# THE DESIGN AND CONSTRUCTION OF A MACH-ZEHNDER INTERFEROMETER FOR USE WITH THE GALCIT TRANSONIC WIND TUNNEL

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# ABSTRACT

A Mach-Zehnder Interferometer has been designed and constructed for use in conjunction with the GALCIT Transonic Wind Tunnel. The instrument is to be utilized in making detailed density measurements of supersonic air streams. The design of the instrument is such that, contrary to general wind tunnel practice, both light beams of the interferometer traverse the test section of the wind tunnel in an effort to minimize boundary layer corrections. A detailed description of the instrument is presented, as well as a "cook-book" adjustment procedure. A discussion of the limitations of the instrument is included.

# INTRODUCTION

During the past few years, the Mach-Zehnder Interferometer has come into increased use throughout the country in the investigation of high-speed aerodynamic phenomena. Ladenburg (Ref. 1-5) and his co-workers have been especially active in this field and the references cited give ample information regarding the optical theory of the instrument. The instrument (Fig. 1) consists of four plane-parallel mirrors, whose essential function is to form two coherent light beams which are brought together to form interference fringes at a given point. In normal practice, one beam of light is passed around the wind tunnel, the other thru the test section of the tunnel, and the fringes are formed at the test section. If the index of refraction of the air in the wind tunnel is changed, the fringe pattern will be changed. The index of refraction of air is a linear function of the density, hence, changes in the fringe pattern may be evaluated to give density changes. Two methods of fringe arrangement are available for use. In the first of these, before the air in the tunnel is started, the optical paths in both legs of the interferometer are exactly equal, resulting in a uniformly bright (or dark) field. This is the so-called fringe of infinite width. As the air in the tunnel is turned on, the resultant changes in index of refraction are shown in a fringe pattern which gives lines of constant index of refraction. This method is used a great deal in heat transfer work, where the lines of constant index of refraction are the isothermal lines. An example is shown in Fig. 2 which is representative of the isotherms in a Bunsen burner flame.*

The second fringe arrangement available for use occurs when one of the four plane-parallel plates is rotated slightly, resulting in a field of uniformly spaced, straight fringes (Fig. 3). As the air is turned on, the fringes will shift, the amount of the shift being a direct function of the index of refraction. Two photographs, a "before" and "after" picture, and some method of determining the fringe shift are necessary for the evaluation of this type. Fig. 4 shows the same Bunsen burner flame of Fig. 2 introduced into the fringe field of Fig. 3. The method of the infinite fringe does not find ready application in high-speed aerodynamics, since the steep density changes that often occur (i.e., shock waves) result in such crowding of the isopycnic lines that evaluation of the data is well-nigh impossible. Zobel (Ref. 6) however, has made a number of impressive photographs of subsonic flow past an airfoil by this method.

The evaluation of interferograms is treated for both the case of uniformly spaced fringes and the fringe of infinite width by Hutton (Ref. 10), by Groth (Ref. 11-14) and by many others and no

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*Since the Bunsen burner flame has an axially-symmetric temperature field, the actual isotherms will be somewhat different from those shown in Fig. 2.

point would be served in reproducing the method here. A word might be said about the various methods of determining the fringe shift, however. There are almost as many methods for determining the fringe shift as there are workers in the field. A tabular summary of these methods, together with references is given below:

| Workers | Method | Reference |
|---|---|---|
| Ladenburg, et al | a) Microphotometer Trace<br>b) Plot from Comparator data | 1-5 |
| Zobel | Photographic superpositions of displaced and undisplaced fringes | 6 |
| Edelman | Photographic superposition of displaced and undisplaced fringes, including printing slightly out of register to give lines of constant fringe shift | 16 |
| Gooderum, et al | Plot from enlarged photographs | 17 |

The simplest method of evaluation appears to be that utilized by Gooderum, which is essentially that of Ladenburg, although no special equipment is required by the former.

## DESCRIPTION OF THE INSTRUMENT

A schematic diagram of the optical path thru the instrument is given in Fig. 1. Light from a mercury vapor lamp is filtered and focussed on a small $45^{\circ}$ mirror which is placed at the focus of a paraboloidal mirror. The parallel beam of light from the latter is split at half-silvered mirror #1 into two coherent beams, one passing thru mirror #1 and reflecting off full-silvered mirror #3, the other reflecting off mirror #1 and full-silvered mirror #2. The two beams are re-combined at half-silvered mirror #4 and are brought to focus by a spherical mirror.

The instrument is set up with each plane-parallel plate at the corners of a 7 3/4" x 35 3/4" rectangle. The ground plane of the instrument, when it is applied to the Transonic Wind Tunnel, is horizontal. The light beams, both of which traverse the tunnel are circular, of 2 1/2" diameter. The horizontal arrangement makes the instrument much easier to adjust. Both beams of light traverse the tunnel in an attempt to eliminate the effect of the boundary layer on the glass walls. The small field of view was chosen so that the light beams would enter the 12" diameter circular window of the tunnel at a maximum separation. Since the instrument can be traversed, and since studies of small flow areas are contemplated, the reduced field of view is no disadvantage.

The adjustment of the instrument is such that fringes can be produced at any point along the light path of the instrument.

For normal aerodynamic use, the fringes are focussed in the plane (AA in Fig. 1) of the region under investigation.

The GALCIT interferometer has been designed with a minimum number of air-glass interfaces, in order to eliminate loss of light; there are four air-glass (or glass-air) interfaces in the light path, two at the lens, and two at the filter. These surfaces are all coated to reduce the light loss to a bare minimum.

Figure 5 is a photograph of the complete interferometer set-up. The central wooden box carries the plane-parallel plates, the light source and the traversing table and is suspended from the piping frame work by means of rubber bands, attached to jack screws which allow the box to be traversed in a vertical direction. The natural frequency of the suspended system is close to one cycle per second. The pipe frame is mounted on casters, which may be locked in position, for ease of traversing along the test section of the wind tunnel.

The auxiliary equipment, i.e., paraboloidal mirror, spherical mirror and camera box, are carried directly on the pipe frame-work, attached by friction fittings which may be easily adjusted.

The various component parts of the interferometer are fitted with a large number of adjustments. This practice, while giving rise to an extremely large number of possible mis-alignments, also results in considerable ease of setting up the instrument. Locking devices are present in most cases to prevent any change in the final set-up.

## DETAILED DESCRIPTION OF THE COMPONENT PARTS

### 1. Light Source

The present light source consists of a mercury vapor lamp, General Electric Type AH-4, housed in a Cenco #87268 lamp housing. The lamp house is attached ? to a brass tube which contains a Bausch and Lomb achromatic lens of 142.9 mm focal length and 46.0 mm diameter. The brass tube also contains a receptacle for a Wratten No. 77A filter. Attached to the top of the brass tube is a U-shaped bracket which supports a rectangular frame which in turn carries two cross wires to which is attached the 2 mm x 4 mm first surface mirror which serves as the secondary light source.

At some later date, it is planned to replace the mercury vapor lamp by a magnesium electrode spark gap, flashing thru an interference-type filter, so that short-duration photographs may be made.

