

Preface for the Instructor

This manual describes a host of things that you can do with the equipment included in TeachSpin's "Modern Interferometry" package. The modular optical devices included in this kit are versatile enough that you and your students can use them to build a variety of interferometers, and do a whole series of experiments, but here's a suggestion: it will rarely be advisable to start at the beginning of this manual, and merely march through it serially.

Much better would be to appreciate the structure of the manual, with its implications for lab practice. The manual includes "Building" chapters (sections 1, 3, 5, and 7), in which you're led to construct certain optical instruments; it also includes "Interlude" chapters (sections 2, 4, 6, and 8), which aim to teach certain optical and conceptual skills. Sections 9-16 are "Experiments", aimed at displaying some applications of interferometry to a variety of physical measurements. Finally, certain technical information is sequestered in Appendices A-S.

No doubt every novice ought to start with Section 0, for an introduction to interferometry, and then work through Section 1, for gaining hands-on familiarity with the apparatus by building a first interferometer. But the rest of the manual can be used in nearly any order, as desired. Certain of the "Experiments" will motivate the construction of various interferometers discussed in the "Building" sections; certain interests of the students will motivate reading some of the "Interludes". Some suggested sequences of mutually reinforcing topics are listed in Appendix A of this manual. But it's important to realize at the outset that TeachSpin is providing you *not* a fully constructed interferometer, but *rather* the components that will allow construction of several kinds of interferometer, and allow many kinds of measurements. Our view is that hands-on assembly skills, and emerging forms of conceptual understanding, are goals as important for students as 'measurement capability' narrowly understood.

We think it would be ideal for each student to encounter this apparatus by starting with an empty optical breadboard, building up a package of achievements, skills, and forms of understanding that might be unique. There are too many experiments listed in the manual, or latent in the apparatus, to expect any one student to perform them all. So it's perfectly appropriate for an instructor, or student, to be selective, aiming to investigate one sort of interferometer, or measure one kind of physical effect. In our view, the goal shouldn't be to *cover* all of interferometry, but to *uncover* some of the wonderful things that interferometry can do.

Preface for the Student

Perhaps you've read about interferometers in textbooks, but now you're about to encounter interferometry in a hands-on, build-it-yourself laboratory way. Here's a little background about the coverage of this manual and the TeachSpin apparatus it describes.

First point is that there are many kinds of interferometers, and you have the potential to use this equipment to construct at least three distinct kinds of interferometers. And construct them you will; ideally, you'll encounter this equipment starting with an empty optical 'breadboard', on which you'll build the very apparatus you're coming to understand. In the process, you'll gain skills in hands-on optical layout and alignment tasks that are a sort of co-curriculum to these investigations.

Second point is that interferometers can be used to measure many different things, and this manual will introduce you to some of these techniques. You can view an interferometer as a tool for measuring displacements (to the level of micrometers or even nanometers), or for measuring time delays (to the level of femtoseconds or even less), or for measuring optical coherence (and you'll come to understand what that is). In fact there are so many things that various interferometers can measure that it's unlikely you can cover them all; there's no shame in being selective, therefore.

Third point is that this manual aims to be a pretty complete description of the TeachSpin equipment that it covers, but it can't pretend to cover interferometry completely. You'll need to supply your own background reading, references, and theoretical derivations to create complete reports on what you do; in general, you'll need to plan your own forms of data taking too, since this manual describes more of 'what you can set up' than 'how to take data with it'. The exception to this is the derivation, on a few occasions, of the signals that are to be expected from clever uses of the polarization of light; these exercises in 'polarimetric detection' are worked out using complex representations of sinusoids, so as to make the algebra as simple as possible.

Fourth point is that the manual contains a lot of words, and you needn't read them all before you start. Every user should read Section 0, and browse Section 1, before starting in the lab; but much of the manual will work best if you read it for real in the context of hands-on contact with the apparatus, and experience eye-hand-mind coordination in the lab. This is where all the words and abstractions have the chance to come alive, as they describe concrete optical objects and visible optical phenomena that you'll encounter and use.

