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A TWIN-MIRRORED GALVANOMETER LASER LIGHT SHEET GENERATOR

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SUMMARY

A galvanometer mirror-based laser light sheet system was developed for use in the Basic Aerodynamics Research Tunnel (BART) at NASA Langley Research Center. This system generates and positions single or multiple light sheets over aeronautical research models being tested in the low-speed tunnel. This report describes a twin-mirrored galvanometer laser light sheet generator and shows typical light sheet arrangements that have been used. Using this system, illumination of smoke entrained in the flow over a delta wing model reveals the vortical flow produced by the separation of the flow at the leading edge of the model. The light sheet system has proven to be very adaptable and easy to use in sizing and positioning light sheets in wind tunnel applications.

INTRODUCTION

The purpose of this paper is to describe the twin mirrored galvanometer laser light sheet generator and show typical light sheet arrangements used at the Langley Research Center's Basic Aerodynamics Research Tunnel.

Light sheets generated with either laser or noncoherent sources have found widespread applications to flow visualization. However, previous systems were usually dedicated to a specific viewing geometry. The present system was designed and developed to provide flexibility and adaptability to a wide range of applications. The design included the capability to control the size and location of the laser light sheet in real time, to generate horizontal or vertical sheets, to sweep the sheet repeatedly through a volume, to generate multiple sheets with controllable separation and to rotate single or multiple laser light sheets.

A survey of techniques used to generate light sheets showed that they included cylindrical rods and lenses, rotating glass blocks, anamorphic prisms, Bragg cells, and mirrored galvanometers. The only technique with the capability of meeting all of the design requirements is the use of mirrored galvanometers.

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A single mirrored galvanometer is required to generate either a single vertical or a single horizontal light sheet. The galvanometer mirror can be driven at scan rates up to 500 Hertz. With two mirrored galvanometers, either vertical or horizontal light sheets can be generated without changing the physical setup. This is accomplished by arranging the mirrored galvanometer axes to be mutually perpendicular. One mirrored galvanometer is used to produce deflections of up to 40 degrees in the X direction and the other mirrored galvanometer is used to produce deflections of up to 40 degrees in the Y direction (see figure 1). By applying a triangular waveform to only the X or Y axis scanner, a horizontal or vertical light sheet will be produced, respectively. Although the galvanometer mirrors used in this test limit the radiated laser power to approximately 4 watts, higher quality mirror coatings should raise this power restriction.

The angular extent of one axis of the light sheet is directly proportional to the amplitude of the drive signal and can be up to 40 degrees while the angular extent of the other axis is determined by the laser beam divergence. The location of the light sheet can be changed by varying the direct current bias to each mirrored galvanometer. To sweep out a volume, one mirrored galvanometer is driven with a high-frequency triangular waveform (to generate the light sheet), while the other mirrored galvanometer is driven with a low frequency triangular waveform or a low frequency sawtooth waveform. The low frequency waveform can be thought of as a slowly varying bias which smoothly shifts the location of the light sheet.

GENERATING MULTIPLE LIGHT SHEETS

By replacing the low frequency waveform with a stepped waveform, multiple light sheets can be generated. For example, two vertical light sheets can be formed when a high-frequency triangular waveform is applied to the Y-axis scanner, to produce a vertical light sheet, and a low frequency square waveform is applied to the X-axis scanner to produce two laser light sheets angularly displaced in the horizontal axis. The height of both light sheets is controlled by varying the amplitude of the high-frequency triangular waveform to the Y-axis scanner. The location of the pair of light sheets is controlled by varying the direct current bias to each mirrored galvanometer. The angular separation between the two light sheets is controlled by varying the amplitude of the square wave signal to the X-axis scanner. Generation of more than two light sheets requires a stepped signal (see figure 2).

A circuit that was developed to generate one to twelve sheets, selected with a thumbwheel switch, is shown in figure 3. The NE555 timing chip, U1, is wired as an astable multivibrator and is used to generate the stepping frequency. The stepping frequency can be adjusted with R3 (a 10K Ω resistor). Alternately, the step/single switch is used to select single steps each time the single step button is pressed. The number of steps (1-12) is selected with the 12-position, 4-pole switch. The 74LS20 NAND gate, U2, resets the 74LS161 counter, U3, when the selected number of sheets has been produced. The binary coded outputs from U3 are also sent to the DAC0808LCN digital-to-analog converter (DAC), U4. The output current from the DAC is converted to a voltage by the transimpedance amplifier U5. The output of U5 is fed to amplifier/adder U6 which has four inputs. In addition to the stepped voltage waveform from U5, U6 has as inputs a variable offset and two auxiliary inputs. The auxiliary inputs will be discussed in a later section on rotating multiple light sheets. The 2N2222 transistor, Q1, and associated timing chip NE555, U7, generate blanking pulses. The timing chip, U7, is connected as a monostable multivibrator. The blanking pulses are routed to an acousto-optical Bragg cell to shutter, or blank, the laser beam when the step transitions occur. This eliminates the lines between light sheets. Transistor Q2 serves to buffer and invert the blanking pulse from U7. The blanking pulse is used to gate the 40 MHz drive from the Bragg cell modulator to the Bragg cell. The first order output beam from the Bragg cell is used to produce the light sheets. Gating the 40 MHz Bragg cell drive blanks the laser beam.

ASTIGMATISM, ITS CAUSE AND ELIMINATION

While the use of the mirrored galvanometers to generate light sheets is simple, the most common arrangement produces astigmatic sheets. Astigmatic light sheets are sheets of light which appear to be formed by a source at one location for horizontal sheets and another location for vertical sheets. This is the direct result of the relative displacement of the two scanners along the optical axis. Figure 4a and 4b illustrate the production of astigmatic sheets. Figure 4a depicts a two-axis, two-sheet generator. The light sheet is generated by driving the Y-axis mirrored galvanometer with a triangular wave. Two light sheets are produced by simultaneously driving the X-axis mirrored galvanometer with a square wave. Tracing the rays of the light sheet back to their virtual source reveals the astigmatism. Similarly, figure 4b depicts a two-axis, two-sheet generator with the generation sequence reversed from figure 4a. The input beam is stepped in angle by a square wave applied to the X-axis mirrored galvanometer while the light sheets are generated by a triangular wave applied to the Y-axis mirrored galvanometer. Tracing the light sheet rays back to their virtual sources reveals the astigmatism.

In most situations, the astigmatism is not perceivable. The system would be set up such that the horizontal spread would be minimized and the resulting vertical spread would not be detectable unless the light sheet was rotated, in which case the astigmatism would be pronounced and the sheet width would vary with rotation angle. The astigmatism can be minimized by reducing the optical separation between the two scanners.

Another method which eliminates the astigmatism also results in higher scan rate capability. Figure 5 shows this method of eliminating the astigmatism. Lens L2 is used to image the Y-axis scanner mirror at a magnification of one and coincident with the X-axis scanner. Tracing the resulting light sheet rays back to their source shows that the source is real and located at the same point for both axes. Lens L2, however, introduces divergence to both axes. If L1 and L2 are set to be afocal, the beam exiting L2 will be recollimated. Shifting L1 along the optical axis will shift the laser beam waist along the light sheets allowing the beam waist to be placed at the point of interest in the flow field.

A significant advantage of this system over the more common astigmatic scanners is the reduction in size of the second scanner mirror. Now both mirrors can be reduced to a diameter of only two or three times of the input beam diameter. The smaller equal size mirrors yield a higher and equal axis frequency response for the system.

GENERATING PARALLEL DISPLACED LIGHT SHEETS

One drawback of mirrored galvanometer scanners is that the light sheets are not parallel to each other but diverge. This means that for a multiple light sheet display only one sheet can be truly perpendicular to the flow. For a swept light sheet display, the light sheet is perpendicular to the flow only at one instant during the sweep. This problem can be rectified with the addition of a large lens or parabolic mirror. Figure 6 illustrates the use of a large parabolic mirror with a multiple light sheet generator. The scanner is placed such that the point of origin of the light sheets is at the focal point of the mirror. The mirror serves to collimate the light sheets rendering them parallel to each other. A similar effect is produced for a swept light sheet display. The light sheet, after being collimated, will now translate without rotation as it is being swept by the scanner.

This technique can be readily applied to some of the wind tunnels at the Langley Research Center by utilizing the existing schlieren mirrors. Alternately, the expense of a mirror can be justified on the basis of its suitability for the light sheets and for schlieren applications. For small diameter tunnels or flow fields, the schlieren mirror can be replaced with a lens yielding the same results.

