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THE EFFECTS OF A GEMINI LEFT-HAND WINDOW ON EXPERIMENTS REQUIRING ACCURACY IN SIGHTING OR RESOLUTION

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Ames Research Center
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SUMMARY

This investigation was undertaken to determine the effect that a standard Gemini left-hand window would have on any experiment in which angular deviation of a line of sight, or loss of optical resolution, would be an important factor. In this completely experimental investigation space pressure conditions were simulated.

The windowpanes were convex as much as 63 wavelengths and concave 35 wavelengths and contained an irregular wedge angle as large as 76 seconds of arc. Angular deviations of a line of sight varied as much as 2 minutes of arc with aperture position on the window, azimuth angle, and angle of incidence. Thus, the window would impose a deviation error of the order of 2 minutes of arc on any pointing experiment. The best resolution without refocussing was 30 seconds of arc and was of the order of 8 seconds of arc when refocussed. Therefore, the window is of reasonable quality for most viewing and photographic experiments.

INTRODUCTION

In future space flights, the viewing port for optical experiments may be a window of the spacecraft, making the window a critical component in the design and evaluation of experiments. It is therefore essential that the window be of high optical quality and that the quality be known. No published studies of the optical qualities of spacecraft windows could be found at the time this study was initiated, but some studies had been made of aircraft photographic windows (ref. 1).

This investigation was undertaken to measure some of the optical characteristics of a standard left-hand Gemini window. Of particular interest is the angular deviation imparted to a line of sight by the window. The only mathematical method for predicting such deviation is a ray trace computing program based upon the window surface shape and wedge angle. Since the Gemini window is a three-pane assembly, uncertainties in the three-wedge angles and six surfaces involved could lead to a wide variation in computed deviations. It thus seemed necessary to actually measure the deviations in a test program. Because of the large window size, the large number of data points necessary, and the need for 1 second of arc precision, special equipment and techniques were used to accomplish the measuring task. The equipment consisted of a projection autocollimator with a large aperture, capable of consecutively measuring angular deviations through many small areas, at a single adjustment of window and autocollimator orientation. These measurements are important in indicating the magnitude of errors and uncertainties the window would cause when optical devices, such as sextants, stadimeters, and pointing lasers are used onboard a spacecraft. Also of primary interest is the effect of the window on the resolution of an optical system because the window is essentially one component of the optical system (e.g., cameras and telescopes).

The major optical parameters, flatness and wedge angle, were measured for a standard Gemini window. These parameters are characteristics of the glass and cause loss of resolution and errors in deviation. Line-of-sight deviation errors are also caused by index of refraction changes from vacuum to spacecraft atmosphere and by distortion of the window caused by pressure differential and stress from the frames. These conditions were simulated so that the line-of-sight measurements would be equivalent to those made in a spacecraft.

.8382 cm →
.9652 cm →
.5588 cm →

WINDOW DESCRIPTION

The Gemini left-hand window consists of outer, center, and inner panes. Thicknesses are 0.330, 0.380, and 0.220 inch, respectively. The center and outer panes are made of Corning Vycor 7900 high-temperature fused silica, and the inner pane is made of Corning 1723 tempered glass. The center and inner panes have an antireflection coating. Acceptance specifications of the contract to Owens Corning Corporation for the windows covered overall light transmission and glass quality, including the maximum size and number of bubbles and inclusions, and the allowable distortion of a grid pattern photographed through the panes. No specifications were given, however, for flatness, wedge angle, or resolution.

The shape of the window (fig. 1) is approximately elliptical, the two inner panes having a horizontal major axis of 14 inches and a vertical minor axis of 8 inches. The outer pane has a horizontal major axis of about 15-3/4 inches and a vertical minor axis of 8-1/2 inches.

The outer pane of the window is attached to the outer spacecraft skin, and is essentially a heat shield. In space, a vacuum exists on both sides of this pane. A distance of 1-1/4 inches separates it from the center pane. The center and inner panes are assembled as a unit. They are separated by 5/32 inch and the volume between them is filled with dry argon at 14.7 psi. The frame assembly holding these two panes forms a seal with the inner hull which is at 5.5 psi. The top of the window is tilted approximately 35° toward the astronaut when it is mounted in the spacecraft.

PROCEDURES AND RESULTS

Flatness

Each of the six glass surfaces was tested for flatness by interferometric comparison to a precision optical flat accurate to 1/20 wave. A sodium vapor lamp was used as the light source. The fringe patterns were photographed in the arrangement shown in figure 2 in which a 6-inch-diameter area in the center of the pane was photographed. All four surfaces of the two innermost panes were first tested unmounted. After being mounted in their frames, the first and fourth surfaces were again tested, the surfaces being numbered consecutively, starting at the innermost surface. The surfaces of the outer pane were only tested in a mounted configuration.