The 2 x 4 mm mirror, is placed at the focus of a 5 1/2" diameter x 15" focal length paraboloidal mirror. This mirror is mounted in a brass mirror cell of the type described by Strong (Ref. 18); a central flexure post and four adjusting screws provide the fine adjustment of position. Coarse adjustment in the horizontal plane is afforded by means of a turntable to which the mirror is attached, while a vertical adjustment is provided by rotation, in a vertical plane, of the beam to which the turntable rider is attached.

## 2. Plane-Parallel Mirrors

The plane-parallel mirrors are carried in the frame which is shown in Fig. 6. The mirror itself is held in a split brass ring, by means of a soft rubber, full circumference support. Two gimbals allow rotation of the mirror about a horizontal and a vertical axis. Rotation of the gimbals is obtained by means of remotely controlled, reversible electric clock motors. The output shaft of these motors, (Haydon #3200) makes 1 revolution per 8 days, resulting in an extremely fine control of the angular displacement of the mirrors. The gear-box on the motor is equipped with stamped metal gears, and a not inconsiderable amount of backlash is present, hence a simple torsion spring is placed at each bearing to supply a backlash-eliminating force.

The frames of all four mirrors are identical in their design. Duralumin castings are used for the outer frame and the inner gimbal. There is no provision for coarse angular adjustment of the mirrors. Mirrors 1, 2 and 3 (see Fig. 1) are bolted directly to the top of the plywood box. Mirror 4 is mounted on a traversing table. This adjustment is required to equalize the length of the light path in the two arms of the interferometer. The traversing mechanism features a Le Blond, lathe bed type, way, a traversing screw of 1 mm pitch, driven by a hand operated 50:1 worm gear reduction unit, a simple nut, and a pin-driven gravity-emplaced traversing table.

### 3. Camera (Picture-Taking Components)

The photographic components consist of a 3 1/2" diameter, 24" focal length spherical mirror, an Ilex #6 Universal Shutter with speeds up to 1/50th second and a 4" x 5" Graphic camera back with ground glass viewing screen and focussing hood.

The parallel beams of light in the two arms of the interferometer which are recombined at mirror 4 are focussed on the ground glass by means of the spherical mirror. The shutter and camera back are mounted at opposite ends of a light-tight box, permitting photographs to be made using the shutter release or, for spark photography, the shutter may be operated by a synchronized solenoid.

## DESIGN PROCEDURE

The procedure that was followed in the design of the GALCIT Interferometer is of some interest, since, to the author's knowledge, the design program represents a significant departure from normal practice. The author's previous experience in the field of optical design had been limited to the Schlieren system of the Transonic Wind Tunnel, an optical instrument of much greater simplicity than an interferometer. The design procedure was as follows:

1. The mounts for the four plane-parallel mirrors were designed. This represented a fairly simple mechanical design and was essentially the kinematic problem of rotating a flat plate about two perpendicular axes with small angular deflections.
2. A temporary set-up was constructed with the mirrors at the corners of a square (Fig. 7).

The arrangement consisted of a large steel plate, resting on two layers of air-filled automobile inner tubes. The mirror frames were placed directly on the steel plate, cemented in place with wind tunnel wax; an inexpensive lathe milling table was used as the translating mechanism for mirror #4. A jury-rigged light source and screen were also included in the temporary set-up.

The author spent several months working with this arrangement; the technique of the adjustment of the interferometer was practiced almost daily. When the fringes were first secured, they were badly curved, e.g. Figs. 8 and 9. This difficulty was eventually traced to the rubber mountings surrounding the mirror plates. Stresses set up by the soft sponge rubber at the edge of the plates proved enough to distort the plates so that they were no longer flat but doubly curved (as the saddle-shaped fringe patterns of Fig. 9 attest). This difficulty was remedied by changing the mounting media from sponge rubber to two split rubber tubes. The resulting fringe patterns are shown in Figs. 5 and 10.

When proficiency in the adjustment of the instrument had been attained, the final configuration of the mirrors was determined; this arrangement of the instrument was set-up on the temporary base and the layout checked for application to the Transonic Wind Tunnel.

Once the final arrangement had been settled, the final design proceeded rapidly. Exclusive of the design and construction time for the plane-parallel mirrors and their frames, the total time for the design, construction and assembly of the instrument was two months. The personnel active in the design and construction included one full-time engineer (the author) and two full-time machinists. It should be noted that this extremely short construction time, is, in the main, due to the simplicity of the design. Of primary importance, in this instance is the use of wood for the base plate of the interferometer. The design of other interferometers which have come to the author's attention is invariably predicated on a massive, rigid, base-plate, which is of necessity accompanied by an equally massive supporting structure. The wooden box on which the GALCIT Interferometer is supported, together with mirrors and frames, light source and traversing table weighs two hundred fifty pounds. The box is allowed to deflect in any fashion it may choose. Once it has assumed its deflected position, and the mirrors have been brought into adjustment, the shock mounting of the system effectively prevents any further misalignment from taking place.

## ADJUSTMENT OF THE INSTRUMENT

The adjustment of the interferometer is accomplished in several steps. These are:

1. The light beams must be made to strike the test section walls at zero degrees incidence.
2. The plane-parallel plates must be made parallel to one another.
3. The light paths in both legs of the interferometer must be equal.
4. The fringes must be focussed at the meridian plane of the test section.
5. The white light fringe must be centered in the field of view.

The adjustment procedure is as follows:

a. Level the optical bench, using the jack screws at each of the four corners. The light beams passing through the test section should be set nearly normal to the test section window by eye.

b. Adjust the light beams to enter the test section normally. This is accomplished by placing a cut-out cross-hair in front of the light beam on the wind tunnel window nearest mirror 3 and reflecting the image of the cut-out back from the window on the far side of the tunnel by means of a small plane mirror held against the far window. The paraboloidal mirror is then adjusted until the reflected image coincides with the cut-out.

c. Set up the auto-collimating telescope at position A (Fig. 11), (after removing the test section walls) and the penta-prism at B, adjusting the telescope position so that the reflection from mirror 3 is coincident with the illuminated cross-hair. Level the telescope; block the reflection from mirror 3 and adjust the penta-prism so that the reflection of the cross-hair from the front face of the penta-prism coincides with the illuminated cross-hair. When all three sets (reflection from mirror, reflection from front prism face, and telescope cross-hair) of cross-hairs are coincident and both the telescope and prism are levelled, the axis of the telescope is normal to the prism and parallel to mirror 3. Do not disturb the telescope between this step and the following step.

d. Set up the penta-prism in position C (Fig. 11). Bring the cross-hair from the front face of the prism into coincidence with the telescope cross-hair by moving the prism only. The prism should be level when this operation is completed. Rotate mirror 2 to bring the third cross-hair into coincidence. Mirror 2 is now parallel to mirror 3 and the cables from the switch box to the mirrors should be disconnected. Repeat d for mirrors 1 and 4.

e. The near and far cross-hair method is used for the remainder of the adjustment. In the present set-up, the small (2 mm x 4 mm) mirror at the light source serves as the far cross-hair while the supporting wires for this mirror serve as the near cross-hair. Set up the telescope at D and examine the images of the small mirror. Rotate mirror 1 until the two images coincide.