ELECTRONIC ROTATION OF A SINGLE LASER LIGHT SHEET

One feature not directly achievable with typical X-Y scan systems is the capability to rotate a single light sheet through 360 degrees. Figure 7 depicts two desirable rotations. The first, figure 7a, is a rotation about an edge of the fanned light sheet. The second, figure 7b, is a rotation about the fan bisector. Several schemes to accomplish this rotation were investigated. They included, direct computer generation of drive signals, a read only memory (ROM) based system and a complex array of preset potentiometers. All of these methods were ruled out as being too complex and/or requiring a long development time. Another approach, the use of a sine/cosine potentiometer, was investigated. This approach yielded the desired result with a reasonable cost and was prototyped in a single day. It is based on technology developed during the early 1940's to generate plan position indicator (PPI) displays for radar systems (Reintjes, et al., 1952). However, this is the first known application to an optical system.

Figure 1 showed a simplified layout of a two-axis laser light sheet system. If a sinusoidal waveform is applied to the Y galvanometer, a vertical ($\theta=0^\circ$) light sheet will be formed as the laser beam is repeatedly scanned through a vertical arc. If the sine wave is applied to only the X galvanometer, a horizontal ($\theta=90^\circ$) light sheet will result. In order to generate a light sheet at any angle θ , the X galvanometer should be fed a signal equal to the input sine wave times $\sin\theta$ and the Y galvanometer should be fed a signal equal to the input sine wave times $\cos\theta$. In practice, a sawtooth or triangular waveform is used for the input instead of a sinewave (see figure 8). The use of linear waveforms yields a fanned beam of uniform intensity. A sinusoidal waveform produces a light sheet that is brighter at the edges than the center, following the probability distribution of the input signal.

The operation of a sine/cosine potentiometer can be explained with figure 9. Shown is a resistance card with two opposing end contacts and central center taps. A rotary arm is provided with two insulated wipers 90 degrees apart. If a voltage of +1 volt and -1 volt is applied to the end contacts, the potential at the center tap will be 0 volts. Initially the potential of the vertical wiper (cosine) will be +1 volt and the potential of the horizontal wiper (sine) will be 0 volts. As the rotary arm is turned through 90 degrees, the cosine output will decrease to 0 volts and the sine output will increase to +1 volt. Turning through another 90 degrees, the cosine output will decrease to -1 volt and the sine output will again go to 0 volts. Therefore, the sine and cosine outputs will be equal to the sine and cosine of the angular position of the rotary arm times the input voltage (1 volt). If the input voltage is replaced with a triangular waveform and the sine and cosine outputs feed to the X and Y galvanometers respectively, the laser light sheet will rotate in direct correspondence to the position of the rotary arm.

The schematic of the electronics used to rotate the light sheet is included as figure 10. The input waveform is combined with a buffered variable offset and inverted with operational amplifier U2. The variable offset determines the axis of rotation for the laser light sheet. If the offset is zero, the light sheet will rotate about the line determined when the sweep input is zero. Varying the offset will shift the axis of rotation in the plane of the laser light sheet. Figure 7 depicted two possible choices. In figure 7a, the offset is zero. In figure 7b, the offset is minus one-half the peak value of the sweep input signal, resulting in rotation about the fan bisector. Operational amplifier U2, figure 10, inverts the input sweep waveform and adds to it an adjustable offset from the high impedance buffer U1. Operational amplifier U3 is a high impedance unity gain inverter used to generate a negative replica of the output of operational amplifier U2. The output of operational amplifiers U2 and U3 are fed to the + and - end contacts of the sine/cosine potentiometer respectively. Since the + and - signals are of the same shape but opposite in polarity, the center taps of the sine/cosine potentiometer are at 0 volts and are connected to ground. The sine and cosine outputs from the potentiometer wipers are buffered with high impedance unity gain amplifiers (operational amplifiers U4 and U5). The buffered outputs are connected to the X and Y galvanometer drivers.

The prototype was tested by substituting the X and Y inputs of an oscilloscope for the galvanometers. If the oscilloscope is left connected to the X and Y outputs while the galvanometers are connected, the oscilloscope can be used to remotely monitor the position of the light sheet in real time. This method of remotely monitoring the light sheet is equally applicable to multiple or position swept laser light sheets.

ROTATION OF MULTIPLE LASER LIGHT SHEETS

The next development that logically follows the single laser light sheet rotator is the ability to rotate multiple laser light sheets. This is accomplished with the addition of an adder circuit internally located in the multiple sheet generator, see figure 11. The sweep waveform is fed into the electronic sheet rotator as though a single laser light sheet is to be produced. The Y output from the rotator is routed directly to the Y-axis driver/amplifier. The X output is sent to the B input of the multiple sheet generator. The multiple sheet generator is set to produce a single sheet. The multiple sheet generator output is connected to the X-axis driver/amplifier. With no signal applied to the A input, a single laser light sheet is produced. If a low frequency sawtooth waveform is applied to the A input, the rotatable single laser light sheet should slowly sweep in a horizontal direction. If multiple sheets are selected at the multiple sheet generator, multiple laser light sheets, horizontally displaced, should be produced. The angular separation between the light sheets would be a direct function of the amplitude of the internal stepped signal. All of the laser light sheets will rotate in unison as the sine/cosine potentiometer is rotated.

RESULTS

Figures 12 through 14 illustrate typical uses of the twin-mirrored light sheet generator in the Basic Aerodynamics Research Tunnel. Figure 12 shows a single vertical laser light sheet, rotated to be perpendicular to the model, above a 75° swept delta wing at an angle-of-attack of 20.5°. Propylene glycol, vaporized at a temperature of approximately 380 °F, produces the smoke which reflects the laser light. The laser light sheet reveals the primary vortices produced by the separation of the flow at the leading edge of the model. Figure 13 shows the single laser light sheet rotated so that the plane of the light sheet passes through the primary vortices along the vortex axis for the same model and condition of figure 12. Figure 14 shows the capability of the light sheet generator to produce multiple light sheets over a F-18 model at an angle-of-attack of 25°. The light sheets are rotated to be perpendicular to the model and are equally spaced along the model. Figure 15 is a photograph

of the complete unit. The electronics and laser are mounted on a portable platform that is easily adjusted in height. The twin-mirrored galvanometer unit is supported by the tripod on the right. The twin-mirrored galvanometer is mounted on the same plate as the laser, but the tripod was added to reduce vibration.

CONCLUDING REMARKS

The laser light sheet system at BART is an evolving system. Initially the system was configured to generate single horizontal or vertical laser light sheets. The capability to generate multiple laser light sheets or sweep the position of a single sheet was added next. The capability to rotate a single laser light sheet using a sine/cosine potentiometer was then added. Rotating multiple laser light sheets was achieved by adding the rotation output to the multiple sheet generator. The latest addition is the Bragg cell to remove the spurious lines between sheets. The addition of each new capability was accomplished without compromising the existing capabilities. The system is capable of producing up to 12 sheets of laser light at an angular divergence of ± 20 degrees. Maximum scan rate for any line is approximately 500 Hertz. The scan rate of the generated line along the orthogonal axis is also controlled. The time averaged line can be rotated to any desired degree and it can be positioned in a lateral or vertical direction by up to 40 degrees.