The flatness measurements showed that the window surfaces were unsymmetrical about a nominal center line, indicating a random variation of flatness across the panes. Three surfaces were primarily spherical, deviating from 3 to more than 30 wavelengths from a mean plane. The other three surfaces exhibited compound curves, that is, they were convex along one cross section and concave along another, varying from 5 to 29 wavelengths from a mean plane. Flatness test results are given in more detail in table I. Representative samples of these fringe patterns are shown in figures 3 and 4. The distortion due to mounting the inner panes in their frames is apparent from a comparison of figures 4(a) and 4(b).

Wedge Angle

Wedge angle of each pane was determined by producing interference fringes between the two surfaces. Collimated light from a sodium light source was used in the arrangement shown in figure 5. The center 6-inch-diameter aperture of each pane was photographed. Wedge angle of the glass was determined from the fringe spacing by the relationship

$$\varphi = \frac{N\lambda}{2nL}$$

in which

φ wedge angle, radians

N number of fringes

L length of zone, in.

n index of refraction

λ wavelength in air

The formula

$$\varphi = \frac{2.39N}{Ln}$$

gives the wedge angle directly in seconds of arc, and was used in obtaining the data of this study.

The wedge angle measurements indicated that the thickness of each pane varied over the aperture in a manner similar to an off-axis lens. Wedge angle over the aperture varied by as much as 100 seconds of arc. Photographs of the fringe patterns for the three panes are shown in figure 6, and a graph showing the computed wedge angles along the vertical axis of each pane is shown in figure 7.

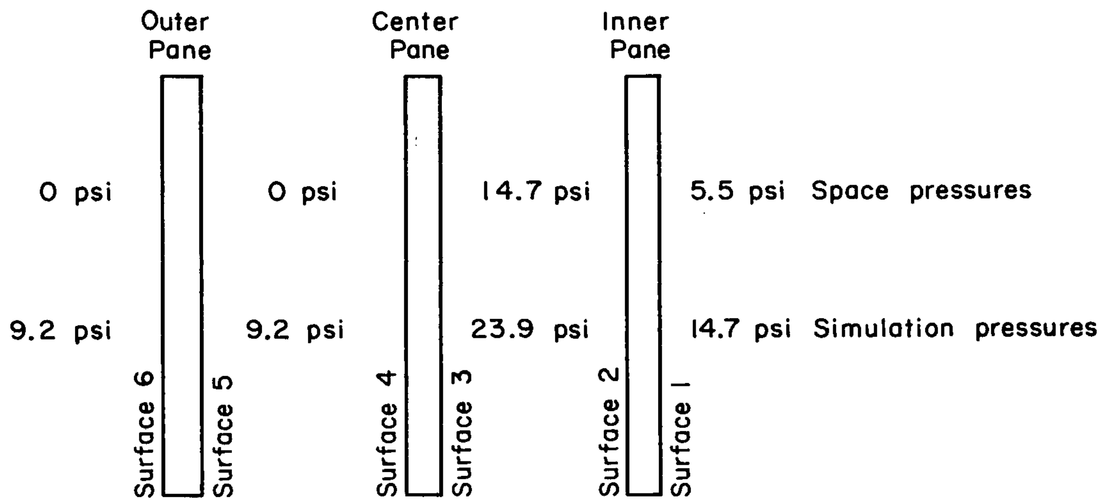
Resolution

Resolution degradation caused by the window was determined by photographing a 1951 USAF 1X resolution chart through the window. A collimating system was used to place the chart effectively at infinity. Parallel light passing through the window was imaged onto high resolution copy film by a lens with an aperture of 5.3 inches in diameter (fig. 8). The camera was first focussed on the resolution chart. After making a control photograph to determine the resolution of the test equipment, photographs were taken with the window normal to the collimator axis. Photographs were also made with the window at 35° incidence at the 90° azimuth angle (fig. 9). This is the nominal angle encountered by an astronaut looking out the window. After the window was installed, photographs were taken before and after refocussing the system. Chart line spacing was converted into angular measure for analysis of the results.

The tests indicated that the window causes a significant loss of resolution in an optical system. In the best test condition the resolution was degraded from 2 seconds of arc to 4 to 6 seconds of arc. The data shown in table II and figure 10 show that the effect on resolution varies with incidence angle and focus. The severe loss of resolution indicates that the window acted as a lens, requiring a focus correction for best resolution in each test case. Differences in resolution between horizontal and vertical lines on on the chart show that the window introduces an astigmatic effect.