f. Examine the images of the wires. Translate mirror 4 until the cross-hairs coincide. This adjustment equalizes the light paths in the two legs of the interferometer.

g. Rotate mirror 1 to bring the images of the small mirror into coincidence. (In general, adjustment f will throw them out of line).

h. Rotate mirror 4 to get the wire images into coincidence. g and h are not independent operations and must be continued until the process converges.

i. As both sets of cross-hairs begin to approach the coincidence point, fringes will appear at or near the image of the small mirror.

j. The fringes must now be brought to focus in the test section of the wind tunnel. This is accomplished by setting up a cross-hair in the test section and moving the fringes until both fringes and cross-hair are in focus. The two splitter plates, mirrors 1 and 4, must be rotated so that the two light beams appear to cross at the test section. In practice, this appears to be most easily accomplished by a trial and error method. That is, mirror 1 may be rotated slightly, the new location of the fringes determined, and rotation in the same direction or in the opposite direction continued, depending on the direction of motion of the fringes. Some care must be exercised at this stage, for the fringes may be easily washed out if mirror 1 is rotated thru too large an angle in an effort to make the beams cross at the test section. To avoid this, it is best to rotate both mirrors 1 and 4 to focus the fringes. If the fringes are lost, however, it is a simple matter to find them again by re-aligning the cross-hairs as noted in g and h.

k. With the fringes at the test section, the next step is the orientation and spacing of the fringes. Again, mirrors 1 and 4 are used for this adjustment. Rotation of the mirrors changes the fringe spacing and their orientation. An example will be described to illustrate the method:

Assume the fringes to be nearly vertical, and that vertical fringes of a somewhat wider spacing are desired. Then, mirror 1 (or 4) is rotated about the vertical axis (i.e., a horizontal displacement of the virtual sources results in a horizontal displacement of the fringes) until the desired fringe spacing is reached. The inclination of the fringes is controlled by rotating the mirror about its horizontal axis. Now the fringes will be found to be oriented correctly and of the proper spacing, but they may no longer be in focus. The focussing, once the fringes are oriented and spaced as desired, is accomplished by displacing mirror 1 on its horizontal axis, thereby making the fringes inclined to the vertical, and then returning the fringes to their vertical position by rotating mirror 4 in the opposite direction on its horizontal axis. This method provides a very fine adjustment on the location of the fringe position.

1. The final step in the adjustment of the instrument requires that the white light fringe be centered in the field. White light from a 6 volt G. E. Projection Lamp is introduced into the interferometer by means of a plane mirror placed in such a fashion that half of the field of mercury light is replaced by white light. Thus, the monochromatic fringes are always visible during the adjustment. With both white and monochromatic light in the field of view, the traversing table under mirror 4 is translated until the white light fringe is found. The translation of the mirror must be performed with care, as one turn of the crank is sufficient to make the white light fringes move completely across the field of view. When the white light fringe has been found, the central dark fringe, representing the zero interference point, is centered in the field of view, and the adjustment is complete.

## USE OF THE INTERFEROMETER IN SUPERSONIC FLOW RESEARCH

The Mach-Zehnder interferometer is, potentially, an extremely useful tool for basic aerodynamic research at high speeds. The difficulties of adjustment of the instrument, as well as the kinematics of the installation can be solved, and useful information can be obtained. There are, however, a few considerations which should be noted so that the limitations of the instrument may be appreciated.

It will be recalled that the interferometer is essentially a density measuring instrument. In aerodynamic studies, however, pressure or velocity data are required. Thus, in compressible flow, the interferometer yields useful data by itself (i.e., without auxiliary data) only if isentropic flow is studied. Hence, any flow involving shock waves requires data other than the interferogram. For example, if the strength of a shock wave is known, the flow on either side of the shock wave may be considered isentropic, but with different values of stagnation pressure and the entire flow field may be determined by means of one interferogram plus two total head readings. Of course, any process in which some one variable of state is held constant may also be studied solely by use of the interferometer; thus, isobaric and isothermal processes are readily susceptible of evaluation. These processes are, in general, exceptional ones and it is to be expected that measurements of total head or some other variable must always be made in conjunction with the taking of interferograms. This in itself, is not to be construed as a disadvantage of the instrument; the measurement of total head, in a compressible gas stream, is a relatively simple operation. As noted above, any region where the flow process remains unchanged may be completely determined by one total head measurement plus one interferogram. The idea of being able to completely determine a given flow field by means of only two distinct measurements has great appeal to the experimental aerodynamicist.

The interferometer is not well suited for the purpose of boundary layer investigations. There are two disadvantages of the instrument which come into play in this respect. The first of these is the fact that the interferometer makes no distinction between changes in the index of refraction (or density) due to temperature variation and those due to velocity variation. Since the boundary layer in compressible flow contains a stagnation temperature profile as well as a velocity profile, the interferometer will reveal a density profile which represents the total effect of both temperature and velocity. I.e., the temperature profile must be known in order to determine the velocity profile and vice versa.

A second difficulty with respect to boundary layer measurements results from the fact that an interferogram integrates the index of refraction changes along the test section. Hence, unless the flow is truly two-dimensional, the results will be in error.

In boundary layer work, true two-dimensional flow is rarely achieved. Consider a flat plate spanning the wind tunnel. There is always a contamination of the flow which spreads downstream from the junction of the plate with the wall at an angle of approximately ten degrees. Hence, at any point upstream of the boundary layer transition region, a spanwise section of the boundary layer contains a turbulent phase, a laminar phase, and a second turbulent phase, in that order. Integrating the density changes across such a path obviously gives an erroneous result. Conceivably, measurements might be made far downstream, where the entire boundary layer is turbulent, but again, this is possible only if the temperature profile is known.

In connection with the idea that the interferometer presents integrated results, note should be taken of the fact that this applies also to the light path outside the wind tunnel, hence, that part of the path which is outside the tunnel must be made as small as possible compared to the path within the tunnel and should also be shielded from stray air currents or temperature variations.

A further possible source of error in wind tunnel measurements is the effect of the boundary layer on the glass walls thru which the light beam passes. The general practice is to use a compensating chamber (i.e., a pressure tight chamber with glass walls the same thickness as those of the wind tunnel walls and of the same width as the wind tunnel; the pressure in the chamber is set at the approximate level of the static pressure in the wind tunnel) for the light beam which does not pass thru the wind tunnel. The beam passing thru the wind tunnel, however, must also pass thru the boundary layer on the glass wall, giving rise to an additional refraction which may influence the resulting interferogram. It is felt that the GALCIT interferometer effectively minimizes this source of error, since both light beams pass thru the wind tunnel walls, and the only error present results from the change in the thickness of the boundary layer as it passes from one beam to the other. This change is small, since the wall boundary layer has already reached a fully-developed turbulent state at the first light beam. The GALCIT interferometer has also been designed with a view toward making relative measurements only. Thus, a downstream area of disturbed flow is measured relative to an upstream area of uniform parallel flow.