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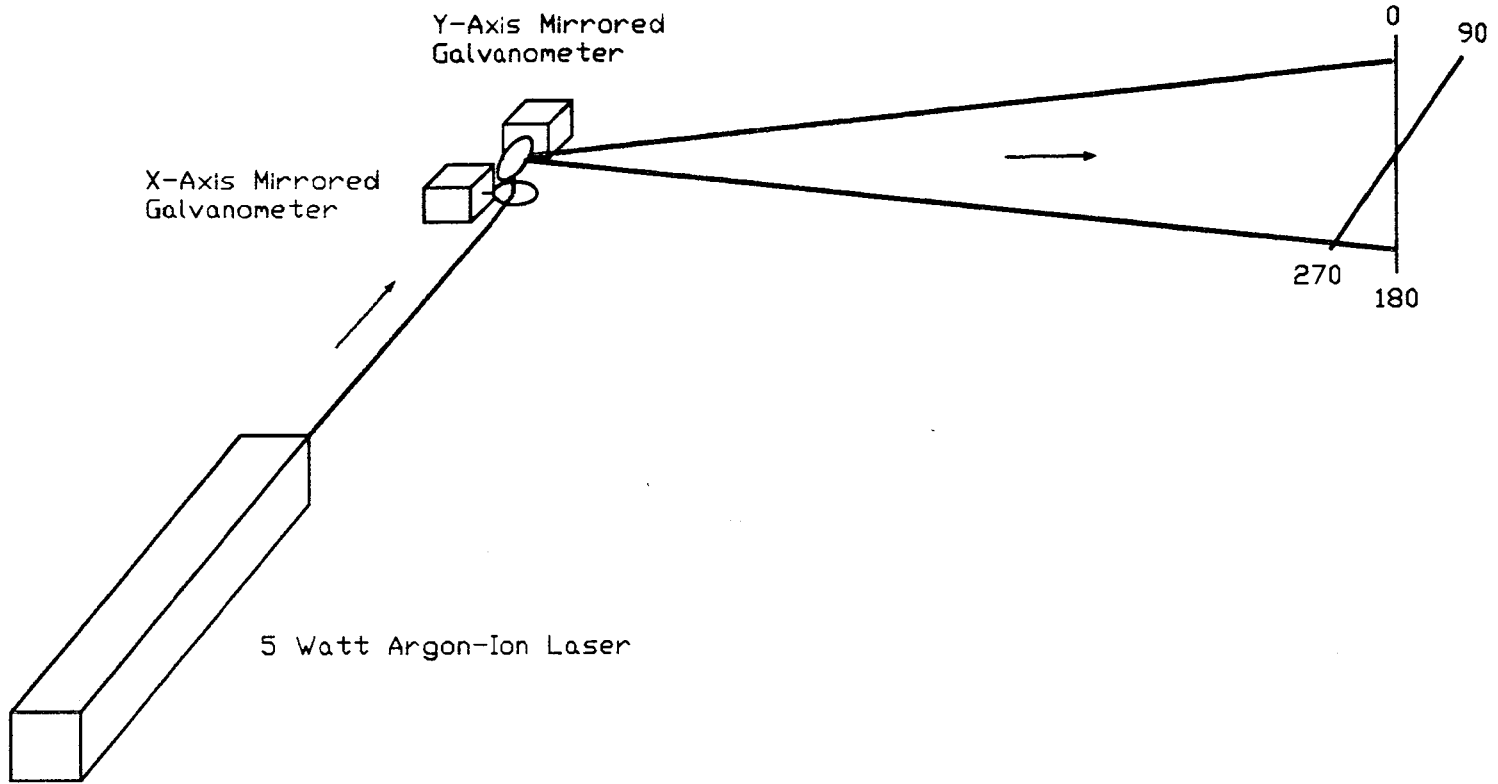
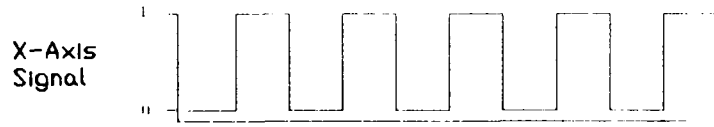


FIGURE 1: SIMPLIFIED LAYOUT OF THE LASER LIGHT SHEET GENERATOR AT BART.



a. Two light sheets.



b. Three light sheets.



c. Four light sheets.

FIGURE 2: WAVEFORMS TO GENERATE MULTIPLE LASER LIGHT SHEETS.

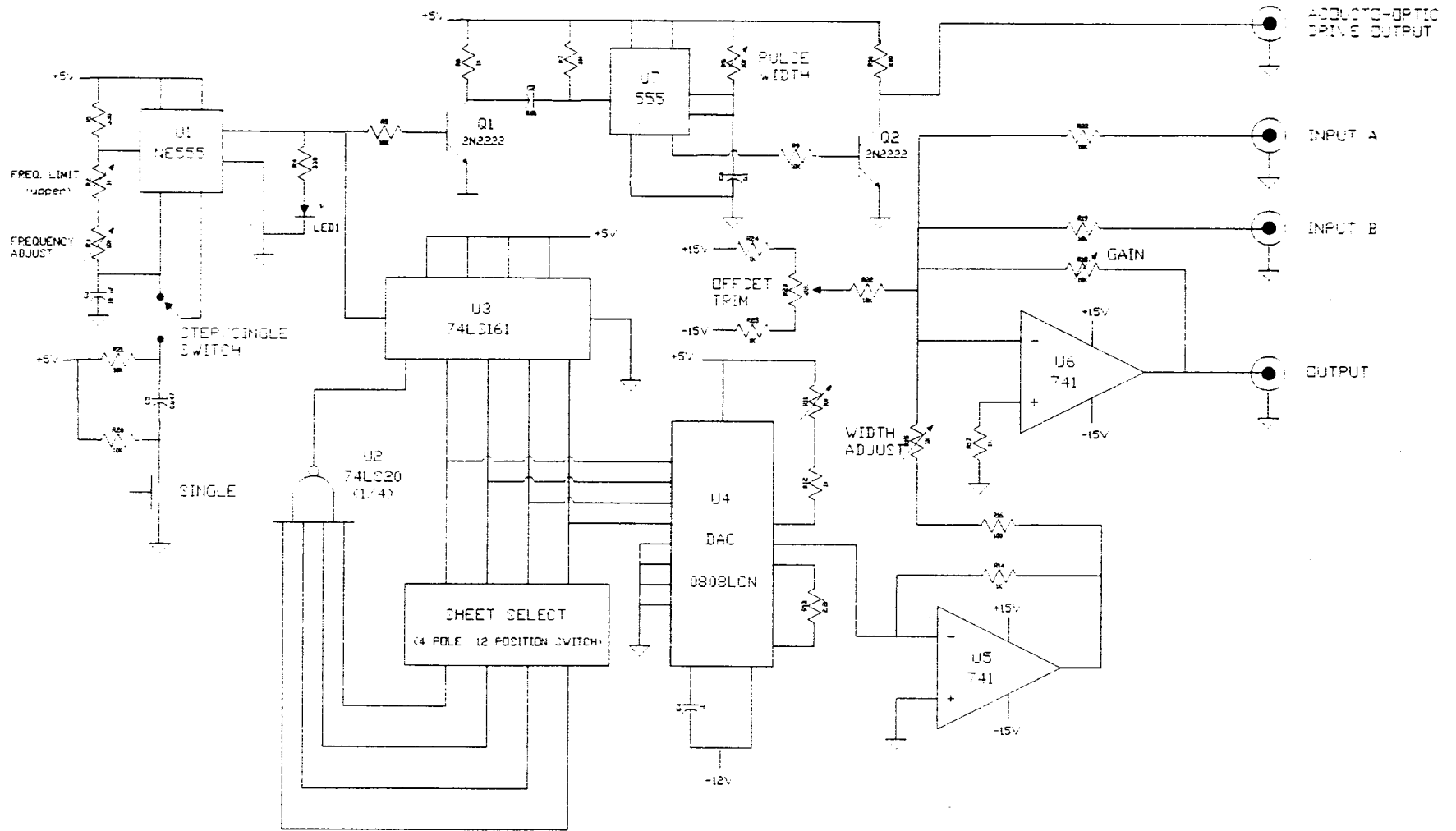
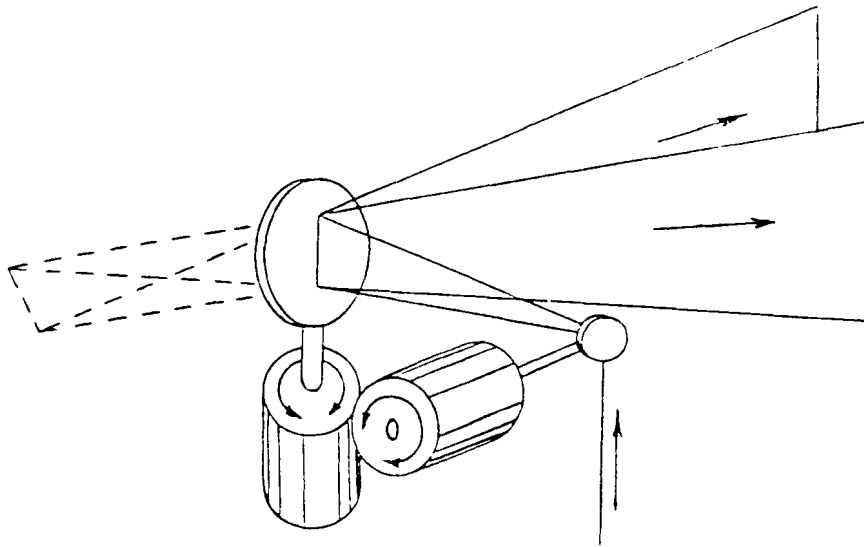
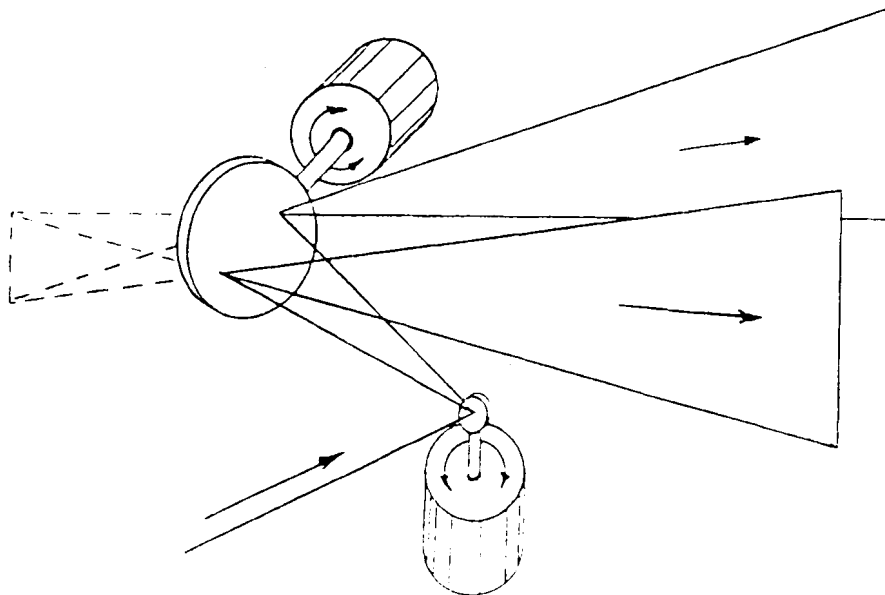