Space Environment

Certain space environment conditions were reconstructed in the laboratory in order to get valid line-of-sight deviation data. The pressure differentials across the window, as they exist in space, were duplicated so that the panes would be properly strained. Simultaneously, the difference in index of refraction between the atmosphere inside the capsule and the vacuum of space was duplicated to give the proper deviation from refraction effects. In orbit, the pressures are as follows: outside pressure and pressure between two outer panes, 0 psi; pressure between the two inner panes, 14.7 psi; internal spacecraft pressure, 5.5 psi. These pressures were raised 9.2 psi in the test condition to 9.2, 23.9, and 14.7 psi, respectively, as shown in sketch (a). A vacuum chamber was constructed which incorporated the spacecraft window as



Sketch (a)

one wall. The chamber was evacuated to 9.2 psi to simulate the vacuum of space. The laboratory at 14.7 psi corresponded to the spacecraft interior. The space between the two inner panes was pressurized to 23.9 psi. The space between the center and outer panes was at 9.2 psi. This uniform increase in pressure satisfied both conditions of pressure differential and index difference as shown in appendix A, in which deviations due to index of refraction differences are compared for both the actual and the simulated environment.

Line-of-Sight Deviations

Line-of-sight deviations were measured through the 1-inch-diameter apertures at positions A-4, C-4, C-6, and E-4, of figure 11. A 12-inch-diameter autocollimating system, accurate to 1 second of arc (fig. 12), was used to measure the deviations at all apertures consecutively at each adjustment of incidence and azimuth angles. Incidence angles of 15°, 30°, and 45° were set by rotating the tank horizontally (fig. 12) about a vertical center line on window surface number 1 (sketch (a)). Azimuth angles (fig. 9) for each incidence angle were set at 45° intervals by rotating the window in its frame about the window center at aperture C-4. Deviations were measured both with no pressure differential across the window and with the simulation pressures of sketch (a).

The experimental data, while not sufficient for a complete mapping of the window, do indicate the deviation characteristics involved. Figures 13 and 14 show the deviations measured at apertures C-4 and C-6. Each figure shows the deviation broken down into the components as measured, one component in the plane of incidence and the other component perpendicular to that plane. The graphs show that the deviations vary as much as 100 seconds of arc depending on incidence angle. The maximum variation with azimuth angle was 170 seconds of arc, and the maximum deviation between successive azimuth angles was 145 seconds of arc. These high slopes indicate that many more azimuth angles would have to be investigated to assure interpolation accuracy of 5 seconds or better between successive incidence and azimuth angles. Position changes produced random variations as high as 100 seconds of arc. The introduction of simulation pressures produced random changes of deviation up to 80 seconds of arc from corresponding angles under no-pressure conditions. The random nature of the measured deviations precludes accurate interpolation of deviations at incidence and azimuth angles and positions between those measured.

SUMMARY OF RESULTS

The standard Gemini left-hand window tested showed that line-of-sight deviations varied about 3 minutes of arc depending on aperture position on the window, azimuth angle, and angle of incidence. As much as 1-1/2 minutes of arc variation in deviation resulted from the pressure differentials used. These variations did not occur in a predictable manner, but rather in a random fashion that seems to preclude analysis or interpolation below this level.

Resolution results before and after the camera was refocussed definitely show a pronounced lens effect due to the combined window panes. The lens effect is also apparent in the astigmatism revealed by the difference in resolution between vertical and horizontal lines. Since Gemini missions are manned missions, it will be possible to refocus instruments through the window and attain resolutions of the order of 8 seconds of arc.

The measurements of the optical parameters, flatness and wedge angle, showed that the glass surfaces deviated excessively from a plane, and that wedge angles between them were large and irregular. The pronounced lack of regularity of the flatness and wedge angle, however, did not eliminate the lens effect as the resolution data show.

The standard Gemini left-hand window is of reasonable quality for most viewing and photographic tasks not requiring higher resolution than about 8 seconds of arc. Instruments not requiring 2 minutes of arc or better pointing accuracy may be used behind this window.

