Instruction Manual
For the PASCO
Models OS-9261,9262, 9263

SPEED OF LIGHT

PASCO Scientific
Hayward CA

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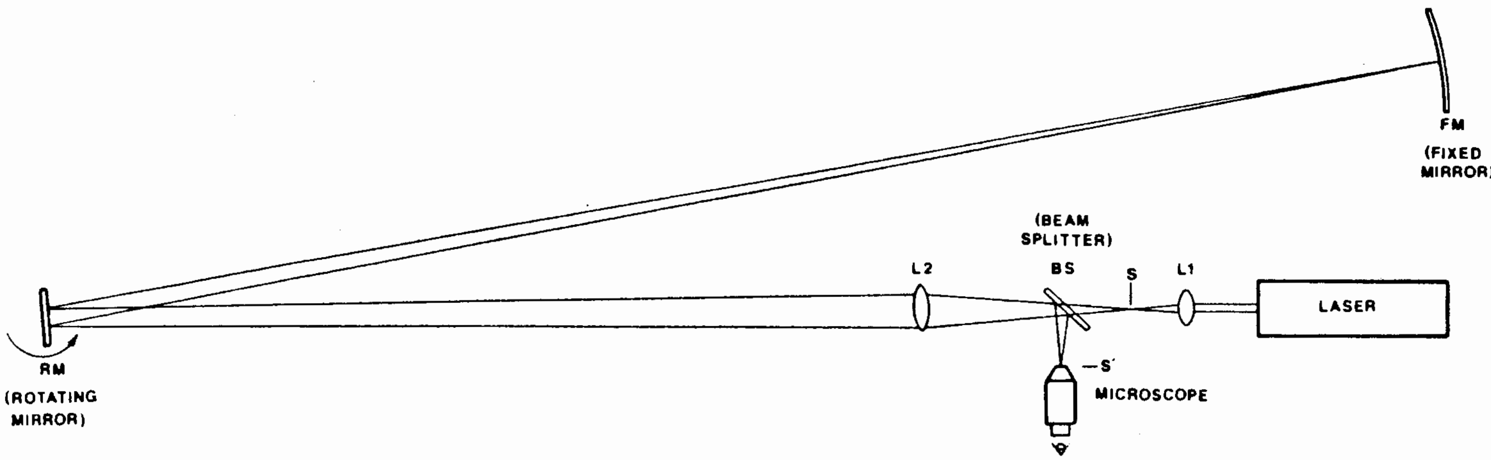
THE FOUCAULT METHOD



In this experiment you will use a method that is basically the same as that developed by Foucault in 1862. A diagram of the experimental setup is shown above.

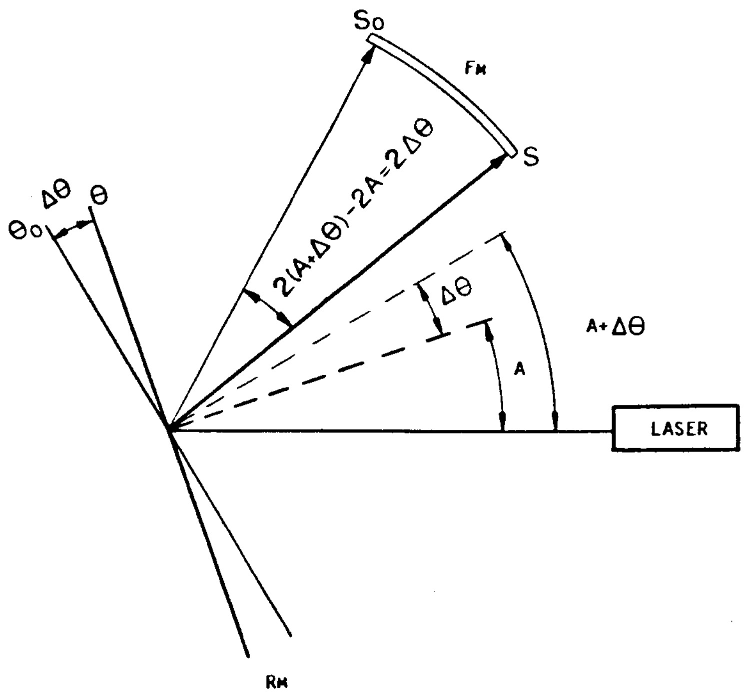
With all the equipment properly aligned and with the rotating mirror stationary, the optical path is as follows. The parallel beam of light from the laser is focused to a point image at s by lens L_1. Lens L_2 is positioned so that the image point at s is reflected from the rotating mirror (R_m) and is focused onto the fixed, spherical mirror (F_m). F_m reflects the image back along the same path to again focus the image at s.

In order that the reflected point image can be viewed through the microscope, a beam splitter is placed in the optical path, so a reflected image is also formed at point s'.

Now suppose R_m is rotated slightly so the reflected beam strikes F_m at a different point. Because of the spherical shape of F_m, the beam will still be reflected directly back toward R_m. An image of the source point will still be formed at s and s'. The only significant difference is that the point of reflection on F_m has changed.

However, when R_m is rotated continuously at high speeds, the image is no longer formed at s and s'. This is because, with R_m rotating, a light pulse that travels from R_m to F_m and back finds R_m at a different angle when it returns then when it was first reflected. As will be shown in the following derivation, by measuring the displacement of the image, the rate of rotation of R_m, the distance from R_m to F_m, and the magnification of L_2, we can determine the speed of light.

To begin, we must determine how the point of reflection on F_m relates to the rotational angle of R_m. In the following diagram, $S_0 - S$ is the displacement of the point of reflection on F_m caused by a rotation of R_m by an amount $\Theta_o - \Theta$. The size of the mirrors and the rotation of R_m have been greatly exaggerated for clarity.