Interferometry offers a combination perhaps unique to you as a learner: there is a very tight and immediate connection between what you do with your hands and what you see directly with your eyes; and yet you are gaining direct access to the wave character of light, with all the prodigious sensitivity thereby made possible. A good deal of your hands-on experience of set-up and alignment will be conducted with more use of geometrical insight than of algebraic formulae, so if you're good at eye-hand coordination, you're going to enjoy what you're about to encounter.

Modern Interferometry: Nanometers, Femtoseconds, and Coherence

Table of Contents

0	Introduction to Interferometry.....	0-1
1	The Michelson Interferometer.....	3
a.	The simplest interferometer	3
b.	Controlling the fringes	Error! Bookmark not defined.
c.	Introducing 'coherence length'	Error! Bookmark not defined.
d.	Micrometer-level path-length control.....	Error! Bookmark not defined.
2	Interlude on <i>Alignment</i>.....	Error! Bookmark not defined.
3	The 'quadrature Michelson' interferometer.....	Error! Bookmark not defined.
a.	Standard, and Non-standard, outputs of a Michelson interferometer	Error! Bookmark not defined.
	not defined.	
b.	Using a metal-film beamsplitter.....	Error! Bookmark not defined.
c.	Manipulating and counting quadrature signals.....	Error! Bookmark not defined.
4	Interlude on <i>Polarization</i>	Error! Bookmark not defined.
5	The Sagnac Interferometer	Error! Bookmark not defined.
a.	The Sagnac topology.....	Error! Bookmark not defined.
b.	Aligning a Sagnac interferometer	Error! Bookmark not defined.
c.	Understanding polarimetric detection.....	Error! Bookmark not defined.
6	Interlude on <i>Relativity</i>.....	Error! Bookmark not defined.
7	The Mach-Zehnder Interferometer	Error! Bookmark not defined.
a.	Setting up the simplest Mach-Zehnder interferometer	Error! Bookmark not defined.
b.	A polarized-light Mach-Zehnder interferometer	Error! Bookmark not defined.
8	Interlude on <i>Quantum Mechanics</i>	Error! Bookmark not defined.
9	Experimental Wavelength Measurement	Error! Bookmark not defined.
10	Experimental Thickness Measurement -- An optical 'keepsake' ..	Error! Bookmark not defined.
	not defined.	
11	Measuring Indices of Refraction	Error! Bookmark not defined.
a.	The index of refraction of gases.....	Error! Bookmark not defined.
b.	The index of refraction of slabs	Error! Bookmark not defined.
12	Detecting thermal expansion.....	Error! Bookmark not defined.
13	Detecting magnetostriction	Error! Bookmark not defined.

- 14 Applications of piezoelectricity -- In pursuit of the nanometer.....**Error! Bookmark not defined.
- 15 The electro-optic effect**Error! Bookmark not defined.
- a. The Kerr and Pockels effects**Error! Bookmark not defined.**
 - b. A 'collinear interferometer'**Error! Bookmark not defined.**
 - c. Conoscopic figures.....**Error! Bookmark not defined.**
- 16 White-light interferometry.....**Error! Bookmark not defined.
- Appendix A. Suggested sequences for experimentation**Error! Bookmark not defined.
- Appendix B. Laser safety.....**Error! Bookmark not defined.
- Appendix C. Laser parameters**Error! Bookmark not defined.
- Appendix D. Vibration control via the stiffening ribs.....**Error! Bookmark not defined.
- Appendix E. The 'bull's-eye' fringes from a Michelson interferometer ...**Error! Bookmark not defined.
- Appendix F. The flexure stage and its mechanical train**Error! Bookmark not defined.
- a. Flexures in general and the 8-bar flexure in particular **Error! Bookmark not defined.**
 - b. Controlling the motions of the flexure stage.....**Error! Bookmark not defined.**
 - c. How a micrometer, and a differential micrometer, work..... **Error! Bookmark not defined.**
- Appendix G. 'Shimming' the optical mounts.....**Error! Bookmark not defined.
- Appendix H. The mounts for 1" x 2 mm beamsplitter plates.....**Error! Bookmark not defined.
- Appendix J. The mathematics of not-quite-quadrature signals..**Error! Bookmark not defined.
- Appendix K. Hysteresis -- its usefulness and detection**Error! Bookmark not defined.
- Appendix L. Choices for table-mounting the mirror mounts**Error! Bookmark not defined.
- Appendix M. Straight-line fringes and spatial frequency**Error! Bookmark not defined.
- Appendix N. The mounts for polarizing beamsplitter cubes.....**Error! Bookmark not defined.
- Appendix P. The miniature rotation stage.....**Error! Bookmark not defined.
- Appendix Q. Preparing a thermal-expansion sample**Error! Bookmark not defined.
- Appendix R. The index of refraction of optical glass**Error! Bookmark not defined.
- Appendix S. The gas-handling manifold, and uses of the pressure transducer**Error! Bookmark not defined.