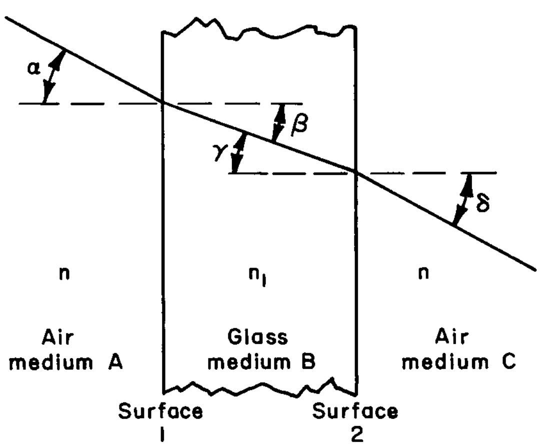
Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., July 28, 1966
125-17-02-09-00

APPENDIX A

LINE-OF-SIGHT DEVIATIONS DUE TO REFRACTION AND ERRORS INTRODUCED IN DEVIATION MEASUREMENTS BY UNIFORMLY INCREASING ENVIRONMENTAL PRESSURES

To provide convenient and safe working conditions in the laboratory, it was necessary to raise the absolute pressures surrounding the test window. As described in the text, the pressures were raised uniformly 9.2 psi from 0 psi outside pressure and between the two outer panes, 14.7 psi between the center and inner panes, and 5.5 psi internal spacecraft pressure to 9.2, 23.9, and 14.7 psi, respectively. This uniform increase satisfies the requirements of distorting the windows the same amount as in actual space flight and allows one side of the window to be at ambient laboratory pressure. Another important consideration is that the line-of-sight deviations caused by the index of refraction differential on either side of the window must be the same in the simulation as in space. The following computations determine the error in the deviation when the simulation pressures are used instead of the actual pressures.

For purposes of analysis, it is assumed that the glass surfaces are flat and parallel. Under these conditions there will be no angular line-of-sight deviations from wedge angles of any type. This fact is demonstrated in sketch (b) and calculations. Surfaces 1 and 2 are assumed flat and parallel. Mediums A and C are the same with an index of refraction n. Medium B is a more dense medium of index n_1. From Snell's law of refraction



Sketch (b)

$$n \sin \alpha = n_1 \sin \beta$$

and

$$n_1 \sin \gamma = n \sin \delta$$

From geometry

$$\beta = \gamma$$

so that

$$n_1 \sin \beta = n_1 \sin \gamma$$

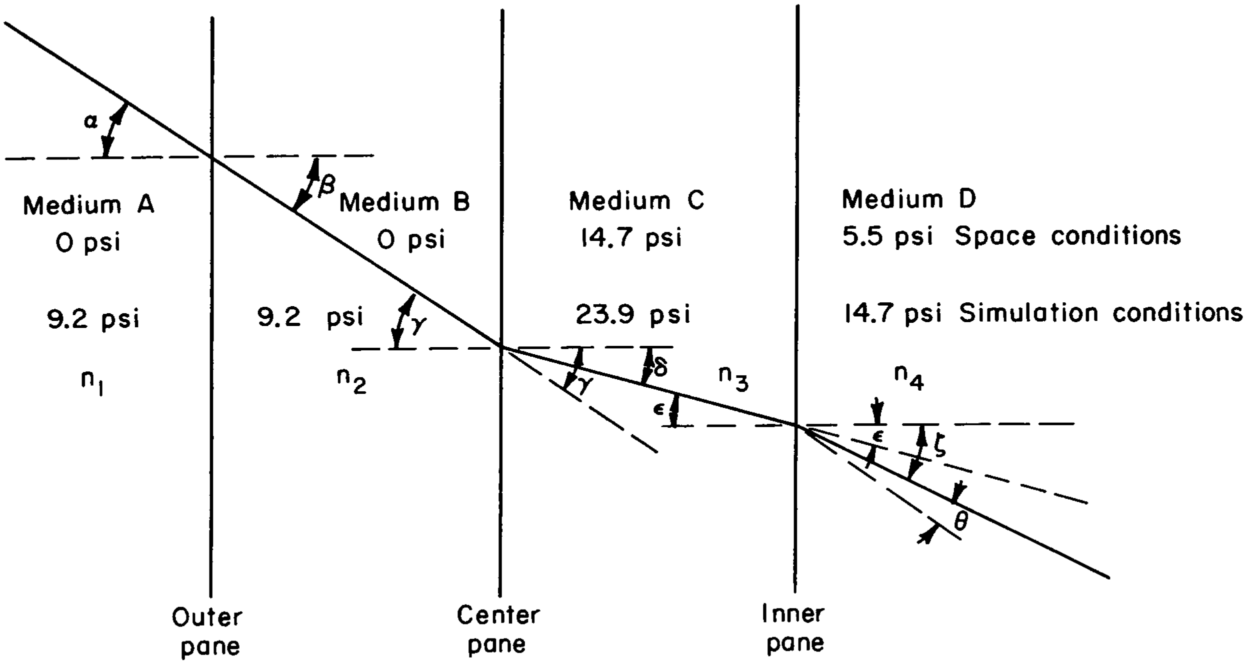
Thus

$$n \sin \alpha = n \sin \delta$$

or

$$\alpha = \delta$$

Although the ray translates, it does not change direction. Therefore, it is apparent that medium B serves only as a boundary between mediums A and C. If this result represents a pane of finite width as a single boundary, the spacecraft window can be represented as shown in sketch (c) in which the panes are assumed parallel.