FIGURE 3: SCHEMATIC OF MULTIPLE SHEET GENERATOR



a. Vertical scan followed by horizontal angular displacement.



b. Horizontal angular displacement followed by vertical scan.

FIGURE 4: ASTIGMATISM WITH DISPLACED SCANNERS.

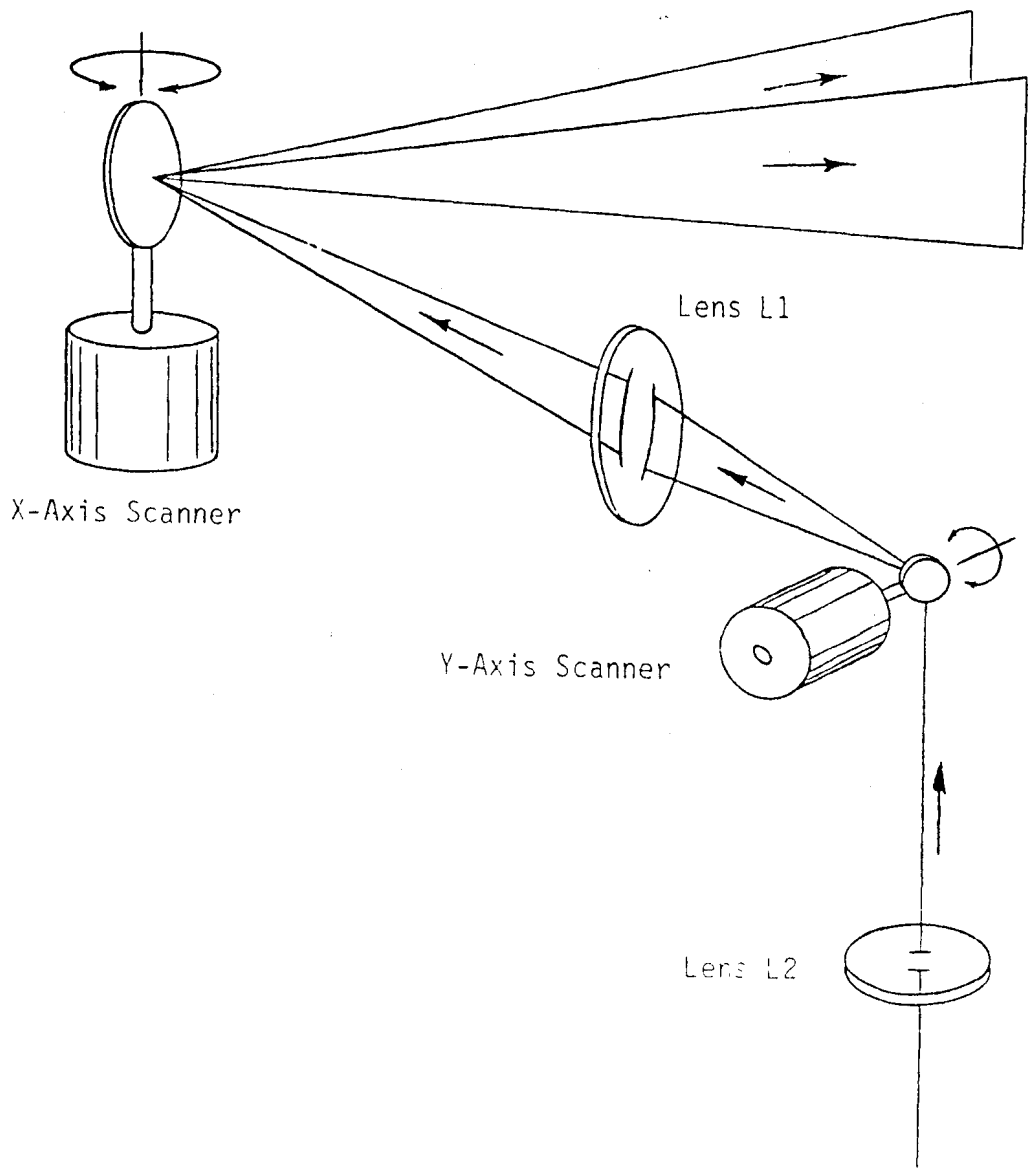


FIGURE 5: DUAL AXIS SCANNER WITHOUT ASTIGMATISM.

