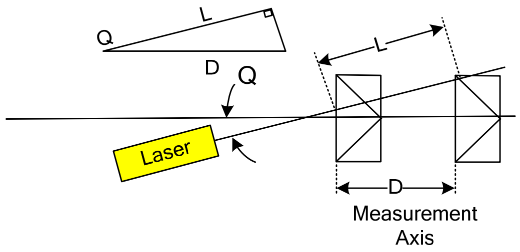


**Figure 7**

# *LASER FREQUENCY STABILIZATION METHODS*

### *TEMPERATURE CONTROL*

The simplest technique to stabilize laser frequency is by controlling the temperature of the laser tube. This, in turn, maintains the tube at constant length. As the laser tube expands from heating, various modes of the polarization components of the laser light propagate in the cavity. By using the amplitude of the sine and cosine polarizations as a reference, special circuitry in the laser head can add heat or provide cooling to control the length of the laser cavity. This simple but effective technique locks the polarization modes within the laser cavity to achieve equal amplitude of the sine and cosine waveforms.

### *MECHANICAL*

Another technique uses piezo-electric elements to position one of the laser cavity mirrors axially, thus varying the cavity length. This technique is effective, but associated with much higher manufacturing cost.

### *COMPENSATION FACTOR CALCULATIONS*

The wavelength (λ) of a single-frequency HeNe laser *in a vacuum* is 632.991269 x $10^9$ meters, or 632.99 nanometers. In air, λ will = 1/**N** times λ in a vacuum. The compensation factor **N** may be calculated with a precision of one tenth ppm using the following formula. Where **P** = Barometric pressure in millimeters of mercury (mmHg), **T** = Temperature in degrees Celsius ($^0$C), and **R** = Relative humidity in percent (%) (NB: “50%” would be 50, not 0.50)

$$\mathbf{N} = 1 + (0.3836391 \times 10^{-6}\,\mathbf{P}) \times \left[\frac{1 + 10^{-6}\,\mathbf{P}\,(0.817 - 0.0133\,\mathbf{T})}{1 + 0.0036610\,\mathbf{T}}\right] - 3.3033 \times 109\,\mathbf{R}\,e^{0.057627\mathbf{T}}$$

Example: **P** = 762 mmHg, **T** = 20$^0$C, & **R** = 50%

Then **N** = 1.00027202, 1/**N** = 0.99972805

And λ/8 = 0.791239 microns

| *Single-Frequency HeNe Laser Wavelength* | | |
|---|---|---|
| Lambda | In Vacuum (Microns) | In Standard Air (Microns) |
| λ | 0.6329913 | 0.6328192 |
| λ/2 | 0.3164956 | 0.3164100 |
| λ/4 | 0.1582478 | 0.1582048 |
| λ/8 | 0.0791239 | 0.0791024 |
| λ/16 | 0.0395620 | 0.0395512 |

| *Laser Optical and Interpolated Resolution* | | | | | | |
|---|---|---|---|---|---|---|
| | Retroreflector - Single Pass | | Plane Mirror - 2 Pass | | Plane Mirror - 4 Pass | |
| | Wave Length | Nano-Meters | Wave Length | Nano-Meters | Wave Length | Nano-Meters |
| Single Frequency | | | | | | |
| Inherent Resolution | λ/28 | 79.124 | λ/16 | 39.562 | λ/32 | 19.781 |
| Divide by 10 | λ/480 | 7.912 | λ/160 | 3.956 | λ/320 | 1.978 |
| Divide by 16 | λ/128 | 4.945 | λ/256 | 2.473 | λ/512 | 1.236 |
| Divide by 32 | λ/256 | 2.473 | λ/512 | 1.236 | λ/1024 | 0.618 |
| Dual Frequency | | | | | | |
| Inherent Resolution | λ/24 | 158.248 | λ/8 | 79.124 | λ/16 | 39.562 |
| Divide by 10 | λ/40 | 15.825 | λ/80 | 7.912 | λ/160 | 3.956 |
| Divide by 16 | λ/64 | 9.890 | λ/108 | 4.945 | λ/21 | 2.473 |
| Divide by 32 | λ/128 | 4.945 | λ/216 | 2.473 | λ/512 | 1.236 |
| | Vacuum Wavelength = 632.991269 nanometers | | | | | |

# *ACCURACY, RESOLUTION, AND PRECISION*

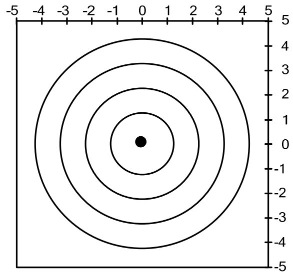
Careless use of the terms, accuracy, resolution, and precision (repeatability), have resulted in considerable confusion in the motion control industry. To compound this confusion, these terms are often used interchangeably.