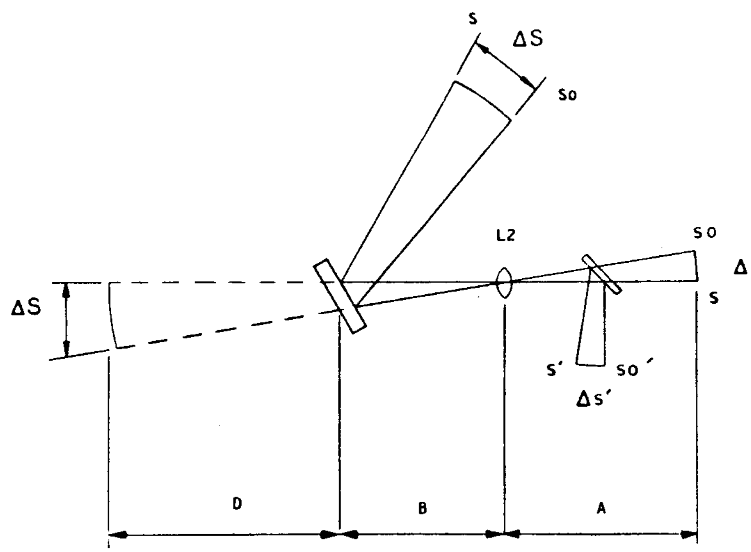


In the diagram, angle A is the angle of incidence of the light from the laser when R_m is at angle Θ. Since the angle of incidence equals the angle of reflection, the angle between the incident and reflected rays is just 2A. When R_m is rotated by an angle $\Delta\Theta$ $(= \Theta_o - \Theta)$, the angle of incidence increases to $A + \Delta\Theta$, and the angle between the incident and reflected rays increases to $2(A + \Delta\Theta)$. The angle between the two reflected rays, therefore, is $2(A + \Delta\Theta) - 2A = 2\Delta\Theta$. If D is the distance between R_m and F_m:

$$S_o - S = D2\Delta\Theta = 2D(\Theta_o - \Theta) \qquad (1)$$

Now suppose R_m is rotating, and a single, short pulse of light from the laser strikes R_m when it is at angle Θ. The pulse will be reflected to point S on F_m. But, by the time the pulse returns to R_m, R_m will have rotated to a new angle, say angle Θ_o. With R_m at Θ_o, a point reflected from S_o would be focused at point s. Clearly the point reflected from S will not.

However, S is in the focal plane of Lens L_2, a distance ΔS away from the central point of focus, S_o. To determine where the point image reflected from point S will be focused, it is convenient to remove the confusion of the rotating mirror and the beam splitter by looking at their virtual images, as shown below. The critical geometry is the same as for the reflected images.



Thinking in terms of the virtual images, the problem becomes a simple application of thin lens optics. An object of height ΔS in the "plane" of F_m will be focused at the plane of point s with a height of $(-i/o)\Delta S$. Here i and o are the distances of the lens from the image and object, respectively, and the minus sign corresponds to the inversion of the image. As shown, reflection from the beam splitter forms a similar image of the same height. Therefore, ignoring the minus sign since we are not concerned that the image is inverted:

$$\Delta s' = s_o' - s' = \frac{S_o - S}{(D + B)/A} \qquad (2)$$

Combining equations 1 and 2, the displacement of the image point relates to the initial and secondary positions of R_m by the formula:

$$s_o' - s' = \frac{2DA(\Theta_o - \Theta)}{D + B} \quad (3)$$

$\Theta_o - \Theta$ depends on the the rotational rate of R_m and on the time it takes the light pulse to travel back and forth between R_m and F_m, a distance of 2D. The equation for this relationship is given by:

$$\Theta_o - \Theta = 2Dw/c \quad (4)$$

where c is the speed of light and w is the rotational rate of the mirror in radians/sec. (2D/c is the time it takes the light to travel from R_m to F_m and back.)

Using equation 4 to replace $\Theta_o - \Theta$ in equation 3 gives:

$$s'_o - s' = \frac{4AD^2w}{c(D + B)} \quad (5)$$

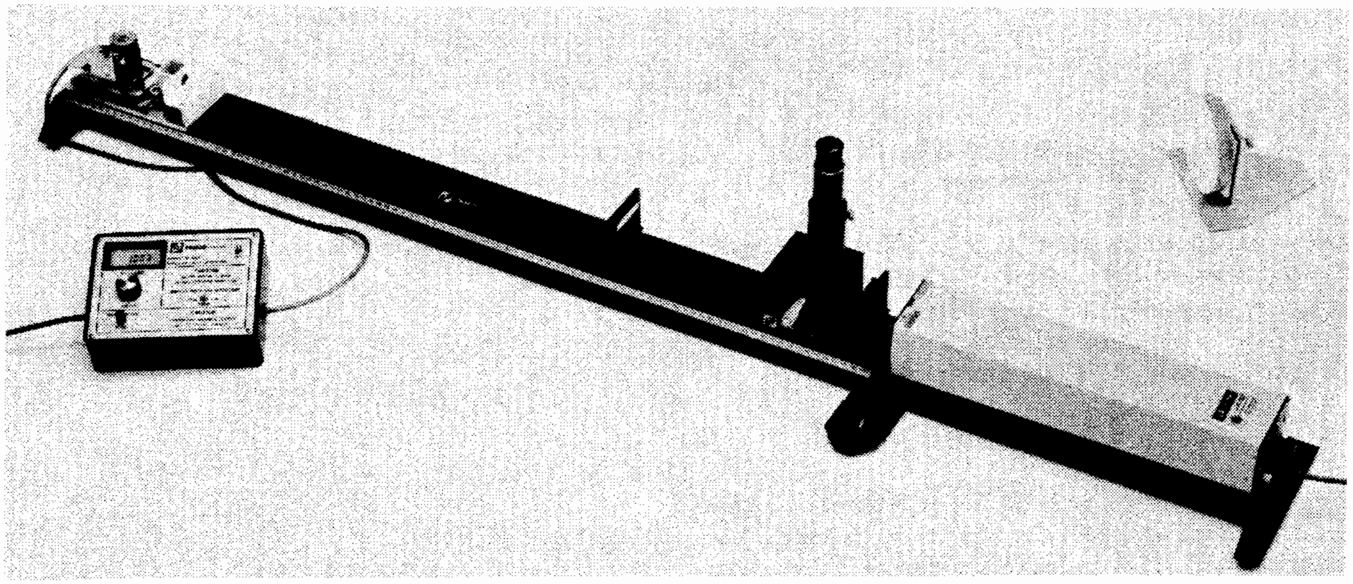
Therefore,

$$c = \frac{4AD^2w}{(D + B)(s'_o - s')} \quad (6)$$

Equation 6 was derived on the assumption that the image point is the result of a single, short pulse of light from the laser. But looking back at equations 1-4, the displacement of the image point depends only on the difference in the angular position of R_m in the time it takes for the light to travel between the mirrors. The displacement does not depend on the specific mirror angles for a given pulse.