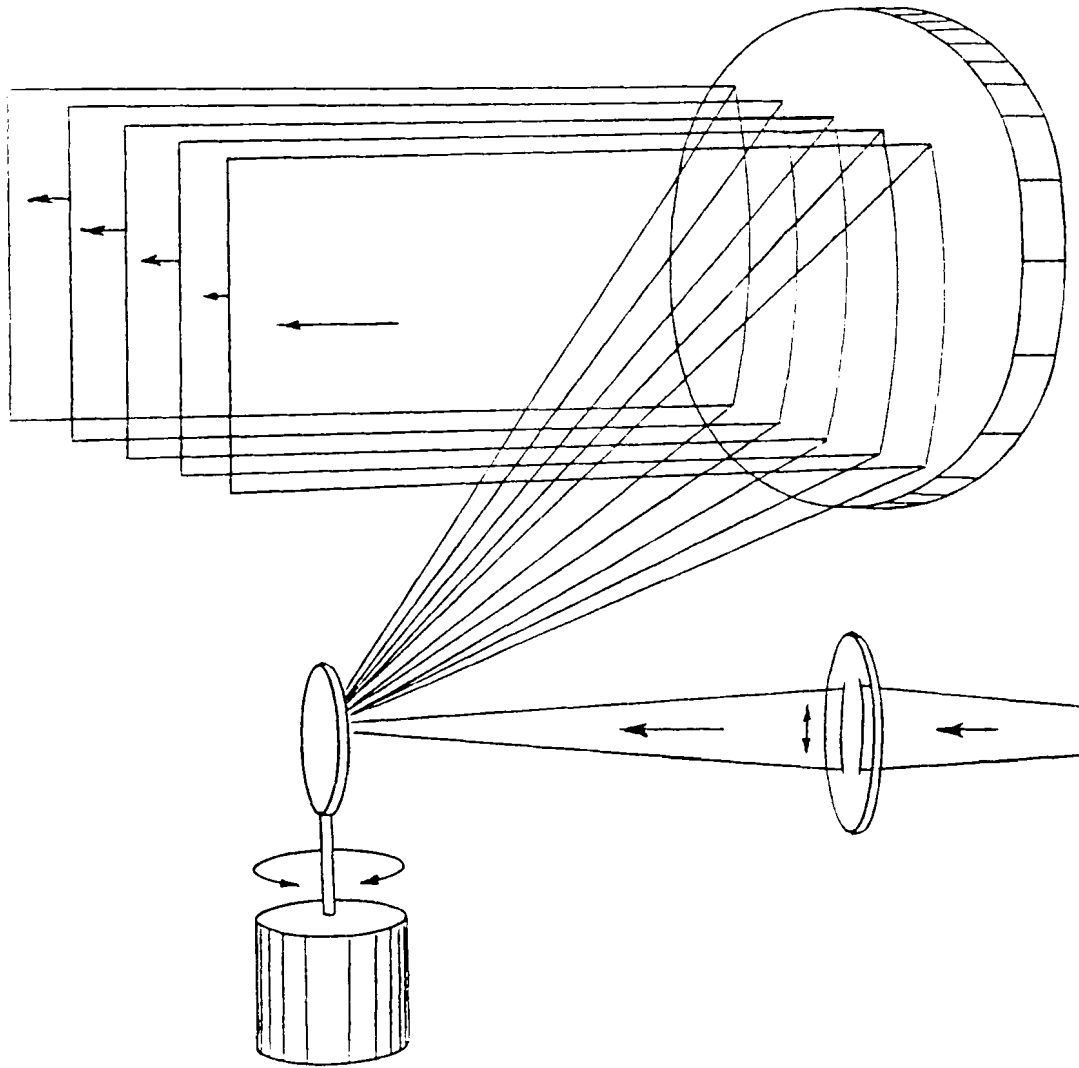
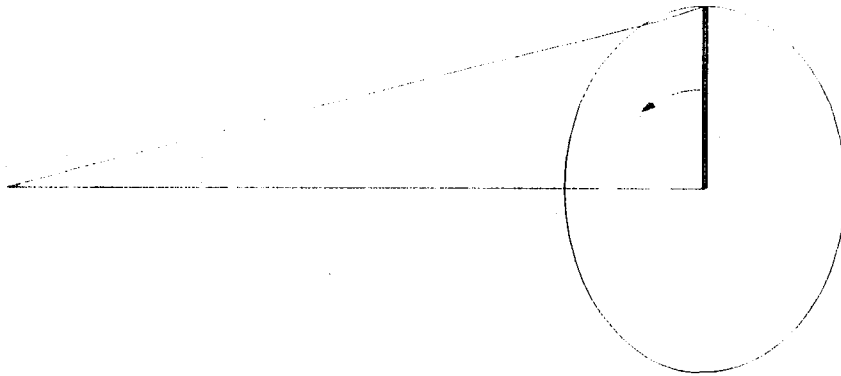
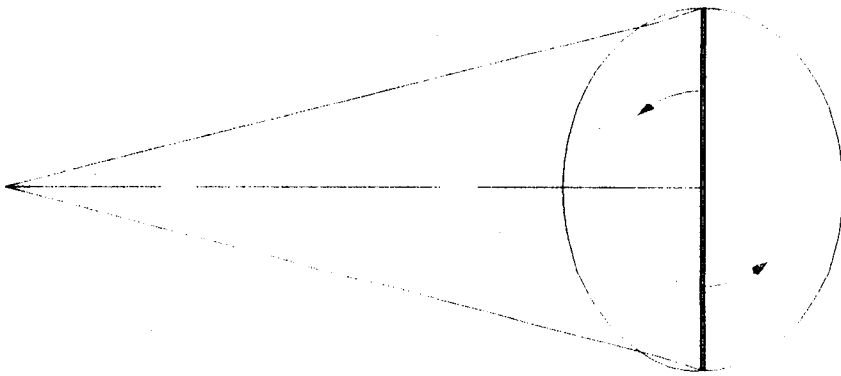


FIGURE 6: METHOD OF GENERATING PARALLEL LASER LIGHT SHEETS.



a. Rotation about the light sheet edge.



b. Rotation about the light sheet bisector.

FIGURE 7: TWO DESIRED MODES OF ROTATION
FOR A LASER LIGHT SHEET.

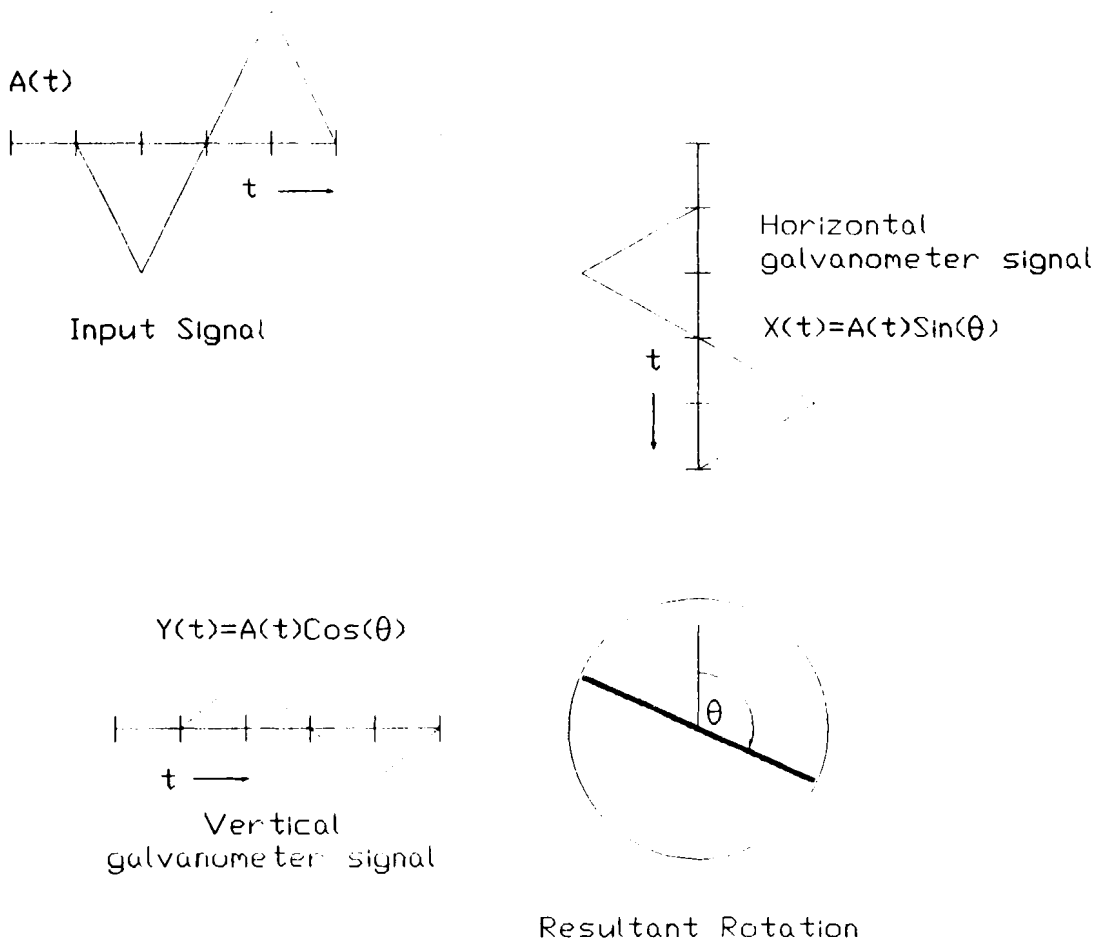


FIGURE 8: X AND Y SIGNALS REQUIRED FOR ROTATION OF LASER LIGHT SHEET.