Sketch (c)

GENERAL DERIVATION

(a) Path of ray from medium A to medium B:

According to Snell's law,

$$n_1 \sin \alpha = n_2 \sin \beta$$

or

$$\alpha = \sin^{-1}\left(\frac{n_2}{n_1} \sin \beta\right)$$

The deviation of the ray is

$$\varphi = \alpha - \beta$$

$$\varphi_1 = \sin^{-1}\left(\frac{n_2}{n_1} \sin \beta\right) - \beta \qquad \text{(A1)}$$

Since mediums A and B are identical

$$n_1 = n_2$$

Thus

$$\varphi_1 = 0$$

that is, the direction of the ray does not deviate.

(b) Path of ray from medium B to medium C:

$$\varphi_2 = \gamma - \delta$$

or

$$\varphi_2 = \sin^{-1}\left(\frac{n_3}{n_2} \sin \delta\right) - \delta$$

or

$$\varphi_2 = \sin^{-1}\left(\frac{n_3}{n_1} \sin \delta\right) - \delta \tag{A2}$$

(c) Path of ray from medium C to medium D:

$$\varphi_3 = \epsilon - \zeta$$

or

$$\varphi_3 = \sin^{-1}\left(\frac{n_4}{n_3} \sin \zeta\right) - \zeta \tag{A3}$$

(d) Total deviation from medium A to medium D:

$$\theta = \varphi_1 + \varphi_2 + \varphi_3$$

or

$$\theta = \sin^{-1}\left(\frac{n_3}{n_1} \sin \delta\right) - \delta + \sin^{-1}\left(\frac{n_4}{n_3} \sin \zeta\right) - \zeta$$

From geometry

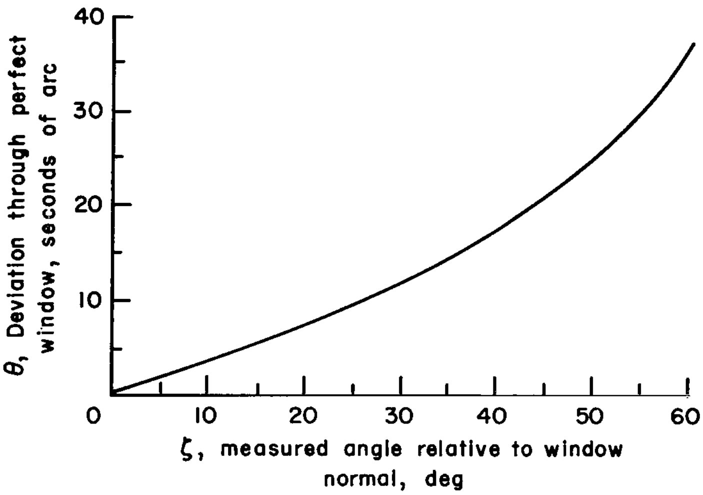
$$\beta = \gamma$$

$$\delta = \epsilon = \sin^{-1}\left(\frac{n_4}{n_3} \sin \zeta\right)$$

The total ray deviation thus becomes, by substitution,

$$\theta = \sin^{-1}\left\{\frac{n_3}{n_1} \sin\left[\sin^{-1}\left(\frac{n_4}{n_3} \sin \zeta\right)\right]\right\} - \sin^{-1}\left(\frac{n_4}{n_3} \sin \zeta\right) + \sin^{-1}\left(\frac{n_4}{n_3} \sin \zeta\right) - \zeta$$

$$\theta = \sin^{-1}\left(\frac{n_4}{n_1} \sin \zeta\right) - \zeta \tag{A4}$$



Sketch (d)

This relationship shows that the deviation of a light ray passing through a perfectly flat and parallel composite window depends only on the refraction angle ζ and the indices of refraction of the mediums outside the window and inside the spacecraft. The angle ζ can be measured inside the spacecraft so that the deviation can be computed if desired. Sketch (d) shows the magnitude of deviations which occur because of index of refraction differences on either side of a perfect window.