0 Introduction to Interferometry

Interferometry means ‘to measure using interference’, and it stands for a whole range of techniques practiced in optics. The TeachSpin apparatus you’re about to encounter will teach you some techniques that can be used, and some targets to which they can be applied, in the very versatile technique of measurement using interference of light beams.

The various interferometers that you will build and use all involve a similar physical concept: this is the division of a beam of light into two separated beams, which (after following separate paths in space) are then brought back to recombine. An optical technique like this is called interferometric if the recombination process can be either constructive or destructive; this is where the ‘interference’ comes from.

The difference between two beams combining constructively, as opposed to destructively, is a matter of phase; you should know that two beams differing by 180 degrees (or π radians) in phase will interfere destructively. You should also realize that to obtain such a phase shift requires a geometrical path difference of half a wavelength, which is (for beams of red light) about $0.3 \mu\text{m} = 0.3 \times 10^{-6} \text{ m}$, or equivalently a travel time difference of half an optical period, which is about 1 femtosecond $= 1 \text{ fs} = 1 \times 10^{-15} \text{ s}$. Numbers like these should illustrate to you how sensitive a measurement technique interferometry can be; what’s more, you’ll be building interferometers which are sensitive to phase changes a *thousand-fold smaller* than those just mentioned.

You may have first encountered interference in a ‘two-slit interference’ experiment, and you can recall that its operation does indeed involve two separated beams, or at least two separate identifiable paths of travel, of light. An opaque screen with two or more open slits in it represents a class of interferometers depending on ‘division of wavefront’, in which the two beams in question come from different places on a single wavefront. The interferometers you’re about to encounter depend instead on ‘division of amplitude’, in which a light beam is (everywhere across its whole wavefront) split into two outgoing beams, each with only a part of the amplitude or intensity of the incoming beam. An essential device in such an interferometer is a beamsplitter, which partially reflects, and partially transmits, a beam of light incident on it.

You will have the opportunity to build interferometers of three distinct topologies, the Michelson, Sagnac, and Mach-Zehnder interferometers. There are yet more interferometric set-ups than these, but these three will show you a range of techniques and applications representative of the whole field. In addition to building these interferometers, you will have the pleasure of learning, on a tabletop and very much in hands-on fashion, a great deal about the arts and crafts of optical layout, assembly, and alignment. Another whole range of skills and insights that you’ll encounter are connected to the clever use, in some of these interferometers, of the *polarization* of the beams of light you’ll use.

What’s so *modern* about ‘Modern Interferometry’? After all, Michelson invented his interferometer around 1880, and the other two topologies you’ll investigate date from the early 20th century. Here are some of the modern touches in the experiments you’ll encounter. First of all, they will all start with laser sources of radiation, and will all involve the electronic detection of the results of optical

interference. Another modern feature is that your experiments will involve the quantitative control of independent variables, and the quantitative measurement of dependent variables. Yet another feature will be the use of modern optical components and mounts, such as multilayer dielectric coatings, and kinematic and flexure-based mountings. Finally, you will be introduced to some very clever applications of polarization in light sources, propagation, and detection.

You should know that the applications of interferometry in modern physics and technology are even broader than those which can be illustrated here. Interferometry shows up nowadays in a host of applications involving high-precision use of the fundamental standard of length, or the very sensitive detection of mechanical displacements. Various interferometric methods are used for all sorts of sensitive testing of the shapes of optical surfaces. Interferometry is the basis of the very important method of Fourier-transform spectroscopy, especially useful in the infrared region of the spectrum. Finally, interferometry of superb sensitivity is the basis of the LIGO project, in which truly tiny distortions of space-time itself, produced by the passage of gravitational waves, are to be detected using optical interferometry.