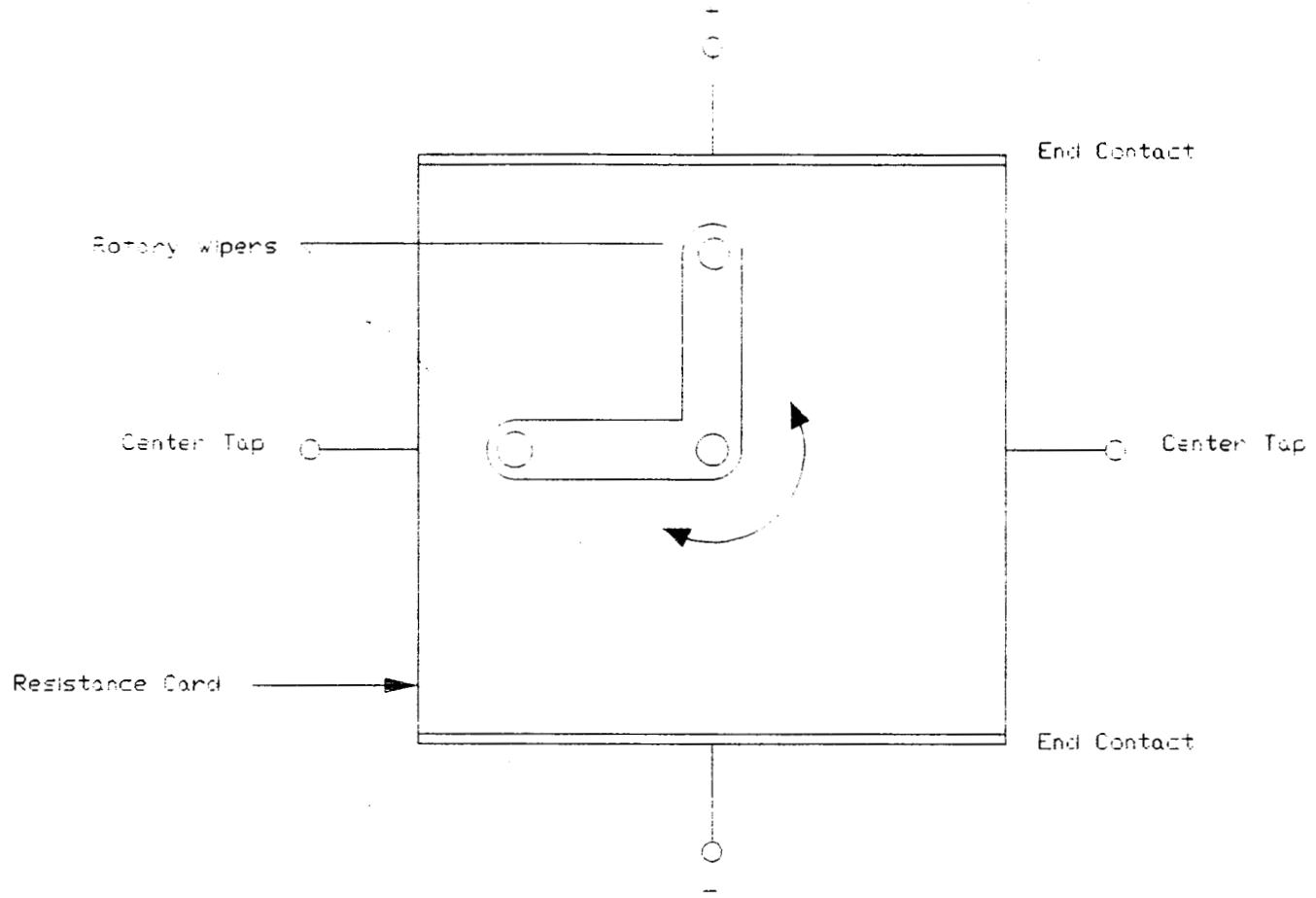


FIGURE 9: SIMPLIFIED VIEW OF SINE/COSINE POTENTIOMETER.