INDEX OF REFRACTION OF A GAS

The index of refraction (n_{TP}) of a gas varies with temperature and pressure according to the relationship

$$n_{TP} - 1 = \frac{n_o - 1}{1 + aT} \frac{P}{14.7} \tag{A5}$$

where

n_o index of refraction at 0° C and 14.7 psi

T temperature, $^\circ$C

P pressure, psi

The value of n_o is 1.0002916 for the sodium D line in air; and a is 0.00366 for air. The index of refraction in a vacuum is unity by definition.

TOTAL RAY DEVIATION IN A SPACE ENVIRONMENT

The deviation of a ray through the window in conditions similar to those in actual Gemini flight is computed as follows: From the temperature-pressure equation (eq. (A5)), the index of refraction of the air inside the spacecraft at 5.5 psi and 21.1° C is 1.0001013. For a measured angle ζ of 60°, the total ray deviation (eq. (A4)) is therefore

$$\theta = \sin^{-1}\left(\frac{n_4}{n_1} \sin \zeta\right) - \zeta$$

$$\theta = 36.19 \text{ seconds of arc}$$

TOTAL RAY DEVIATION IN THE PRESSURE ENVIRONMENT OF THIS STUDY

As computed from equation (A5), the index of refraction of air, n_1, in medium A at 9.2 psi, and 21.1° C is 1.0001694. The index of air in medium D at 14.7 psi and 21.1° C is 1.0002706. For a measured angle ζ of 60°, the ray deviation is

$$\theta = \sin^{-1}\left(\frac{n_4}{n_1} \sin \zeta\right) - \zeta$$

$$\theta = 36.15 \text{ seconds of arc}$$

According to the computations there is less than one-tenth second of arc error when the environmental pressures are increased uniformly by 9.2 psi; thus the pressure environment used in this test is a valid simulation. This increase permitted the investigators to work under convenient laboratory conditions.

REFERENCE

1. Forman, Paul F.: The Photographic Window. In: New Developments for Aerial Photography, A Program of Talks Presented to Members of OSA, ASP, SPIE, and SPSE at a Joint Technical Meeting, Sept. 16, 1964. The Perkin-Elmer Corp., Electro-Optical Div., Norwalk, Conn.

TABLE I.- FLATNESS TEST RESULTS
(6-in.-diameter central area)

Surface	Condition	Maximum flatness deviation (wavelengths at 5890 Å)
1	Unmounted	39 convex
1	Mounted	63+ convex
2	Unmounted	35 concave
3	Unmounted	6 convex
4	Unmounted	6 convex, 4 concave
4	Mounted	25 convex, 33 concave
5	Mounted	44 convex, 7 concave
6	Mounted	25 convex, 19 concave

TABLE II.- LIMIT OF RESOLUTION THROUGH STANDARD GEMINI WINDOW

Condition	Resolution, seconds of arc	
	Horizontal lines	Vertical lines
Collimator with no window	2	2
Window normal to collimator axis before refocussing	63	32
Window normal after refocussing	6	4
Window at 35° before refocussing	45	32
Window at 35° after refocussing	8	8

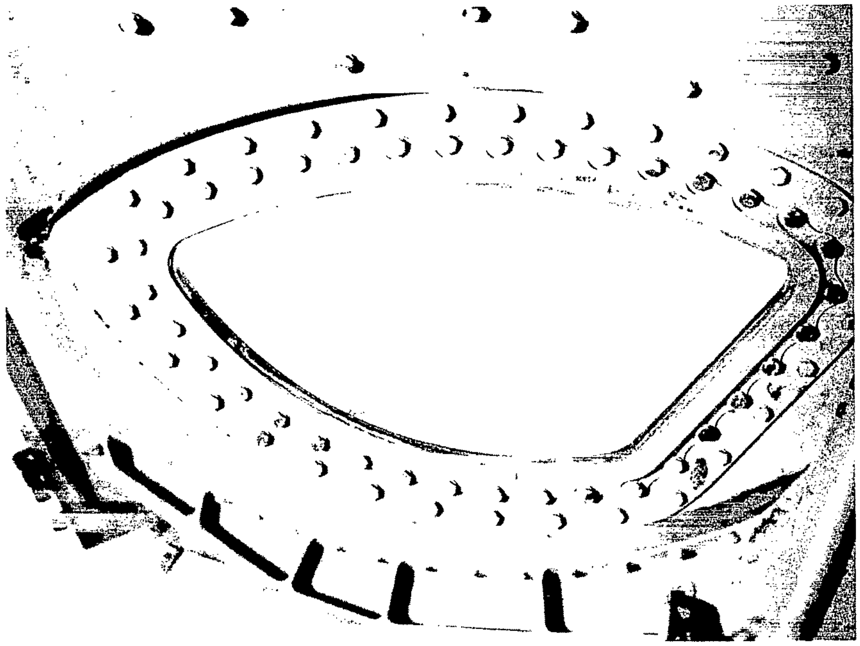


Figure 1.- Standard Gemini window mounted in hatch.