The easiest of the three to define is resolution: it is the smallest increment of motion which can be commanded in a system.

Accuracy and precision are more difficult to define and are measured using statistical techniques. The system under test is directed to perform a number of identical positioning moves. The result of these trials are measured independently and the actual versus expected results compared statistically. Accuracy measures the statistical difference between the desired and actual result. The smaller the difference, the more accurate the system is said to be. If the system statistically produces the same result in each of the trials, it can be said to be precise. Systems can be accurate and not precise and also inaccurate but precise. Confused?

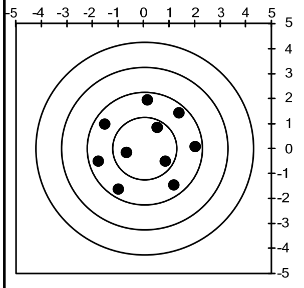
Perhaps an example would be helpful. Imagine 3 rifles clamped to a bench and very carefully aimed at the center of a target. Ten rounds are fired from each rifle and the target is inspected. The smallest circle which circumscribes all ten holes is drawn. Very roughly, the diameter of this circle measures precision and the offset of the center from the center of the 4th target determines accuracy.

Accurate
Precise



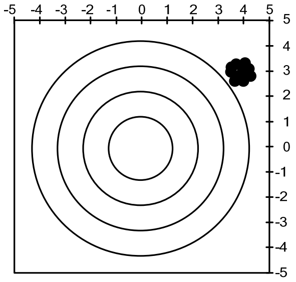
All ten shots of Rifle 1 have pierced the center target at exactly the same spot. The rifle is both accurate and precise.

Accurate
Not Precise



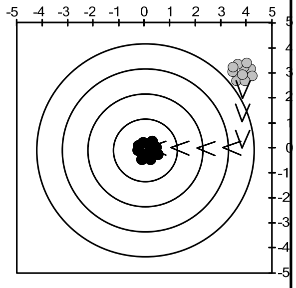
Rifle 2 is accurate but not precise. On the average, the shots group uniformly around the center of the bulls-eye despite the fact that they are scattered over a fairly large circle. Hence, Rifle 2 is not precise.

Not Accurate
Precise



Rifle 3 produces a tight cluster of shots (precise) but the center of the cluster is displaced from the center of the target. This rifle is precise but inaccurate.

Accurate (adjusted)
Precise



If the aiming point on Rifle 3 is offset –3 units in Y and –4 units in X, the result would be as shown above. A precise system can be forced to be accurate by measuring its performance and adjusting for its inconsistent positioning errors.

# *ULTIMATE RESOLUTION AND ACCURACY*

### *Most Demanding Applications*

Laser interferometers are used almost exclusively in leading edge applications for positioning systems. Why? No other technology can achieve the nanometer resolutions and sub-micron area accuracies required for fabricating chrome-on-glass and diffraction masks for silicon wafers and the sub-micron overlay registration required for wafer steppers.

### *Resolution ≠Accuracy*

For decades, the makers of linear encoders would have designers believe that the resolution of their products was equal to their accuracy. Nothing could be further boundaries of precision motion control, we recommend that you read Frame of Reference which is on page ____ of this catalog. In it, you will learn the pivotal role played by having your feedback element mounted in an external frame of reference to measure and correct for geometric errors in stage construction and alignment.

### *Difficult and Expensive to Use*

Laser interferometers have an undeserved reputation for being difficult to apply. Application difficulties are usually due to the bright light thrown on marginal mechanical, optical, and motion control systems designs.