A comparison of the interference method with other optical methods of flow observation reveals a number of interesting characteristics of each method. The interferometer is sensitive to density changes; the Schlieren system responds to density gradients; while the shadow method shows the curvature of the density variation. The amount of quantitative information gained from each method appears to be in direct proportion to the cost and complexity of the installation. On the other hand, the less complex methods, due to the very nature of their response, show steep density fronts much more clearly than does the interferometer. This is the reason that turbulence phenomena, e.g., in the wake of a projectile, and shock waves show up so much more clearly in a shadow or a Schlieren picture than in an interferogram. For quantitative results, the interferometer is vastly superior, since quantitative data can be obtained from a Schlieren or shadow photograph only by costly and tedious photometry followed by equally tedious integration of the photometer record.

A further advantage of the interferometer method lies in its ability to present a great deal of data in a single photograph, thus allowing precise quantitative studies of non-stationary phenomena. For example, to determine the pressure distribution over an airfoil requires the evaluation of but a single interferogram, and the number of points at which the pressure is measured may be varied at will by simply changing the original fringe spacing.

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## STATISTICS OF THE GALCIT INTERFEROMETER

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|---|---|
| Diameter of Plane-Parallel Plates | 5.0 in. |
| Thickness of Plane-Parallel Plates | 0.5 in. |
| Index of Refraction | 1.5725 |
| Coating Material | Aluminum |
| Thickness of Coating on "Full" Mirrors | 1/4 λ |
| Thickness of Coating on Beam Splitters | 1/16 λ |
| Speed of Turning Motor | 450 RPM |
| Speed of Mirror | 1/8 RPD |
| Gear Ratio | 5,184,000 : 1 |
| Dimensions of Base Rectangle | 7 3/4" x 35 3/4" |
| Wave Length of Light Used | 5461 Å |
| Traversing Table Lead Screw Pitch | 1 mm |
| Traversing Table Hand Crank Gear Ratio | 50 : 1 |

## LIST OF DETAIL DESIGN DRAWINGS FOR THE GALCIT INTERFEROMETER

| GALCIT Dwg. No. | Title | Date |
|---|---|---|
| 5-273-49 | Mirror Support | 8- 6-46 |
| 5-273-50 | Outer Gimbal, Mirror Support | 8-13-46 |
| 4-273-51 | Inner Gimbal, Mirror Support | 8-14-46 |
| 2-273-74 | Layout, Control Panel | 11-12-47 |
| 4-273-167 | Assembly, Traversing Table | 6- 1-49 |
| 1-273-168 | Nut, Traversing Table | 5-31-49 |
| 2-273-169 | Lead Screw, Traversing Table | 5-31-49 |
| 4-273-170 | Bed, Traversing Table | 6- 1-49 |
| 2-273-171 | Carriage, Traversing Table | 6- 2-49 |
| 1-273-172 | Bearing Block, Traversing Table | 6- 2-49 |
| 2-273-173 | Bracket, Worm Drive, Traversing Table | 6- 3-49 |
| 1-273-174 | Drive Plate and Thrust Collar, Traversing Table | 6- 3-49 |
| 1-273-175 | Mirror Table, Traversing Table | 6- 3-49 |
| 5-273-176 | Mounting Bench | 6-10-49 |
| 5-273-179 | Suspension Frame | 6-17-49 |
| 4-273-180 | Suspension Spring Eye | 6-20-49 |
| 4-273-181 | Suspension Base | 6-21-49 |
| 1-273-182 | Revised Swivel Detail, Suspension Spring Eye | 6-22-49 |
| 5-273-183 | Rail, Rail Calmp and Rider | 6-22-49 |
| 5-273-184 | Mirror Cells | 6-24-49 |

| GALCIT Dwg. No. | Title | Date |
|---|---|---|
| 5-273-185 | Light Source Assembly | 6-30-49 |
| 5-273-187 | Details, Light Source | 7- 5-49 |
| 4-273-188 | Detail No. 7, Light Source | 7- 6-49 |
| 2-273-189 | Mounting Bracket, Traversing Table | 7- 7-49 |
| 2-273-190 | Suspension Spring | 7-11-49 |
| 5-273-195 | Shutter, Film Holder | 7-19-49 |

## COST OF THE GALCIT INTERFEROMETER

| | |
|---|---|
| Plane-Parallel Plates | $2000.00 |
| Mirror Frames | 75.00 |
| Turning Motors | 50.00 |
| Light Source | 50.00 |
| Filter | 30.00 |
| Lens | 18.00 |
| Spherical Mirror | 27.50 |
| Paraboloidal Mirror | 100.00 |
| Shutter | 40.00 |
| Camera Back | 18.00 |
| Suspension Frame | 34.00 |
| Optical Bench | 25.00 |
| Traversing Table, Switch Box, Mirror Cells, Rails, Suspension Clamps, etc. -- Shop Labor | 1500.00 |
| Temporary Set-Up | 40.00 |
| Engineering Time | 2000.00 |
| **TOTAL** | $6007.50 |