If we think of the continuous laser beam as a series of infinitely small pulses, the image due to each pulse will be displaced by the same amount. All these images displaced by the same amount will, of course, result in a single image. By measuring the displacement of this image, the rate of rotation of R_m, and the relevant distances between components, the speed of light can be measured.

EQUIPMENT



The equipment provided with the OS-9262 Complete Speed of Light Apparatus is shown above. It includes:

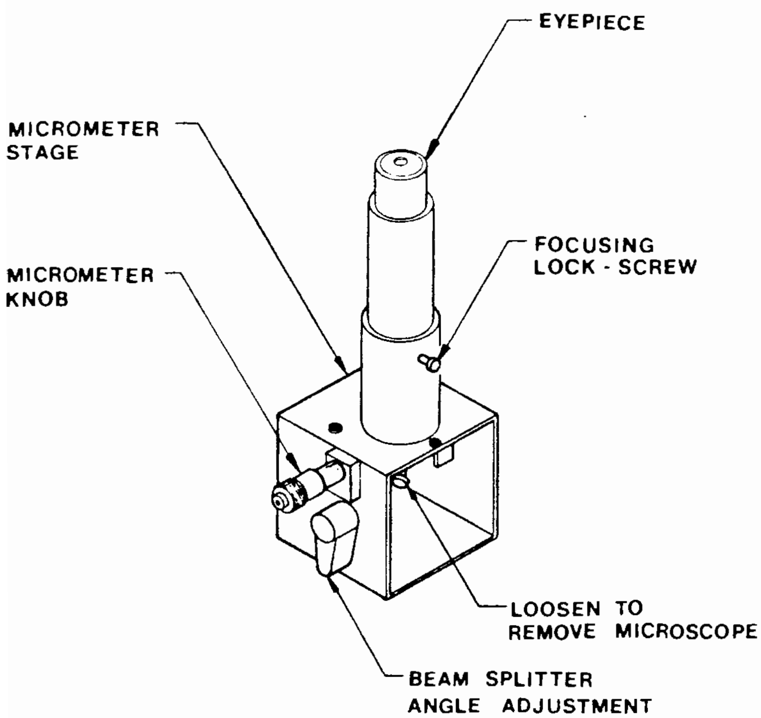
CAUTION: Before turning on the motor for the rotating mirror, carefully read the cautionary notices in the section of this manual entitled "MAKING THE MEASUREMENT".

1. <u>High Speed Rotating Mirror Assembly</u>

   This assembly comes with its own power supply and digital display of rotation speed. The mirror is one-cm in diameter and is flat to within 1/4 wavelength. It is supported by high speed ball bearings, mounted in a protective housing, and driven by a DC motor with a mylar belt. A plastic lock-screw is provided to hold the mirror in place during the alignment procedure.

   An optical detector and digital readout provide measurements of mirror rotation speed to within 0.1% and 1 rev/sec. The digital readout and the controls for mirror rotation are on the front panel of the power supply. Rotation is reversible and the rate is continuously variable from 100 to 1,000 rotations/sec. In addition, holding down the MAX REV/SEC button will bring the rotation speed quickly to its maximum value at approximately 1,500 revolutions/sec.

2. Measuring Microscope



The 90X microscope is mounted on a micrometer stage for precise measurements of the image point displacement. Measurements are most easily made by visually centering the image point on the microscope cross-hairs. The micrometer graduations then permit the displacement to be resolved to within 0.005 mm.

To focus the cross-hairs, slide the eyepiece up or down in the microscope. To focus the microscope, loosen the lock-screw on the side of the mounting tube and slide the microscope up or down within the tube. In locating the image point, it is sometimes helpful to remove the microscope from the micrometer stage. This can be done by loosening the lock-screw that projects diagonally from one corner of the micrometer stage.

3. Fixed Mirror--The fixed mirror is a spherical mirror with a radius of curvature of 12.5 meters. It is mounted to a stand and has separate X and Y alignment screws.