In terms of being expensive, there is no denying that laser interferometer feedback systems can cost more than linear encoders. However, this difference need not be 2x or 3x, but is more like 50% when constructed with MotionX components.

### *The Rubber World*

In the sub-micron world, even the most massive structures must be considered to be plastic at best and rubber at worst. Vibration isolation for the entire system and the resonance frequencies of critical components are often overlooked until laser interferometer feedback is installed.

### *Drive Considerations*

The torsional wind-up and stick/slip characteristics of motor/leadscrew combinations are often shown for the first time by upgrading to laser interferometers. Consider replacing these drive components with direct drive linear motors. There is little or no increase in cost and system performance generally improves dramatically. This is particularly true in applications requiring both high resolution/slow speed positioning and rapid, full-travel slew rates.

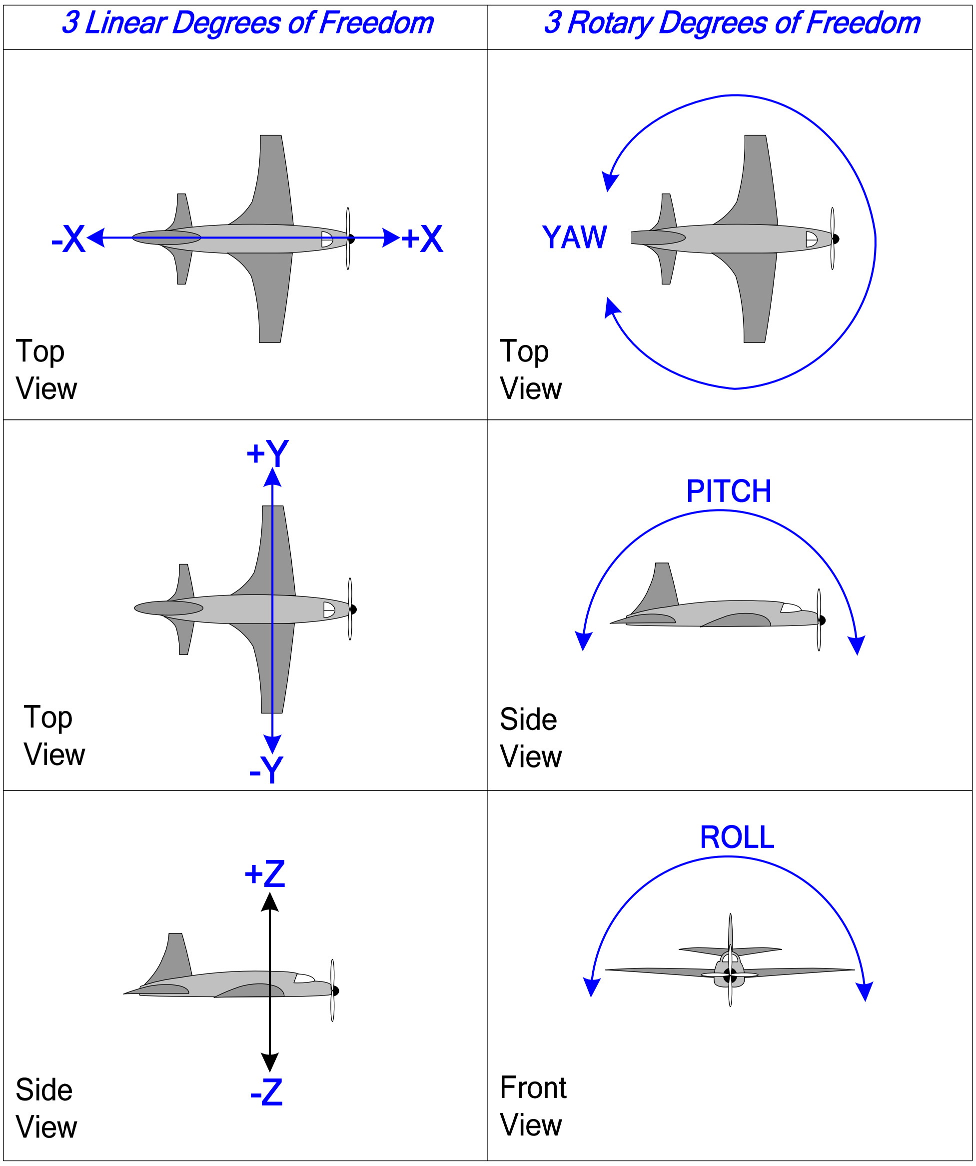
### *System Design and Integration*

As systems designers and integrators as well as component suppliers, MotionX stands ready to assist you from initial design to full production. We have worked primarily with Fortune 500 companies over almost 2 decades of leading edge applications. Write, call, or email us. We have a wealth of information to share.