1 The Michelson Interferometer

a. The simplest interferometer

It's very easy to draw the basic topology of a Michelson interferometer, given the concept of a narrow beam of coherent radiation propagating in space, and the idea of a beam splitter. Figure 1-1 below shows a more simplified layout, and deliberately depicts the components involved as somewhat misaligned, just to make the various beams more visible.

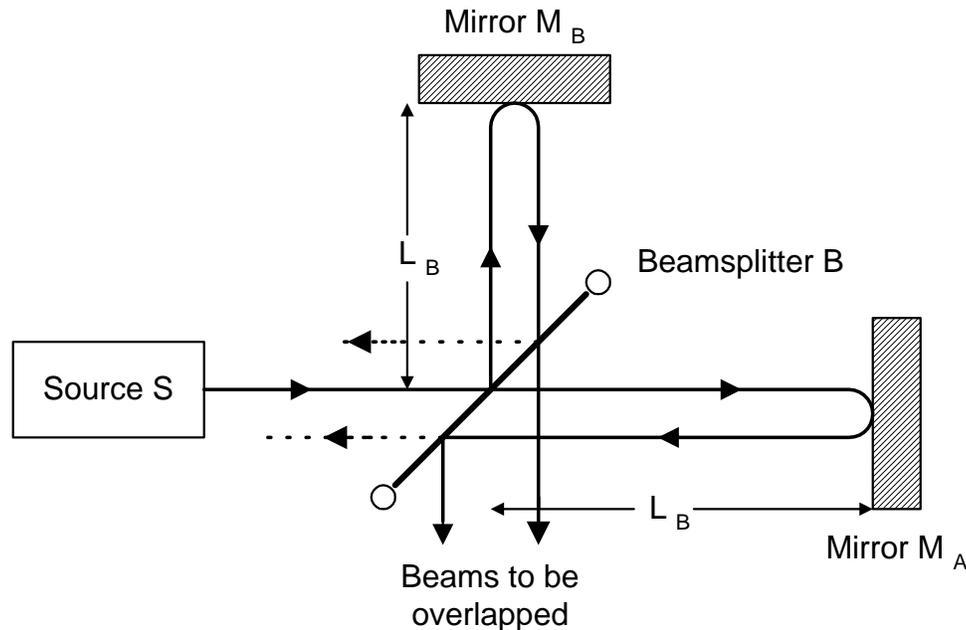
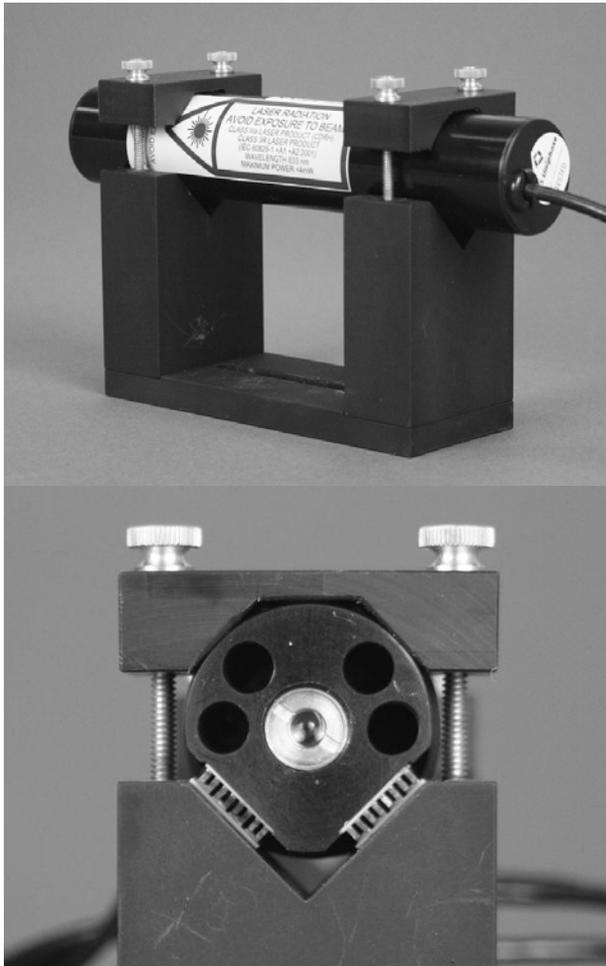