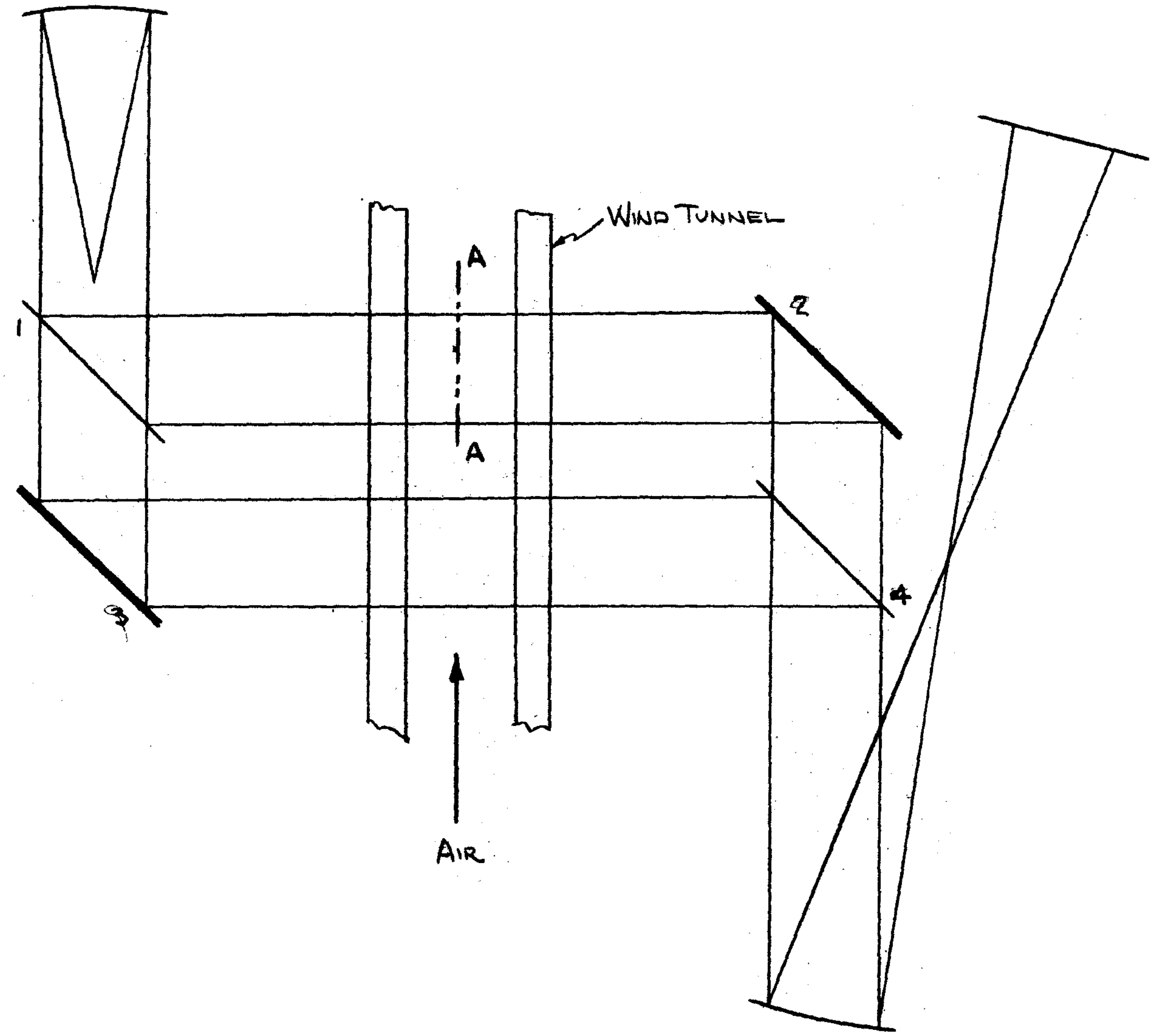

FIGURE 1

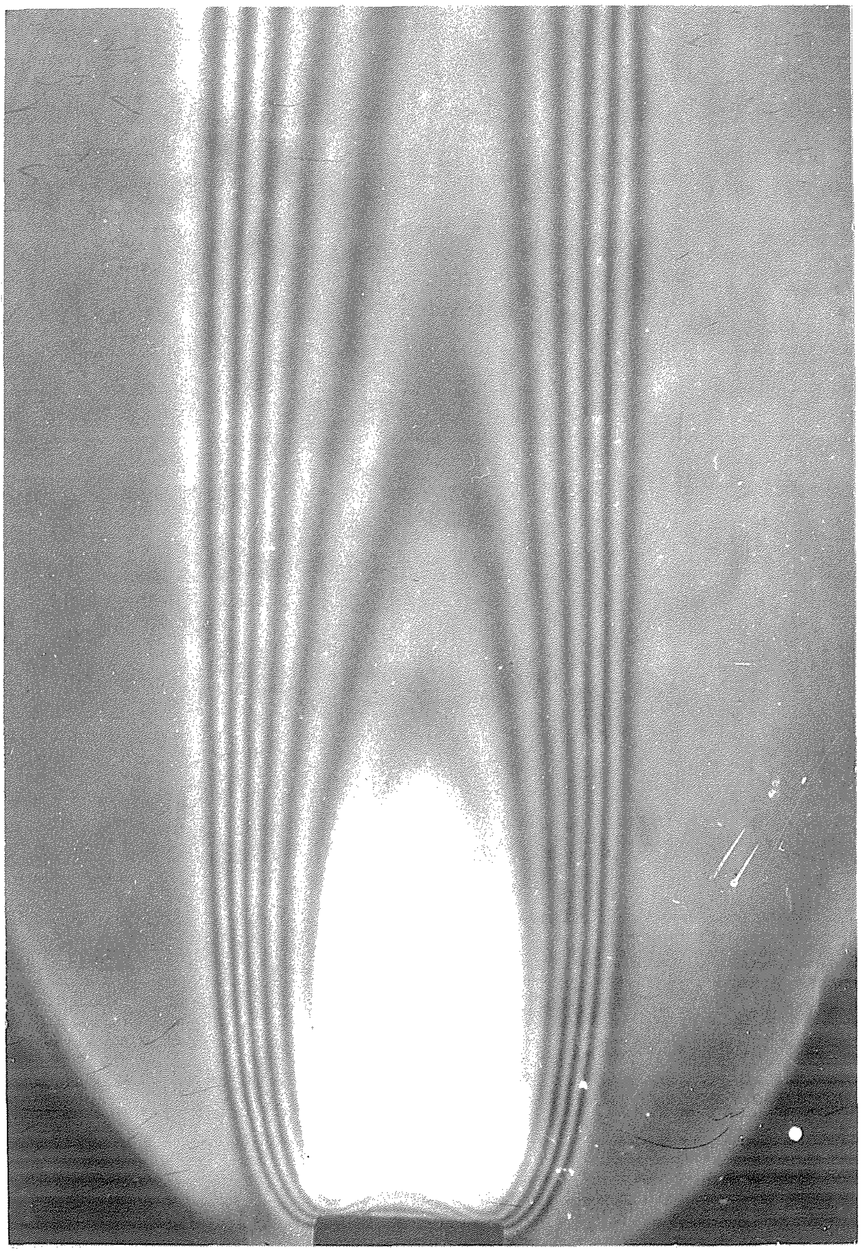

Figure 2

Bunsen Burner Flame in the Field of the Fringe of Infinite Width

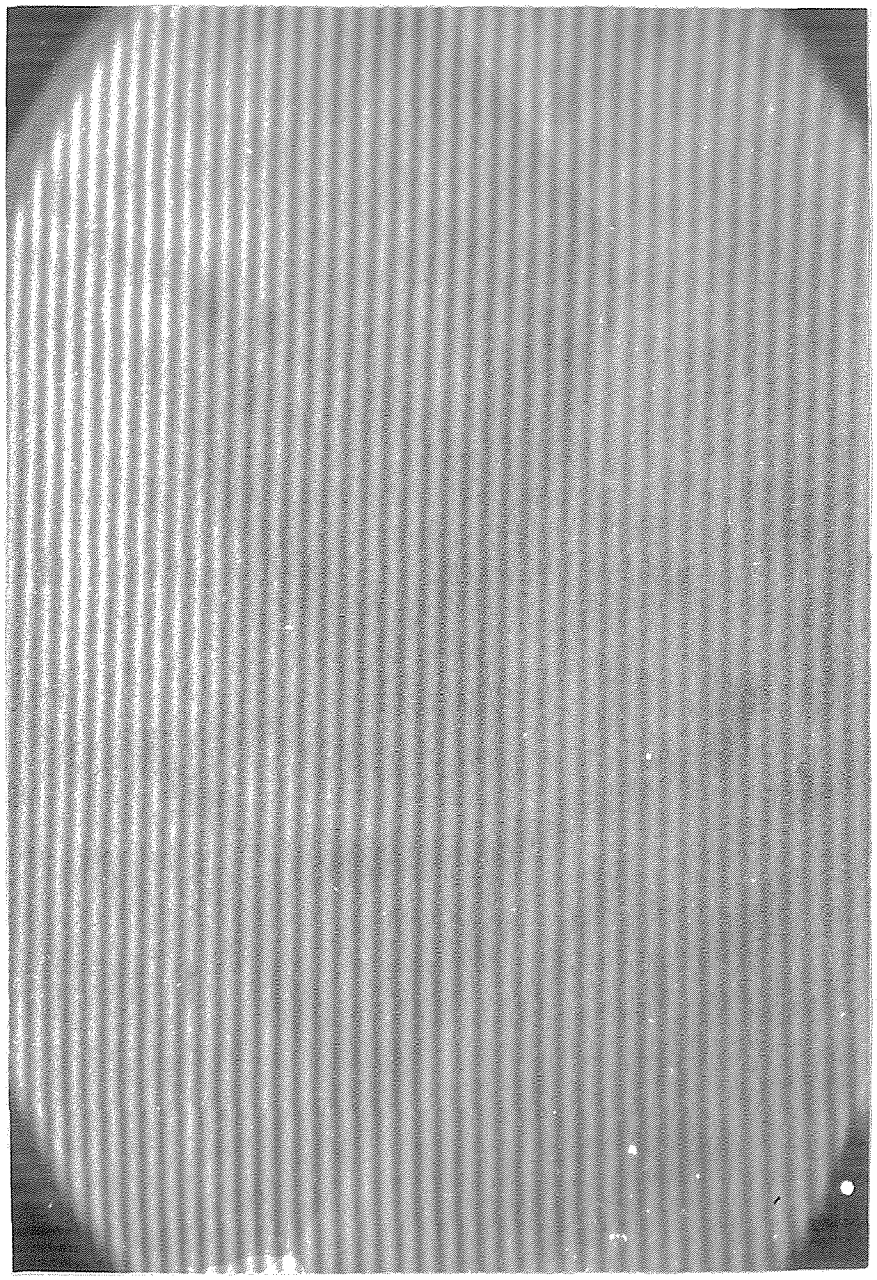

Figure 3