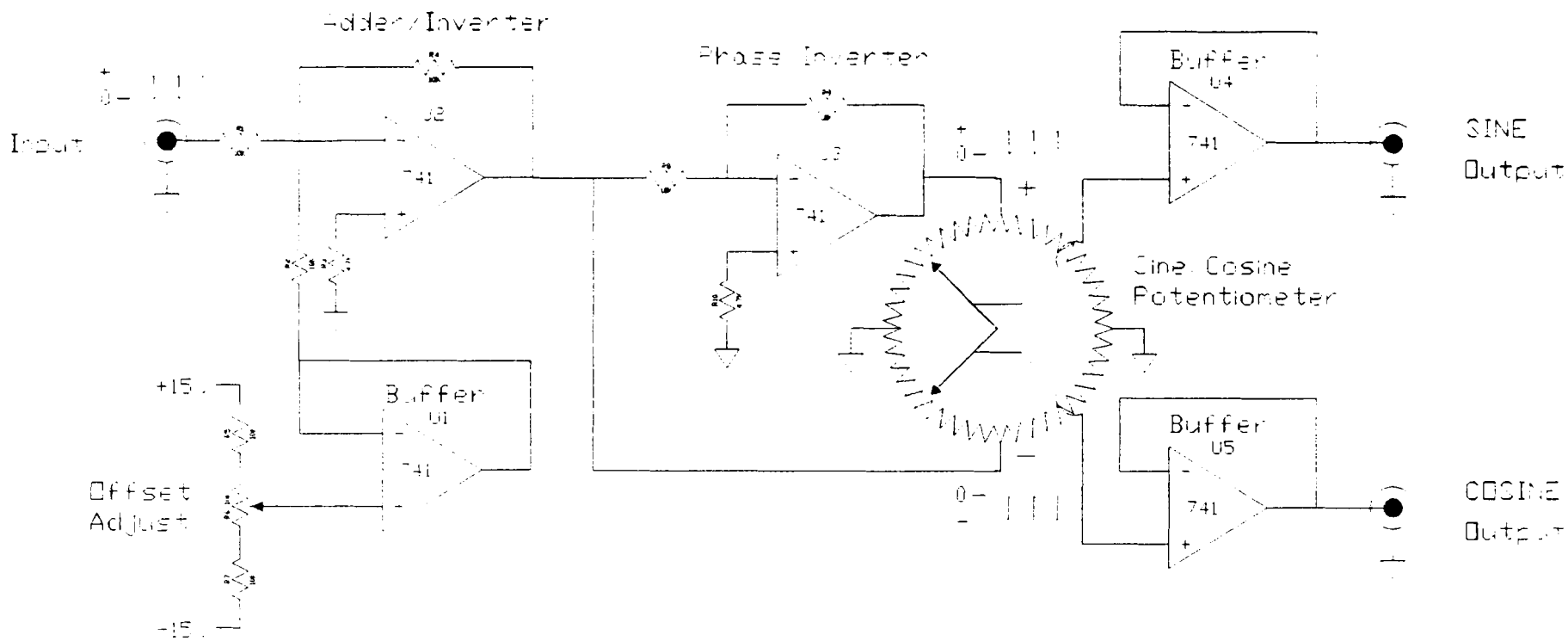


FIGURE 10: LASER LIGHT SHEET ROTATOR SCHEMATIC

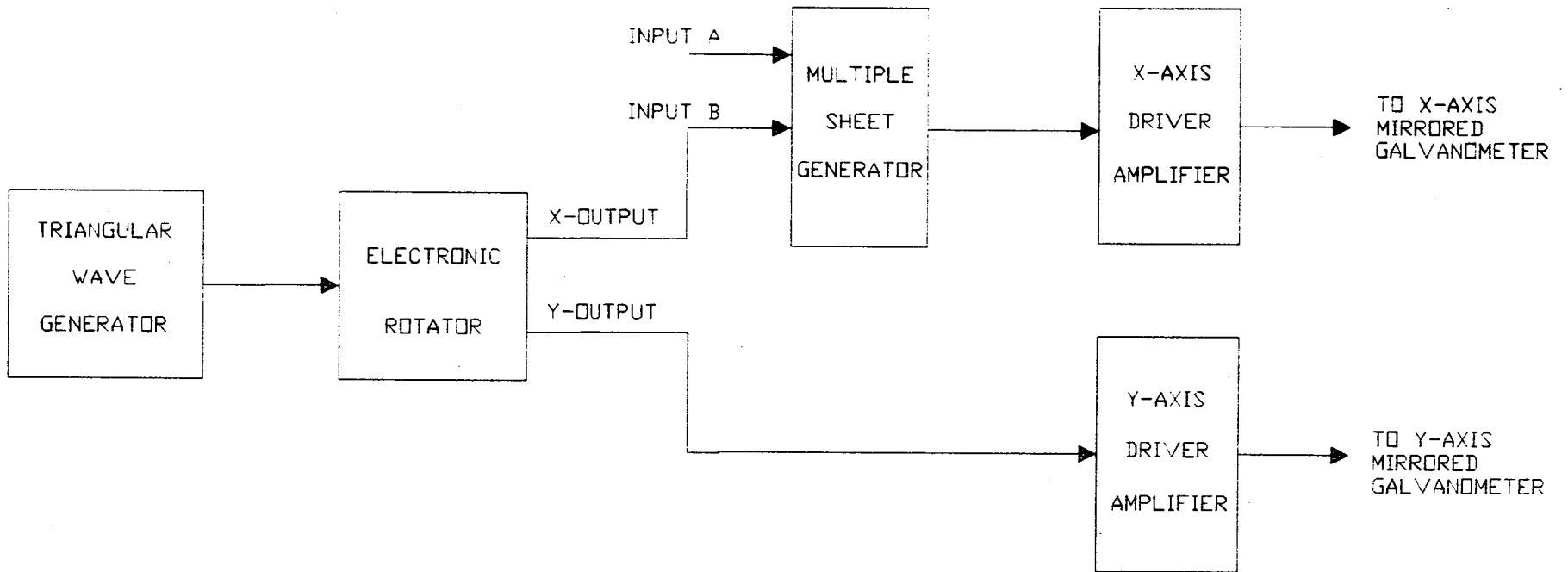


FIGURE 11: BLOCK DIAGRAM OF LASER LIGHT SHEET SYSTEM

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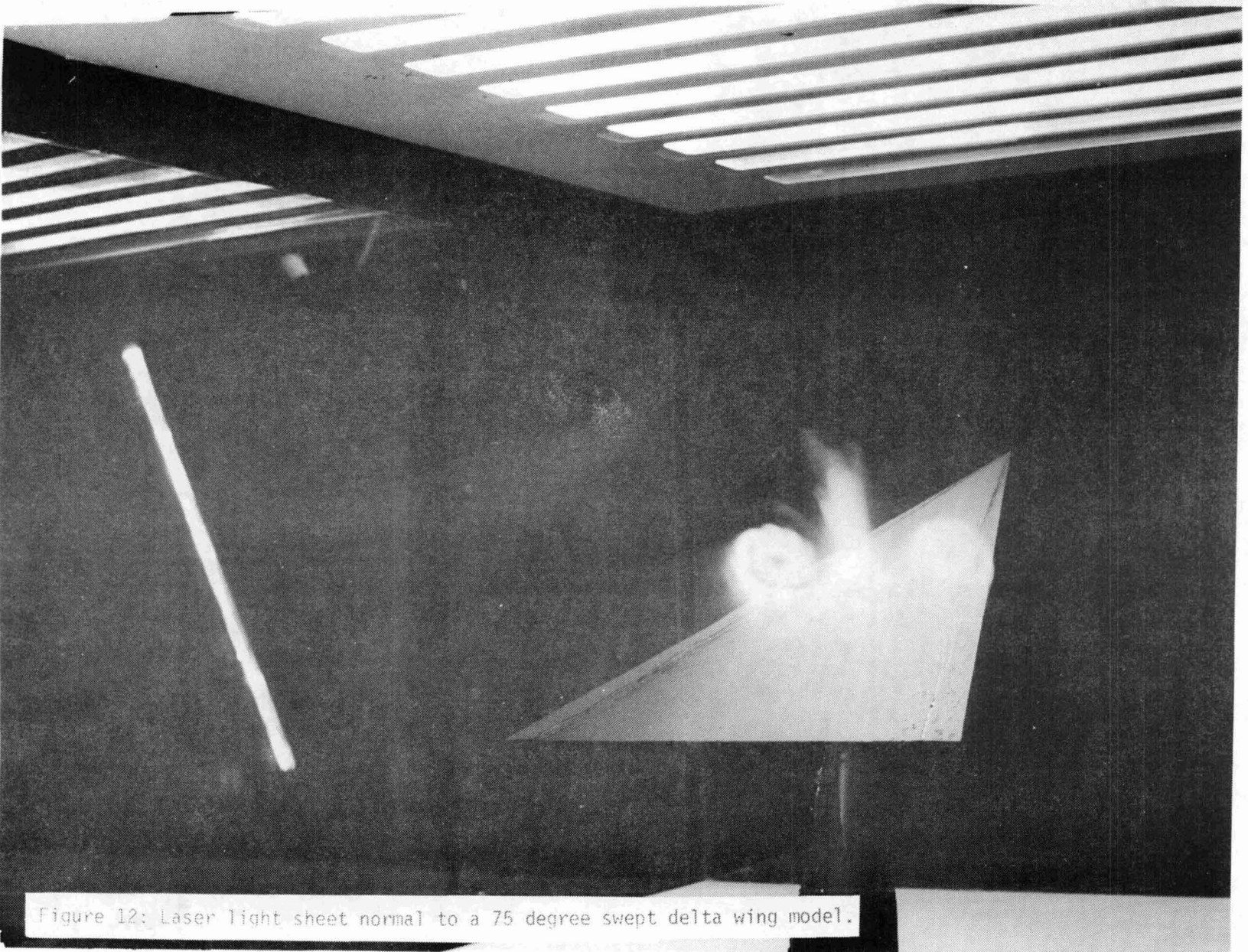
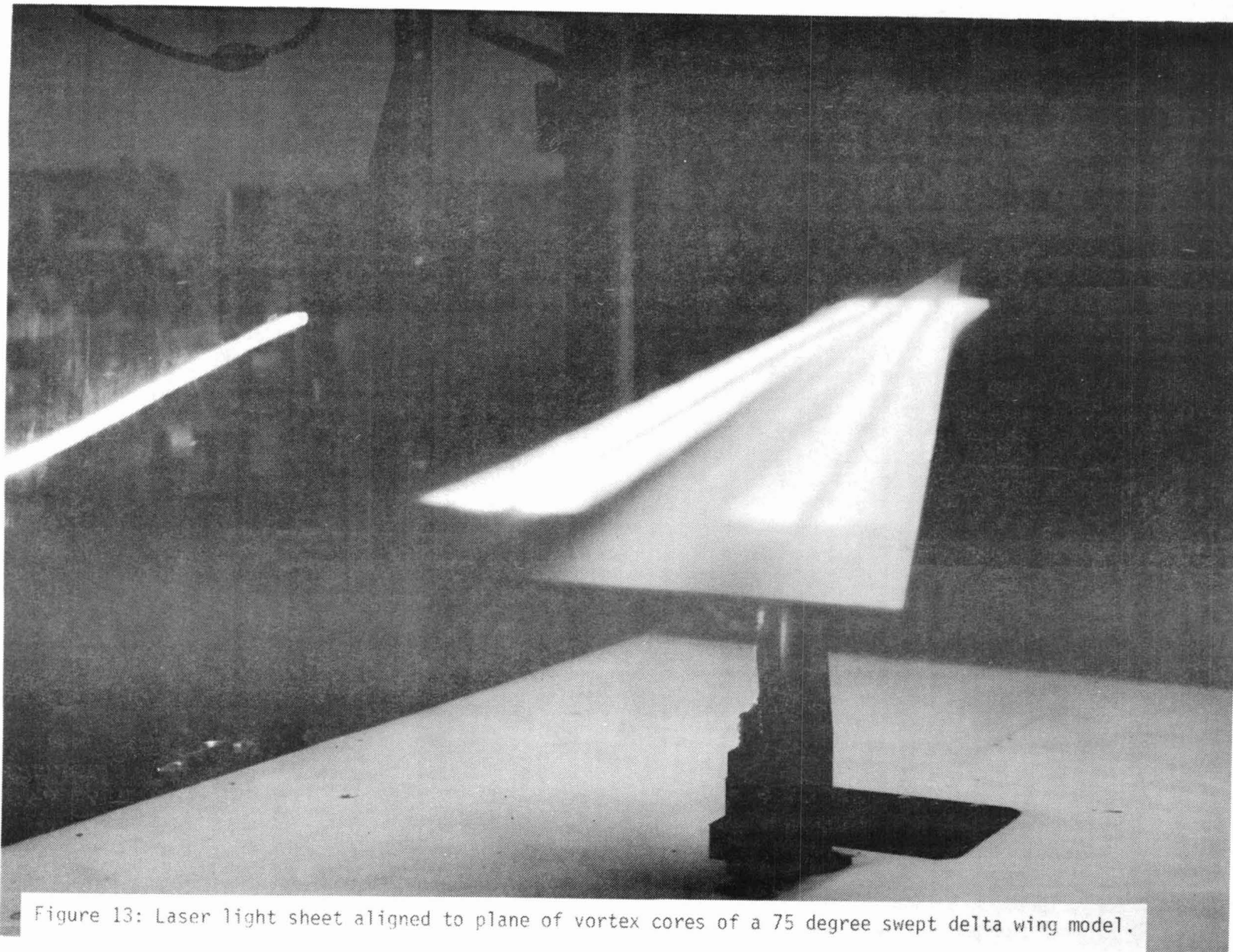


Figure 12: Laser light sheet normal to a 75 degree swept delta wing model.