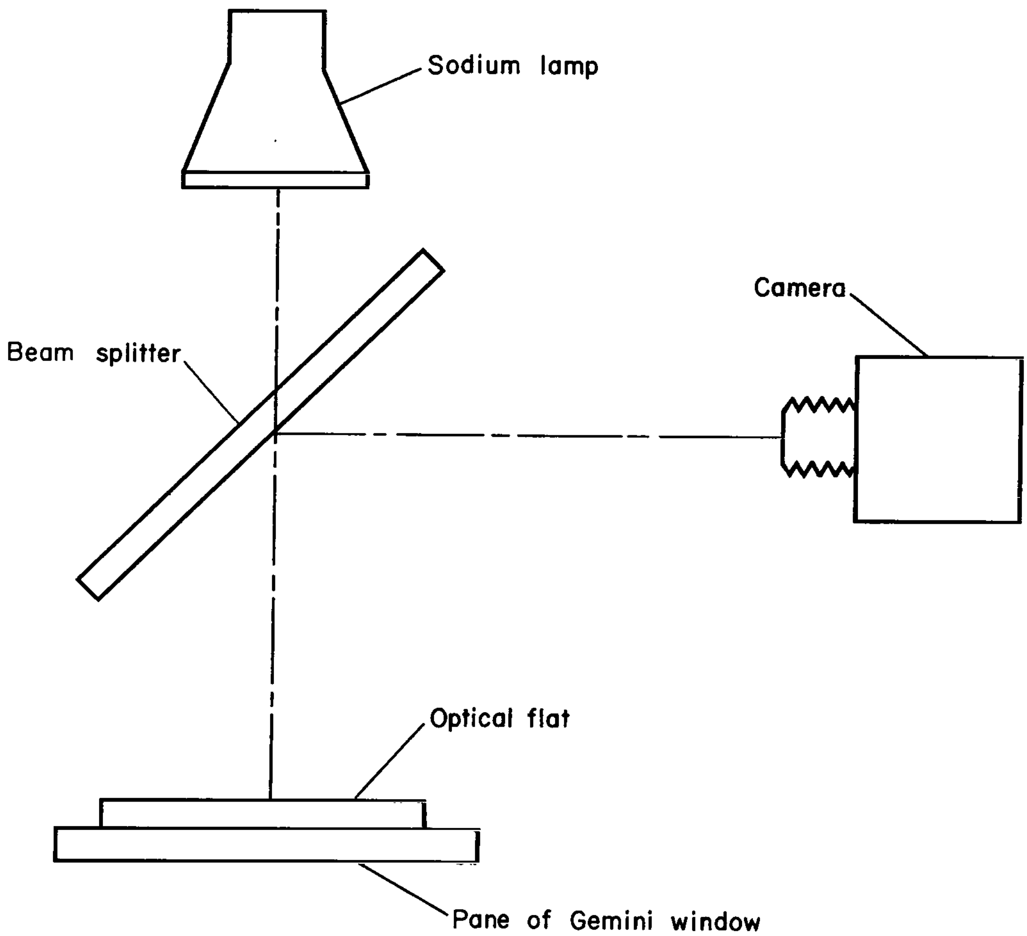


Figure 2.- Flatness measurement, interference method.

(a) Surface 2, unmounted.

(b) Surface 3, unmounted.

Figure 3.- Flatness interferogram.

(a) Surface unmounted.

(b) Surface mounted.

Figure 4.- Flatness interferogram on surface 4.