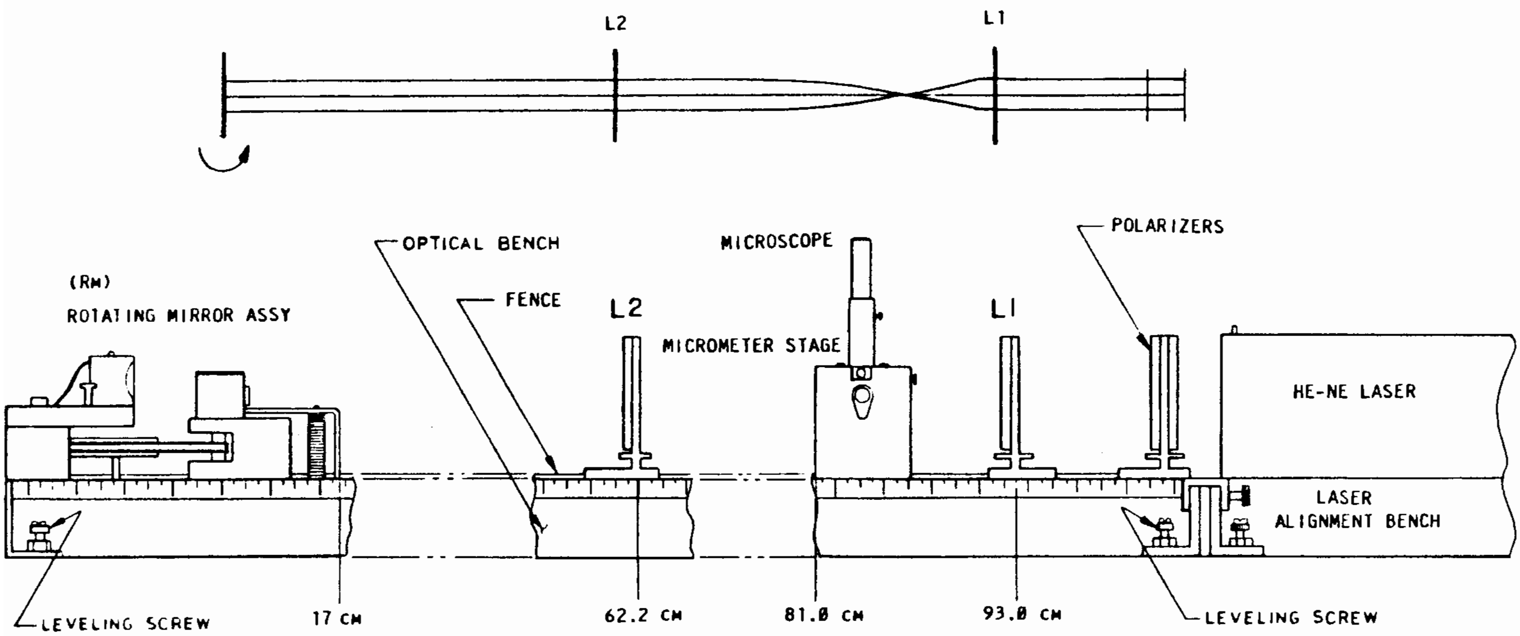
4. OS-9171 Laser with the OS-9172 Alignment Bench--The 0.5 mW, TEM_{00} mode, random polarization laser has an output wavelength of 632.8 nm. It comes with an Alignment Bench for precise, stable positioning of the laser.

5. OS-9103 Optical Bench--The 1.0 meter long optical bench provides a flat, level surface for easy alignment of the optical components. The bench is equipped with a one meter scale, four leveling screws, and a magnetic top surface. A raised edge on the back of the bench provides a guide for aligning components along the optical axis.

6. Optical Components--The optical components attach magnetically to the optical bench. They include the OS-9132, 48 mm FL Convex Lens; OS-9135, 252 mm FL Convex Lens; two OS-9109 Polarizers (not shown); and three OS-9107 Component Carriers.

7. Two Alignment Jigs--The alignment jigs are not shown in the above photograph. They are right-angled aluminum pieces with 2 mm diameter holes and are used to align the laser beam onto the center of the rotating mirror.

ALIGNING THE EQUIPMENT



The following alignment procedure is tailored for those using the PASCO OS-9261 Complete Speed of Light Apparatus. For those using only some of the components of that system, the general procedure is the same, though the details depend on the optical components being used. In any case, read the following procedure carefully; the summary at the end of this section should help generalize the instructions for use with different equipment.

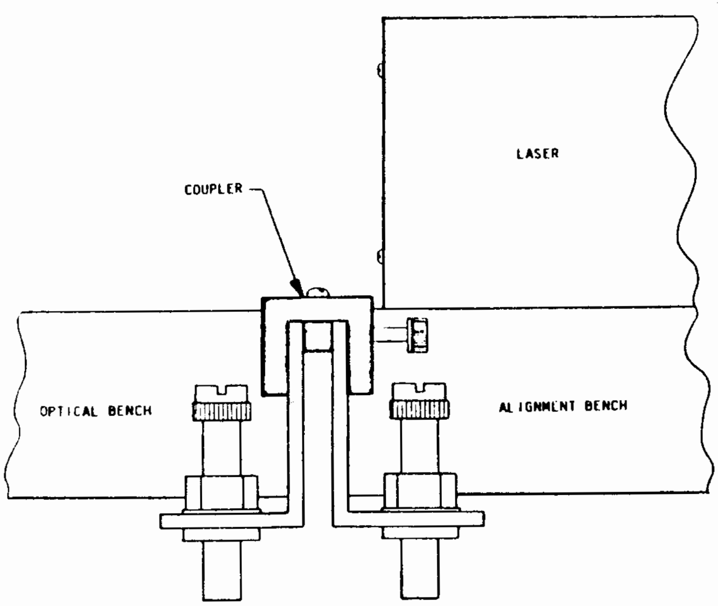
IMPORTANT: The alignment procedure is critical, not only for getting good results, but for getting any results at all. If the optical components are not properly aligned, the measurement can not be made. To avoid frustration, follow this alignment procedure carefully.

For reference, the above diagram shows the approximate positioning of the components with respect to the metric scale on the side of the optical bench. The exact placement of each component depends on the position of the fixed mirror (F_m), and should be determined by carefully following the steps of the alignment procedure as described below.

All component holders, the beam splitter assembly, and the metal base for the optical mirror assembly should be mounted flush against the "fence" of the optical bench. (The fence is the protruding metal lip that runs the length of the optical bench, on the side opposite the metric scale.) This will insure that all components are mounted at right angles to the beam axis.