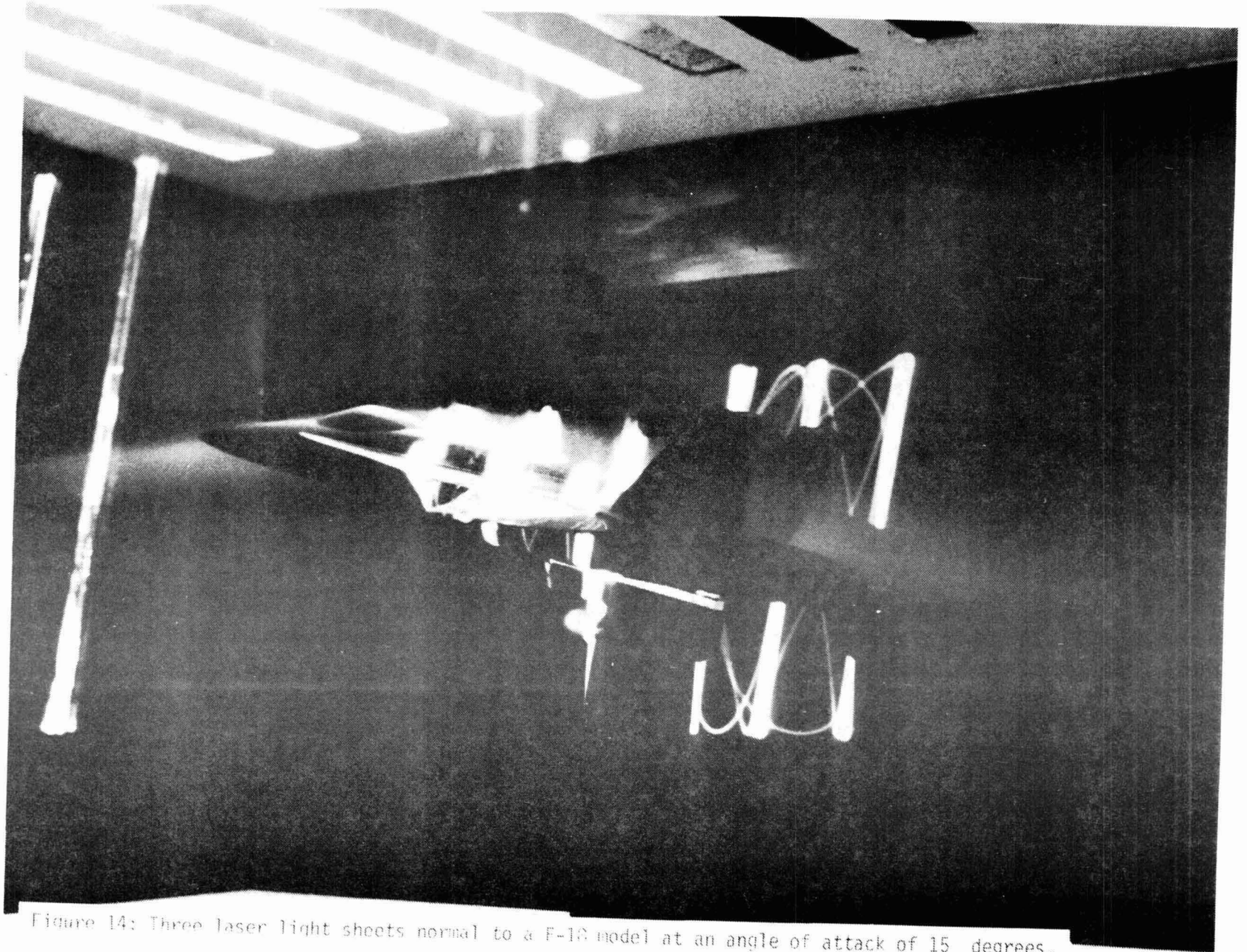


Figure 14: Three laser light sheets normal to a F-16 model at an angle of attack of 15 degrees.

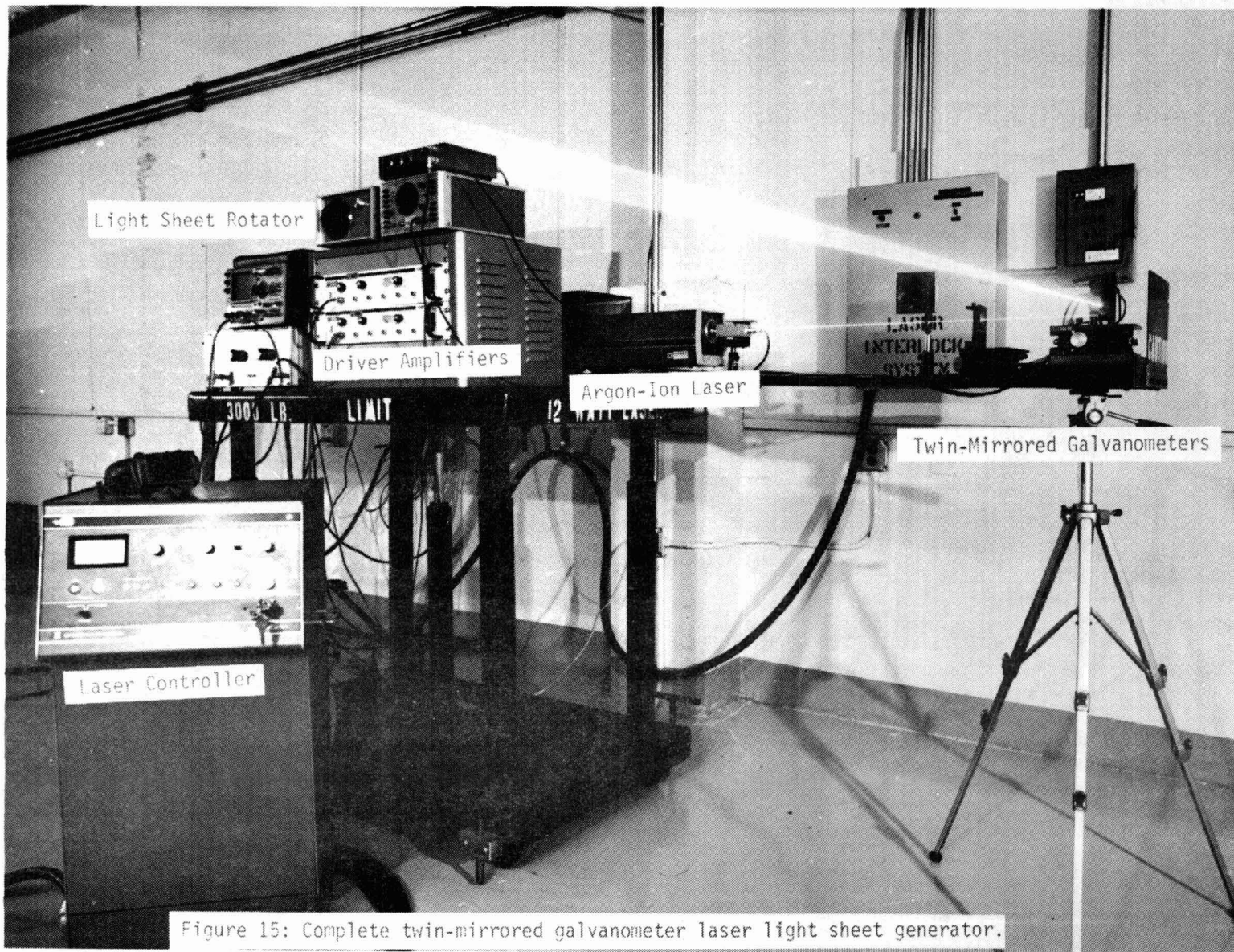


Figure 15: Complete twin-mirrored galvanometer laser light sheet generator.



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