Figure 1-1: A simplified Michelson Interferometer

We start with a source S , producing a monochromatic beam of wavelength λ or frequency f , and some irradiance I_0 . We let that beam fall on a beamsplitter plate B at a 45° angle of incidence, so that the partially reflected and partially transmitted beams that emerge are at nearly right angles in space, and are both of irradiance $I_0/2$. Then we let both these beams impinge on fully reflecting mirrors M_A and M_B , so that they are both retro-reflected back toward beamsplitter B . [We consider that the two beams will have traveled one-way distances L_A and L_B (from beamsplitter to mirrors) which may *differ* by an amount that might be a small fraction of a wavelength, or perhaps many meters.] Now at the beamsplitter, each returning beam will again be split into two outgoing beams; these four beams are shown in the diagram. Two of them are headed back toward the source S , and are inconvenient to access; but two others leave the beamsplitter B in a convenient and accessible direction. To *align* an interferometer is to arrange these two outgoing beams to overlap in position and direction. If certain ‘coherence requirements’ can be met, then these two beams, each of irradiance $I_0/2$, will *not* merely add up in power to yield a beam of irradiance I_0 , but instead will superpose, constructively or

destructively, to produce a single beam whose irradiance will fall somewhere in the range 0 to I_0 . Where in this range the irradiance will fall will depend, with interferometric sensitivity, on the value of $L_A - L_B$.

Now it's time to translate this drawing on paper to a working three-dimensional reality. This requires an introduction to the components available to you in the Modern Interferometry kit, and the technique of handling them safely. You might start by using as light source the Helium-Neon (HeNe) laser that's available to you, mounting it in its holder near a corner of the optical table as shown in Fig. 1-2. If you're the first-ever user of the laser holder, you can assemble it from its parts.



the HeNe laser

Figure 1-2b: Mounting the Diode Laser

Figure 1-2a: Mounting

Now locate one of the white-painted 'alignment towers' from the kit, and place it some distance downstream of the laser's output port to form a viewing screen. You'll now need to plug the laser's electrical connector into the mating receptacle at the back of the Modern Interferometry control box, and then find out how to turn on that control box (switch on the back panel) and how to turn on the HeNe laser (toggle switch on front panel). After a few seconds' delay, you should see a fine red beam emerge from the

laser. You may now learn how to use the alignment tower as a combination shutter/view screen for the beam propagating across the table.

Now is the time to read and master the safety information in Appendix B, and to understand why you mounted the laser first, and turned it on later. Note that for safety reasons, it's conventional to have laser beams propagate in a horizontal plane, and one that is **not** at typical eye level. It's also conventional to pick a standard for height of beams above the surface of the optical breadboard; in this optical kit, the standard is 3 inches (where 1 inch = 1" is an ancient, non-SI, but perfectly well-defined unit of length, 1 inch \equiv 25.4 mm, much used in optical manufacturing for historical reasons).

This is also a good time for you to become acquainted with the 1/4-20 mounting screws and their socket heads, and the ball-ended socket driver, which are the standard tools for mounting on this sort of optical table. You'll find that there's no need to over-tighten such screws, and they'll provide more than adequate strength and stability using mere hand tightening with the socket-driver. Finally, you might identify those smaller brass thumbnuts which hold the HeNe laser into its mounting bracket, and check that they are snug but not over-tightened.

The simplified diagram above shows the laser beam flying right into the interferometer, but in practice it's necessary to get control over the alignment of this beam. So emulate Fig. 1-3, which shows the two steering mirrors in the kit used in such a way as to deliver a beam that can be fully adjusted, in position and in direction, before it encounters the beamsplitter that marks the entrance to the interferometer proper.