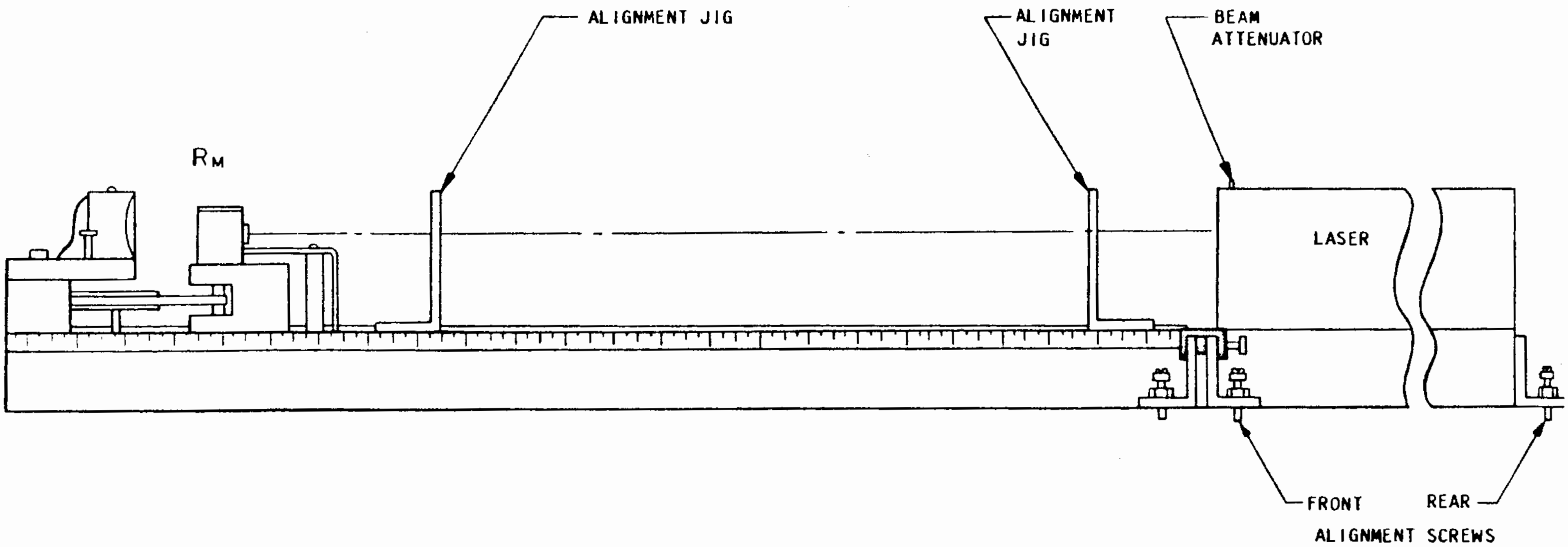
1. Place the optical bench on a flat, level surface. Adjust the optical bench leveling screws so the bench is level and stable.

2. Place the laser, mounted on the laser alignment bench, end-to-end with the optical bench, at the end corresponding to the 1-meter mark of the metric scale. Place the bench couplers as shown below, but do not tighten the coupler screws.



3. Mount the rotating mirror assembly on the opposite end of the bench. Be sure the base of the rotating mirror assembly is flush against the fence of the optical bench and align the front edge of the base with the 17 cm mark on the bench.

4. Align the Laser:



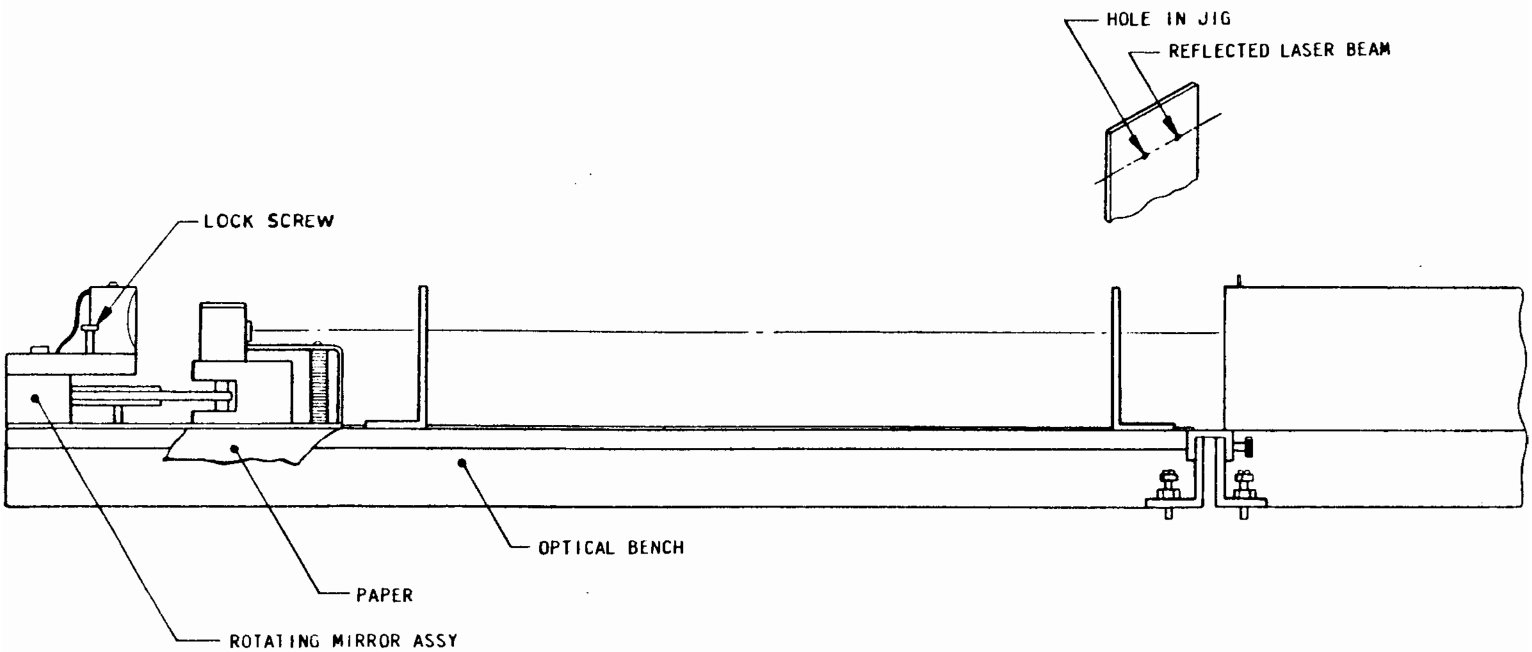
The laser must be aligned so the beam strikes the center of the rotating mirror (R_m). Two alignment jigs are provided for this purpose. Place one jig at each end of the optical bench as shown above, with the edges flush against the fence of the bench. When properly placed, the holes in the jigs define a straight line that is parallel to the axis of the optical bench.