## *ACHIEVING ULTIMATE ACCURACY*

### *Wafer Step Stage*

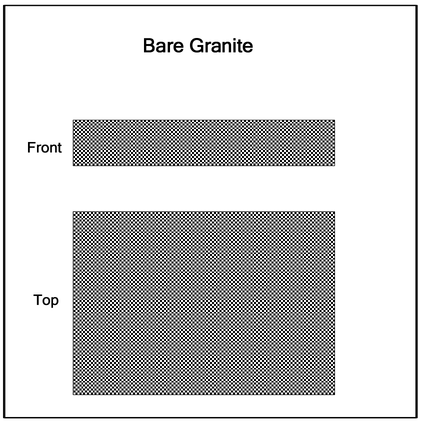
One of the most advanced positioning systems in the world is at the heart of every micro-lithographic wafer stepper for producing advanced microprocessor and DRAM semiconductors. These simple, elegant designs allow positioning accuracy and repeatability for the most dense semiconductor chips emerging from production wafer fabs around the world. To accomplish this difficult task, every aspect of precision positioning must be exploited to the fullest.



### *6 Degrees of Freedom*

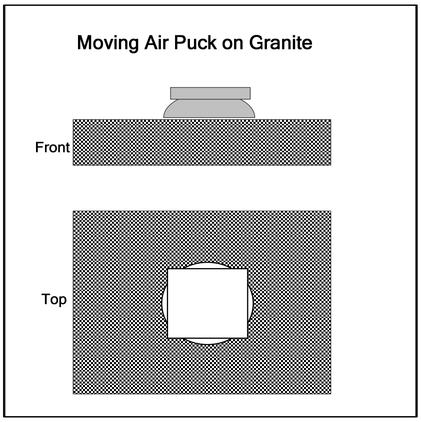
The wafer itself can be thought of as flying an airplane in space with six, independent degrees of freedom; three linear and three rotary as shown. The three linear degrees are labeled X, Y and Z. The three rotary degrees are pitch, roll

To make wafer stepper stages, designers use the most precision fabrication techniques available. These are the techniques developed for optical grinding and polishing. Their next step was to establish a rigid and stable frame of reference for the entire machine. By designing a huge granite slab and grinding and polishing its upper surface optically flat, the engineers solved a number of problems in one step.



## *Controlling Z, Roll and Pitch*

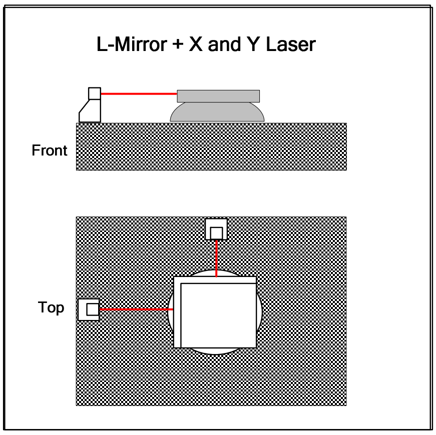
By flying a large, air-bearing puck on the extremely flat granite, the stage can be made to fly within a millionth of an inch of the granite surface. Vertical deviations in Z are eliminated; as are the two rotations about horizontal axes, roll and pitch.



## *Stage Position Feedback*

To track the location of the stage on the granite's surface, a stable frame of reference is established. Laser interferometer/receiver modules are mounted on pedestals and those pedestals are bolted directly to the upper surface of the granite.

Mirrors are mounted to the top of the air-bearing stage. Laser beams from the interferometer/ receiver modules are reflected off of these mirrors and returned to the modules. Readings from the modules accurately compute the relative distance from the module to the mirror in both X and Y.