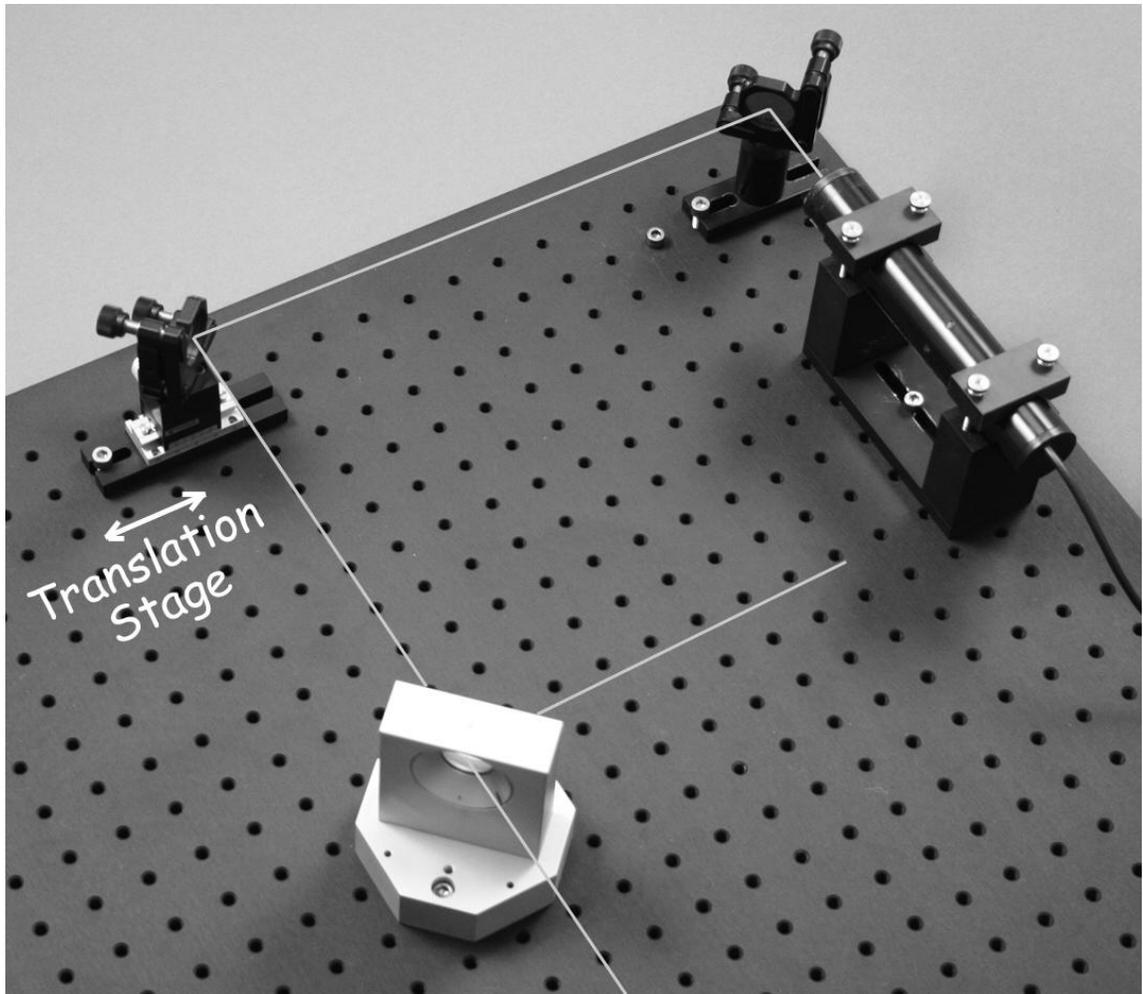


Figure 1-3: One way to use the two steering mirrors

Each of the steering mirrors is a ‘front-surface mirror’, whose (metal) reflective coating is on the *outer* surface of a glass substrate. These metal surfaces, like many others you will see in the Modern Interferometry kit, are working optical surfaces, and are vulnerable to damage either by scratching or contamination, so a basic rule you should hereafter observe is NEVER TO TOUCH AN OPTICAL SURFACE. There are always safe ways to handle optical components that respect this rule; in the present case, you may handle the steering mirrors by their baseplates. You should note that each mirror-mount has two adjustable thumbscrews on its back surface; one of them also has a one-dimensional slide adjustment near its baseplate. For now, you may set these adjustments to mid-range, since you will soon learn how to use optical diagnostics to adjust them.