Turn on the laser. Check that the beam attenuator on the top of the laser, directly above the aperture, is fully open.

CAUTION: Do not look into the laser beam, either directly or as it reflects from either mirror. Also, when arranging the equipment, be sure the beam path does not traverse an area where someone might inadvertently look into the beam.

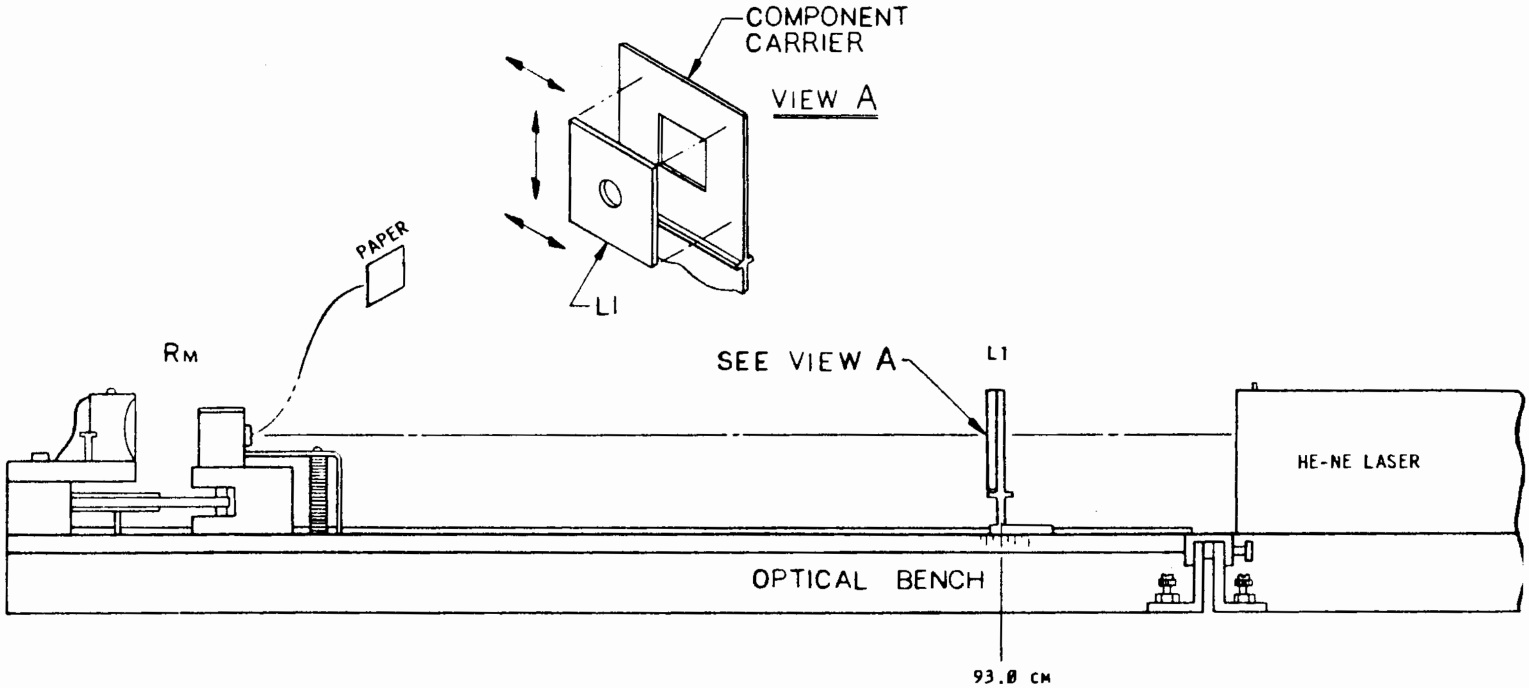
Adjust the position of the front of the laser so the beam passes directly through the hole in the first jig. (Use the two front leveling screws to adjust the height. Adjust the position of the laser on the alignment bench to adjust the lateral position.) Then adjust the height and position of the rear of the laser so the beam passes directly through the hole in the second jig.

To fix the laser in position with respect to the optical bench, tighten the screws on the bench couplers. Recheck the alignment of the laser.



5. Align the Rotating Mirror: R_m must be aligned so its axis of rotation is vertical and perpendicular to the laser beam. Rotate R_m so that the laser beam reflects back toward the hole in the alignment jig. Be sure to use the silvered side of the mirror as the reflecting surface, and tighten the lock-screw on the rotating mirror assembly just enough so R_m holds its position as you adjust its rotation.

   If needed, use pieces of paper to shim between the rotating mirror assembly and the optical bench so that the laser beam is reflected back through the holes in both jigs. **NOTE:** The beam need not go through the hole in the second jig, but it must strike the second jig at the same height as the hole. Remove both alignment jigs.