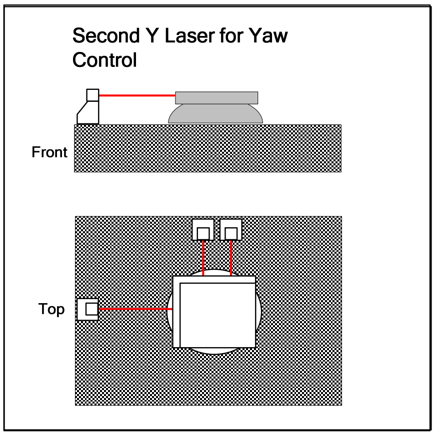
The mirrors must be extremely flat and as orthogonal possible. If the mirrors are not flat, the laser would be unable to determine whether actual stage movement or deviations in flatness are causing a change in the interferometer readings.

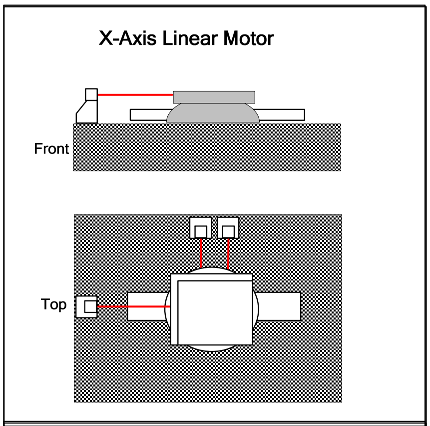
## *Establishing Axis Orthogonality*

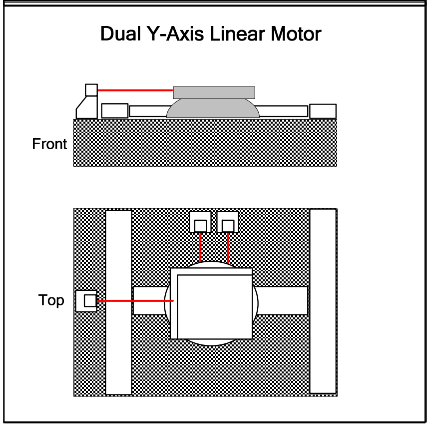
Mirror orthogonality is essential because positioning deviations of 0.1 micron can be caused by each arc-second of orthogonality error. Expensive, optical lapping techniques can produce orthogonality of 0.1 arc-seconds or less. For less demanding applications, alignment techniques can be employed to physically set two independent mirrors square to better than 2 arc seconds.

## *Correcting Yaw Errors*

Yaw is the rotation of the stage around the axis normal to the granite surface. Using single laser beams in both X and Y, stage rotation around its center point would be undetected by the interferometers. However, by moving the Y laser beam off the center Y axis of the mirror and adding a second laser beam, a lever arm is established which show a difference if the mirror does not move absolutely normal to the two laser beams.







A single linear motor is used to drive the air-bearing stage

### *Laser Wavelength Stability*

The HeNe laser light wavelength for a single frequency (DC) laser is a primary standard recognized by the National Institute of Standards and Technology (NIST). This wavelength standard only applies to measurements made in a vacuum, however. In air, the wavelength of the laser light varies according to the density of the air in the laser path. Air pressure, temperature, and relative humidity combinations exert subtle but predictable changes to the laser wavelength. New values for the laser wavelength in air are tabulated or may be computed from a formula. By measuring the air density and applying the appropriate correction, the potential errors induced by laser wavelength deviation can be eliminated.

### *Environmental Control*

Of course, for the type of application being described, the entire instrument would be kept in a temperature controlled environment. Since materials expand and contract with temperature, control is usually better than +/- 1.0 $^0$C. Humidity is also controlled but within looser limits. Air pressure is more difficult to control but double doors with air locks are used in all semiconductor fabs to prevent air pressure spikes from disrupting the process equipment.

### *Elements of Ultimate Accuracy*

Hopefully it will be easier to understand how other positioning systems fall down in their ability to achieve accurate positioning. Take away the environmentally-controlled clean room, the laser interferometer's external frame of reference, the flat granite to clamp roll and pitch errors and Z-axis deviations, the flat and orthogonal mirrors to control yaw, straightness, and squareness, and accuracy and repeatability suffer badly.

## *FRAME OF REFERENCE*