Vertical Fringe Pattern

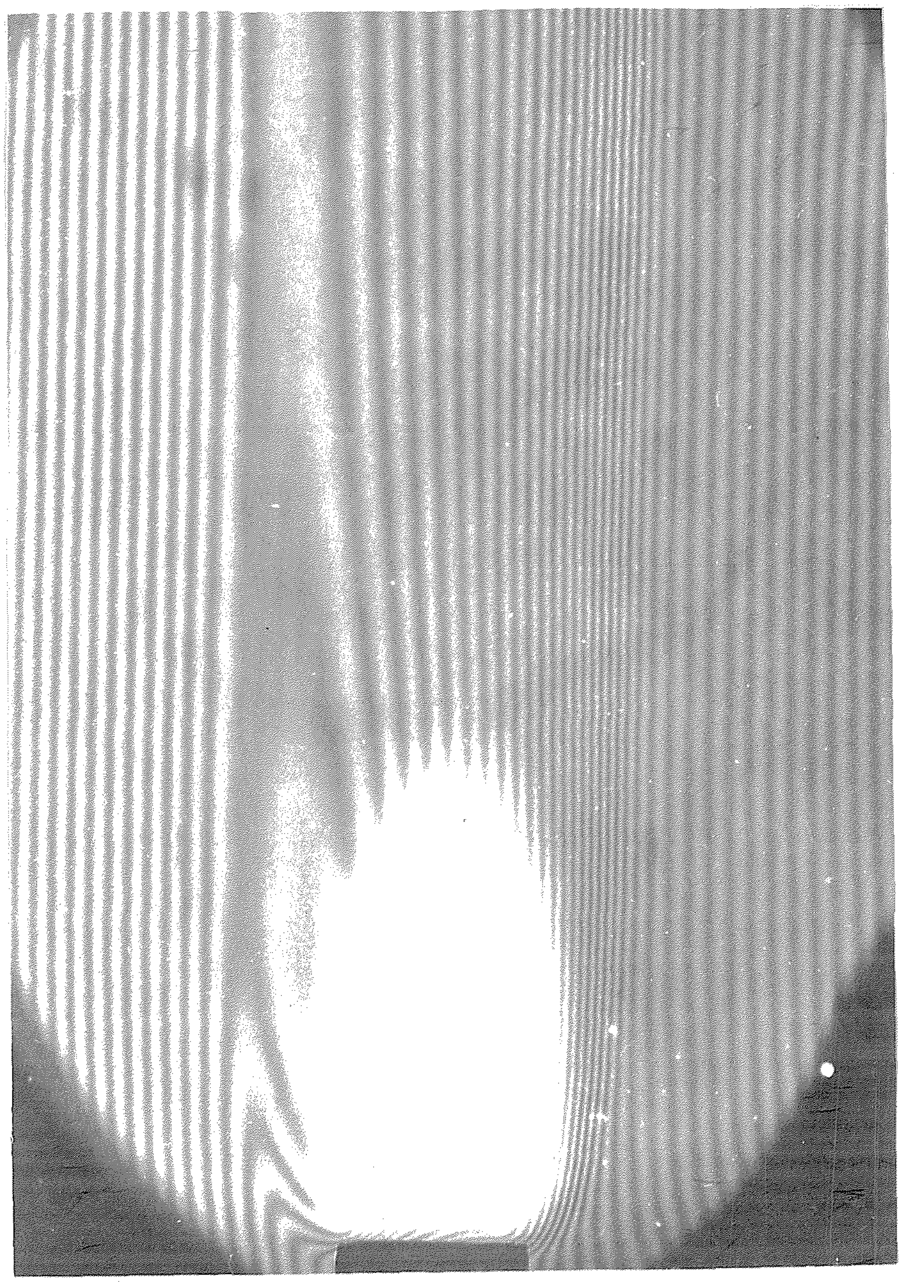

Figure 4

Bunsen Burner Flame in the Fringe Field of Figure 3

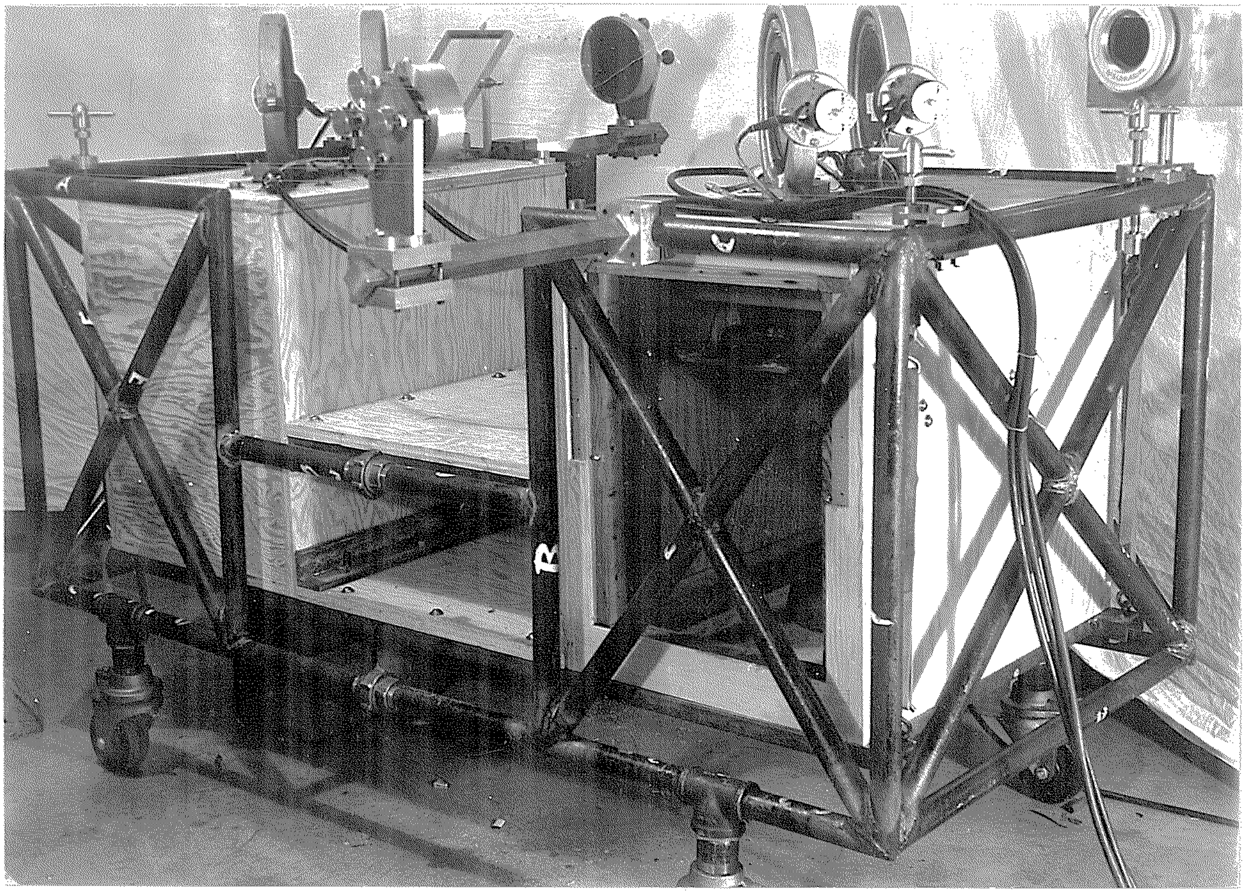

Figure 5

Three-quarter View of the Complete Instrument