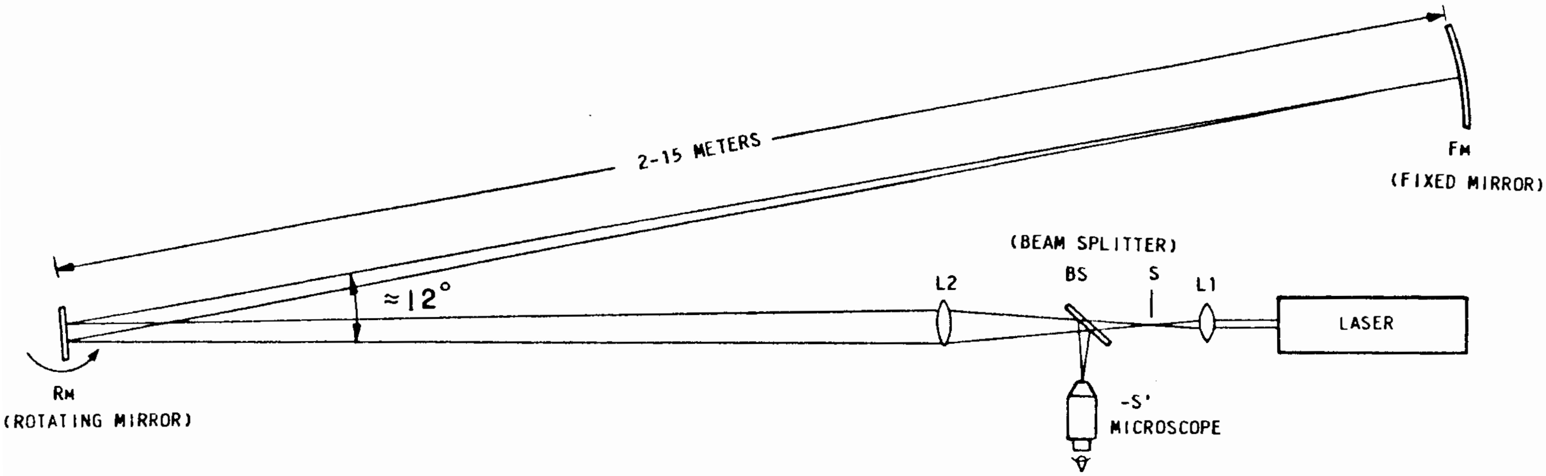
6. Mount the 48 mm focal point lens (L_1) on the optical bench so the center line of the component carrier is aligned with the 93.0 cm mark on the metric scale. Place a piece of paper in front of the window of the rotating mirror enclosure to see the beam. Without moving the component carrier, slide L_1 as needed on its component carrier to center the beam on R_m. (Notice that L_1 has spread the beam at the position of R_m.)

7. Mount the 252 mm focal point lens (L_2) on the optical bench so the center line of the component carrier aligns with the 62.2 cm mark on the bench. As for L_1 in step 6, adjust the position of L_2 on the component carrier so the beam is again centered on R_m.

8. Place the beam splitter and microscope assembly on the optical bench so the front edge of the micrometer stage is aligned with the 81.0 cm mark on the bench. The lever that adjusts the tilt of the beam splitter should be on the same side as the metric scale of the optical bench. Position this lever so it points directly down.

> **CAUTION:** Do not look through the microscope until the polarizers have been placed between the laser and the beam splitter. See step 11.

The beam splitter will slightly alter the position of the beam. Readjust L_2 on the component carrier so the beam is again centered on R_m.



9. Place the fixed mirror (F_m) at a distance of from 2 to 15 meters from R_m, as shown in the above diagram. The angle between the axis of the optical bench and the line between R_m and F_m should be approximately 12-degrees. (If it is greater than 20-degrees, the reflected beam will be blocked by the rotating mirror enclosure.) Also be sure F_m is not on the same side of the optical bench as the micrometer knob, so you will be able to make the measurements without blocking the beam.

   Position R_m so the laser beam is reflected back toward F_m. Place a piece of paper in the beam path to locate the beam and "walk" the beam back toward F_m. Adjust the position of F_m so the beam strikes it in the center. (A piece of paper against the surface of the mirror will make it easier to see the beam.)

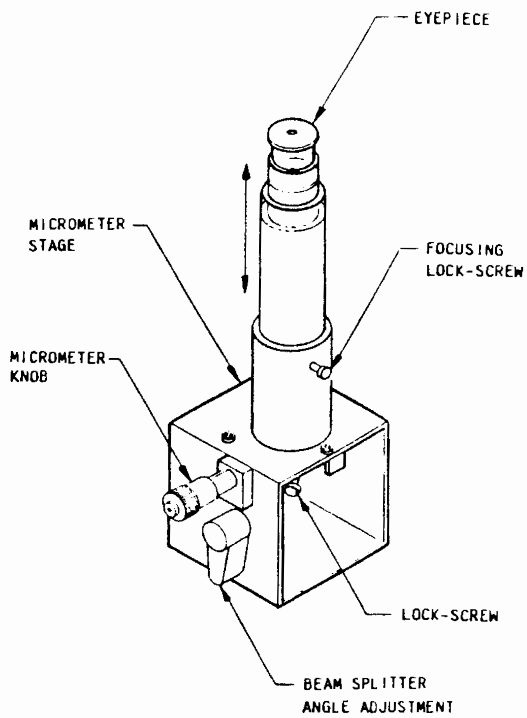
> **NOTE:** Best results are obtained when F_m is 10 to 15 meters from R_m. (See "NOTES ON ACCURACY" near the end of this manual.)

10. With a piece of paper still against the surface of F_m, slide L_2 back and forth along the optical bench to focus the beam to the smallest possible point on F_m. Then adjust the two alignment screws on the back of F_m so the beam is reflected directly back to the center of R_m. This step is best performed with two people; one adjusting F_m, and one watching the beam position at R_m.

11. Place the polarizers (attached to either side of a single component holder) between the laser and the beam splitter. Begin with the polarizers at right angles to each other, than rotate one until the image in the microscope is bright enough to view comfortably.

12. Bring the cross-hairs of the microscope into focus by sliding the microscope eyepiece in and out. Focus the microscope by loosening the lock-screw and sliding the scope up and down. If the apparatus is properly aligned, you will see the the point image through the microscope.

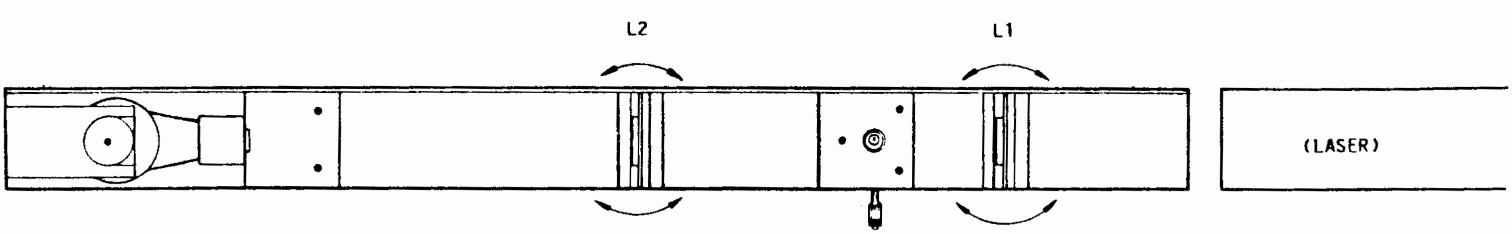
If you do not see the point image, vary the tilt of the beam splitter slightly (no more than a few degrees) and turn the micrometer knob to vary the transverse position of the microscope until the image comes into view.