If you have mounted the beam-steering mirrors to the table properly, you should be able to trace the HeNe laser’s beam through two right-angle bends until it emerges roughly as shown in Fig. 1-3. Now it’s time to mount the beamsplitter, and the two end mirrors, that’ll form the interferometer. What you want is the base-and-upright structure which holds a thin flat optic of 1” diameter, and which can be used to split the input beam into a

transmitted beam and another (reflected) beam, emerging at right angles. (You want to use a dielectric-film 50-50 beamsplitter, not the metal-film beamsplitter you'll use later. See Appendix H on how to tell the difference.) For now, set it down on the optical table in such a way that your beam encounters its optical surface, and use your alignment tower to find the two output beams. Then position the beamsplitter's base above some mounting holes in the table, and screw it down into place. You may have to reposition, or adjust, the steering mirrors to restore the beam to hitting the beamsplitter.

Once you have two output beams, of comparable intensity, you need to choose two end mirrors. From those available in the kit, you need to pick two different kinds, differing in the kind of hinge that they have in their one degree-of-freedom of adjustability. If you can find their adjusting thumbscrew on the back face of the upright, you can see where it bears on the plate holding the mirror, and you can identify the 'flexure hinge' which gives them a combination of extreme rigidity in all other motions, and some flexibility in one rotation. You're looking for one mirror to have a 'horizontal hinge line' and the other to have a 'vertical hinge line', so that your interferometer will have just enough degrees of freedom to allow alignment.

You might put those mirrors down on the table after the fashion of Figure 1-4, and arrange them to retroreflect the laser beams back toward the beamsplitter. Before you attach them to the tabletop with screws, ensure that they define two arms of the interferometer of equal length (to the 1" quantization interval defined by the hole pattern in the table). You might also check that the laser beams are incident near the centers of the front-surface mirrors.

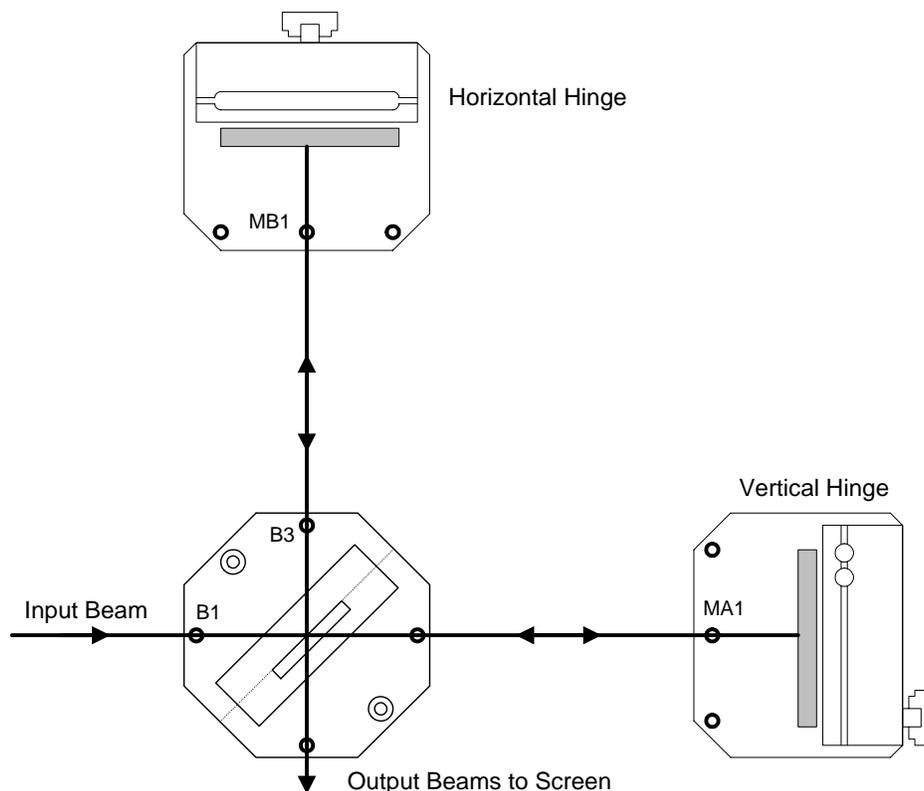


Figure 1-4: A first Michelson interferometer in action