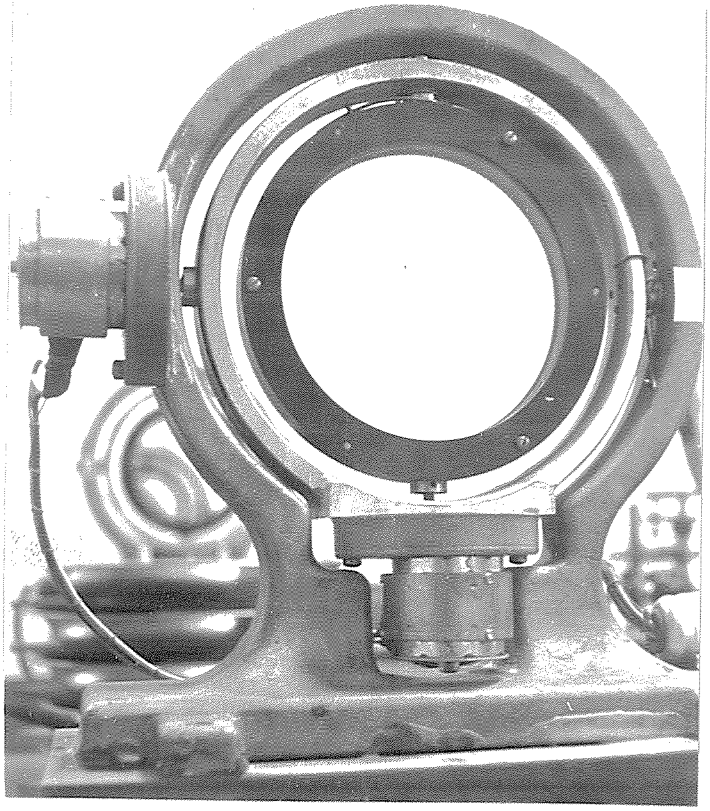

Figure 6

Close-up of Mirror Frame

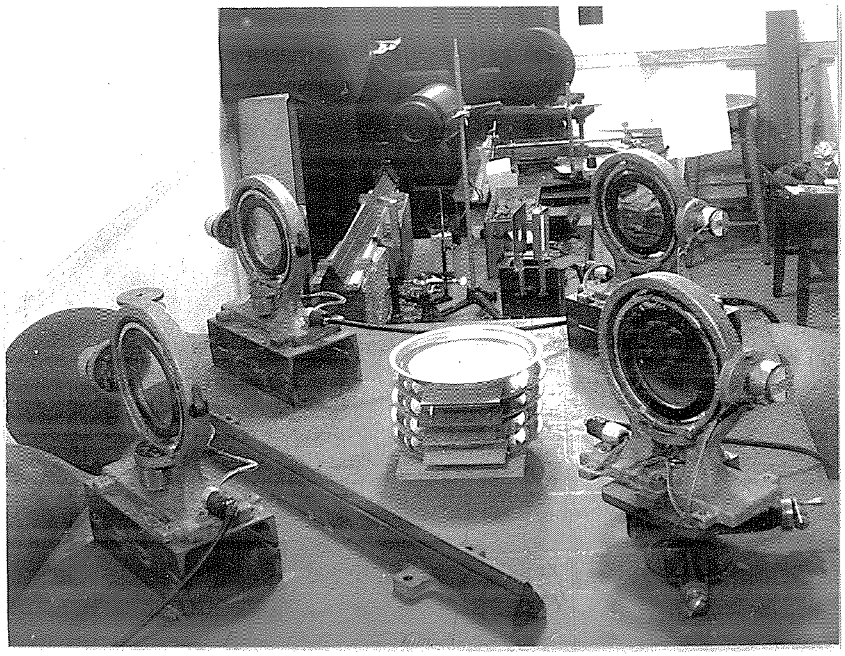

Figure 7

View of the Temporary Set-up

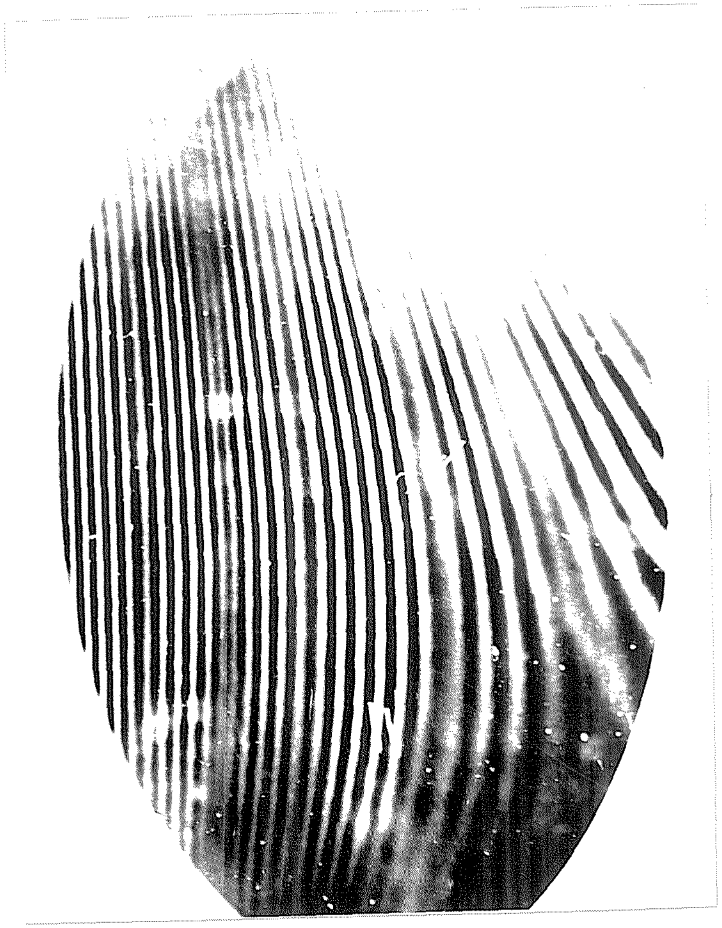

Figure 8