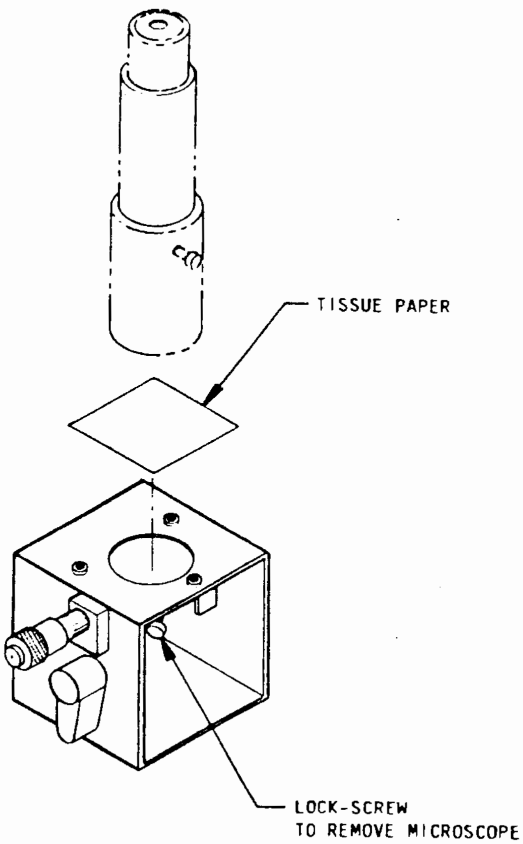


IMPORTANT:

In addition to the image point, you may also see some extraneous beam images resulting, for example, from reflection of the laser beam from L_1. To be sure you are observing the right image point, place a piece of paper between R_m and F_m while you watch the image in the microscope. If the point does not disappear, it is not the correct image.

There may also be interference fringes visible in the microscope. These fringes cause no difficulties as long as the point image is clearly visible. However, the fringes and extraneous beam images can sometimes be removed without losing the point image. This is done by turning L_1 or L_2 slightly askew, as shown below.

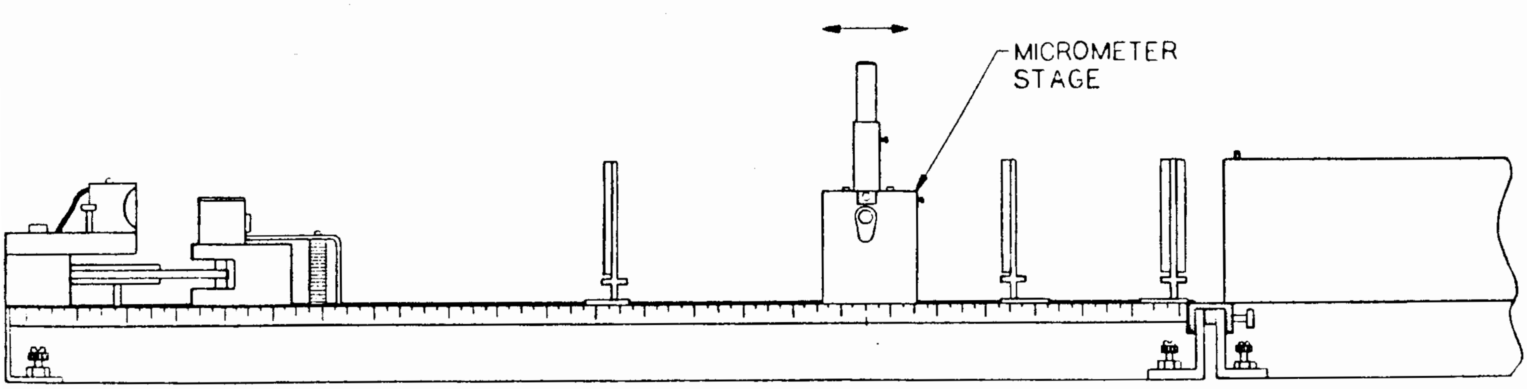




If you still find no point image, try adjusting the longitudinal position of the micrometer stage on the optical bench, as shown below. If this does not work, recheck the alignment beginning with step 1.

When you find the point image, focus the microscope for the sharpest possible image. Avoid sliding the microscope tube more than about a centimeter in its mounting tube. If necessary, adjust the longitudinal position of the beam splitter along the optical bench, as shown below, so the image point lies within the focal range of the microscope.

If you still can not find the point image, loosen the screw that attaches the microscope to the micrometer stage. As shown above, remove the microscope and place a piece of tissue paper over the hole in the stage to locate the beam. Adjust the beam splitter angle and the micrometer stage position to center the point image in the microscope hole.



Alignment Summary

1. Align the laser so the laser beam strikes the center of R_m.
2. Adjust the rotational axis of R_m perpendicular to the beam (i.e., as R_m rotates there must be a position for which the laser beam is reflected directly back into the laser aperture).
3. Insert L_1 to focus the laser beam to a point. Adjust L_1 so the beam is still centered on R_m.
4. Insert L_2 and adjust so the beam is still centered on R_m.
5. Insert the beam splitter and, again, be sure the beam is centered on R_m

> **CAUTION:** Do not look through the microscope until the polarizers have been placed between the laser and the beam splitter.

6. Position F_m at the chosen distance from R_m (2-15 meters), so the reflected beam from R_m strikes the center of F_m.
7. Adjust the position of L_2 to focus the beam on F_m.
8. Adjust F_m so the beam is reflected directly back onto R_m.
9. Insert the polarizers between the laser and the beam splitter.
10. Focus the microscope on the image point.