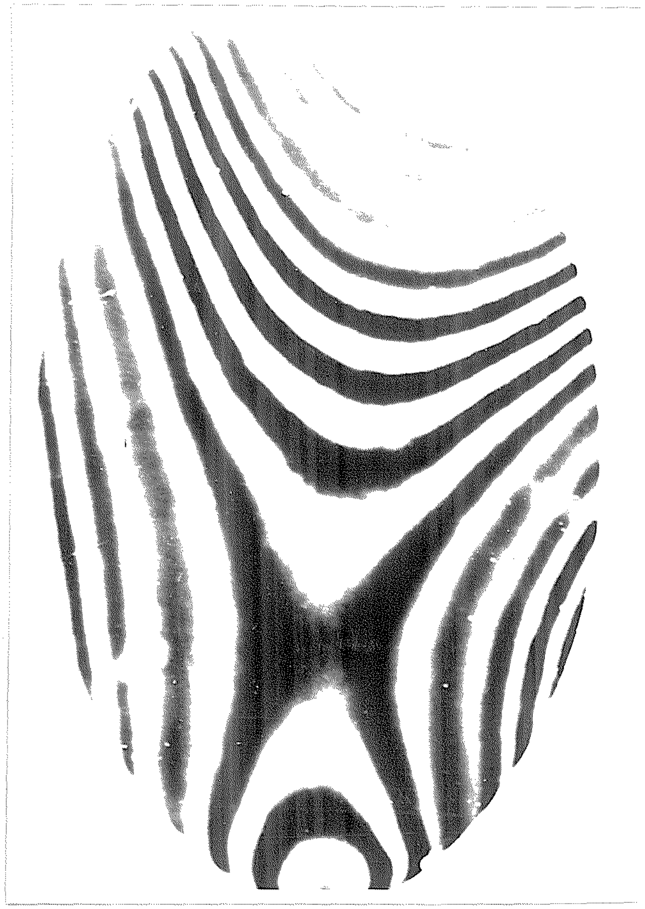

Figure 9

Distorted Fringe Patterns due to Stresses at the Edges of the Plane-parallel Plates

Figure 10

Horizontal Fringe Pattern

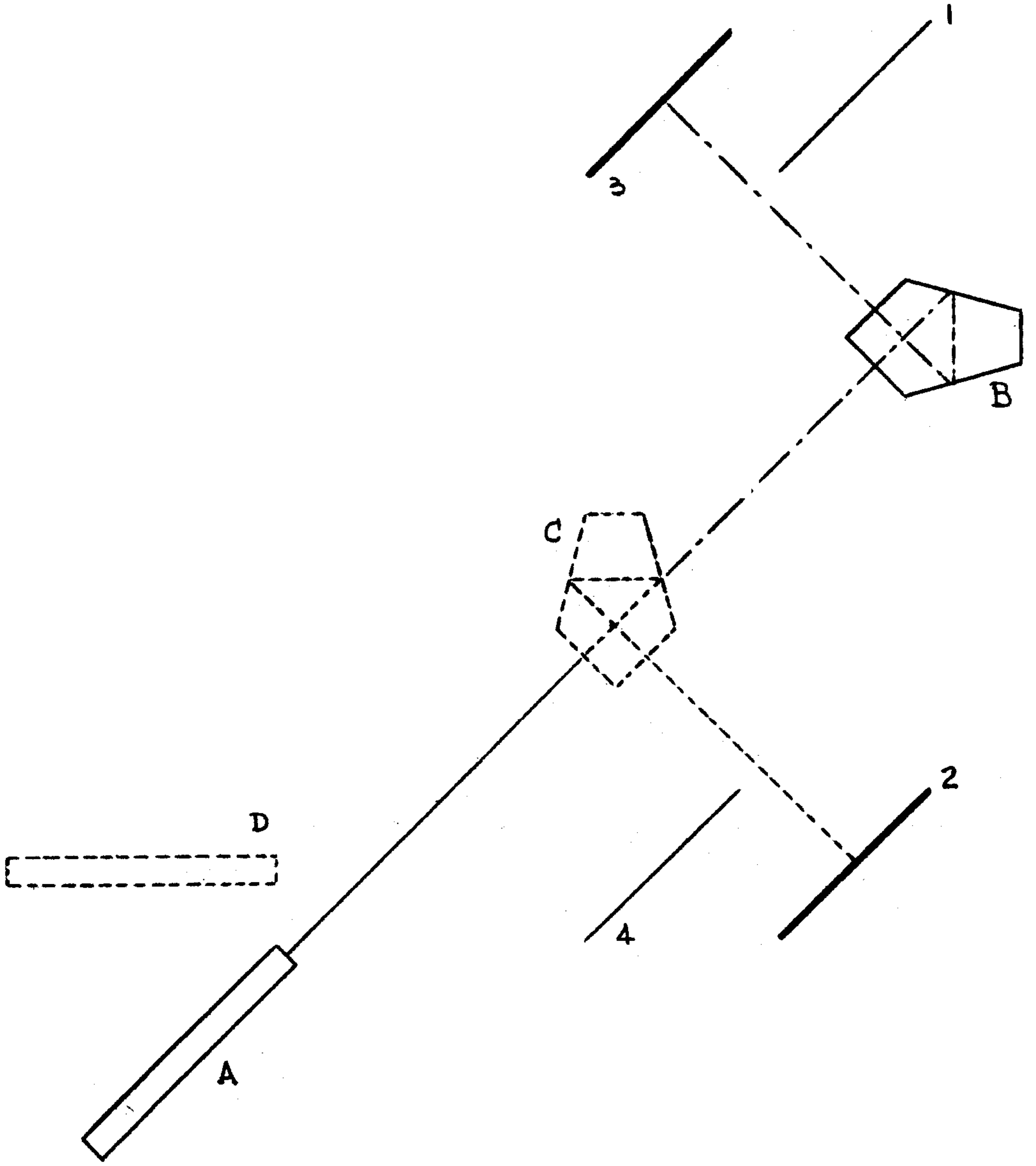

Figure 11