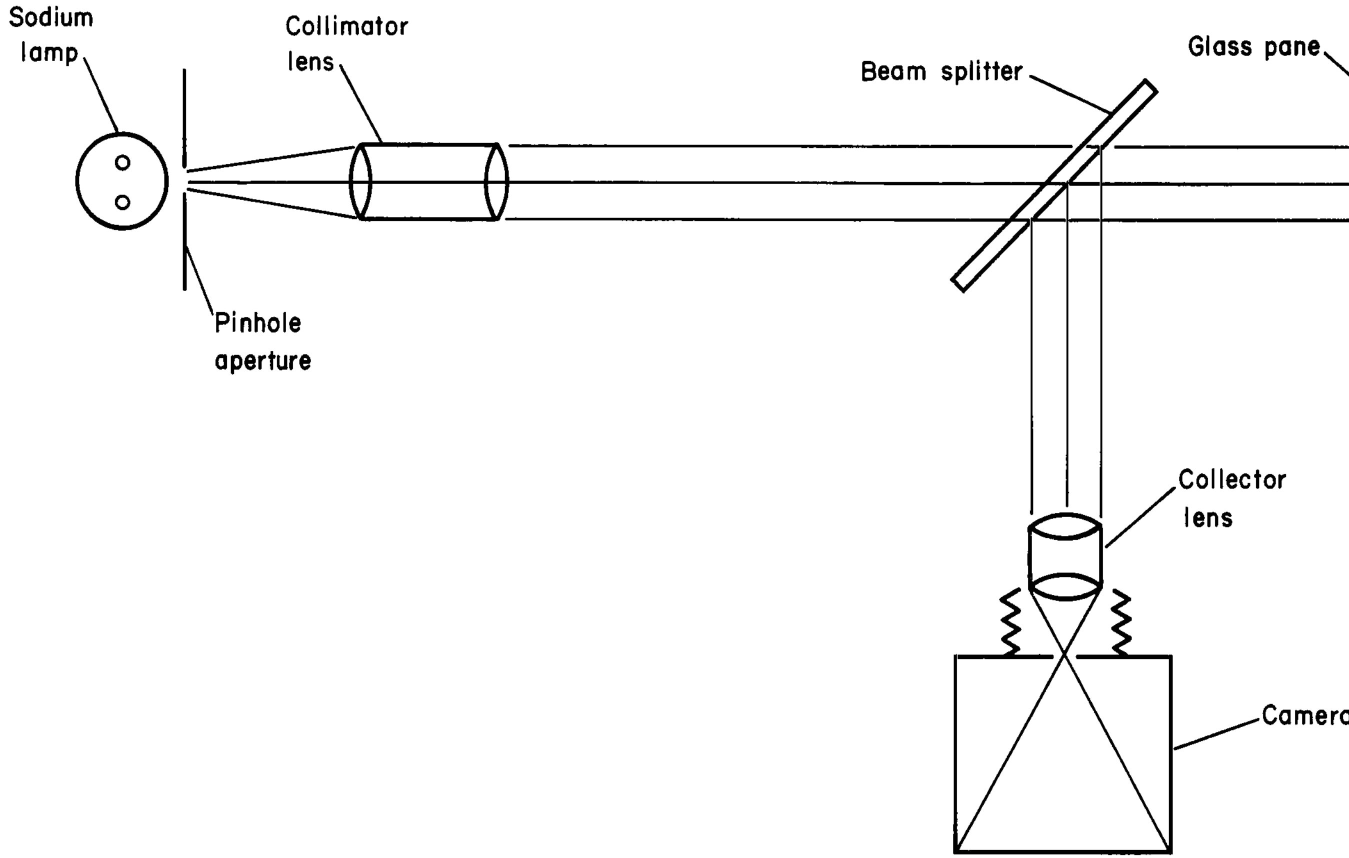
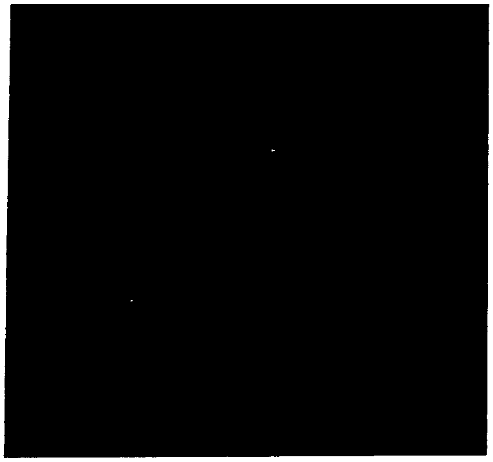
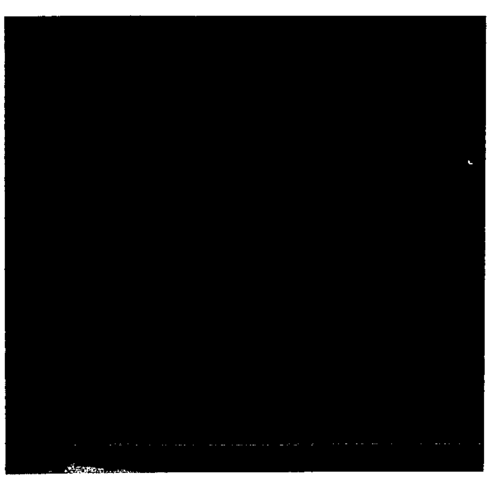


Figure 5.- Wedge measurement, interference method.



(a) Inner pane.

(b) Center pane.



(c) Outer pane.

Figure 6.- Wedge interferograms.

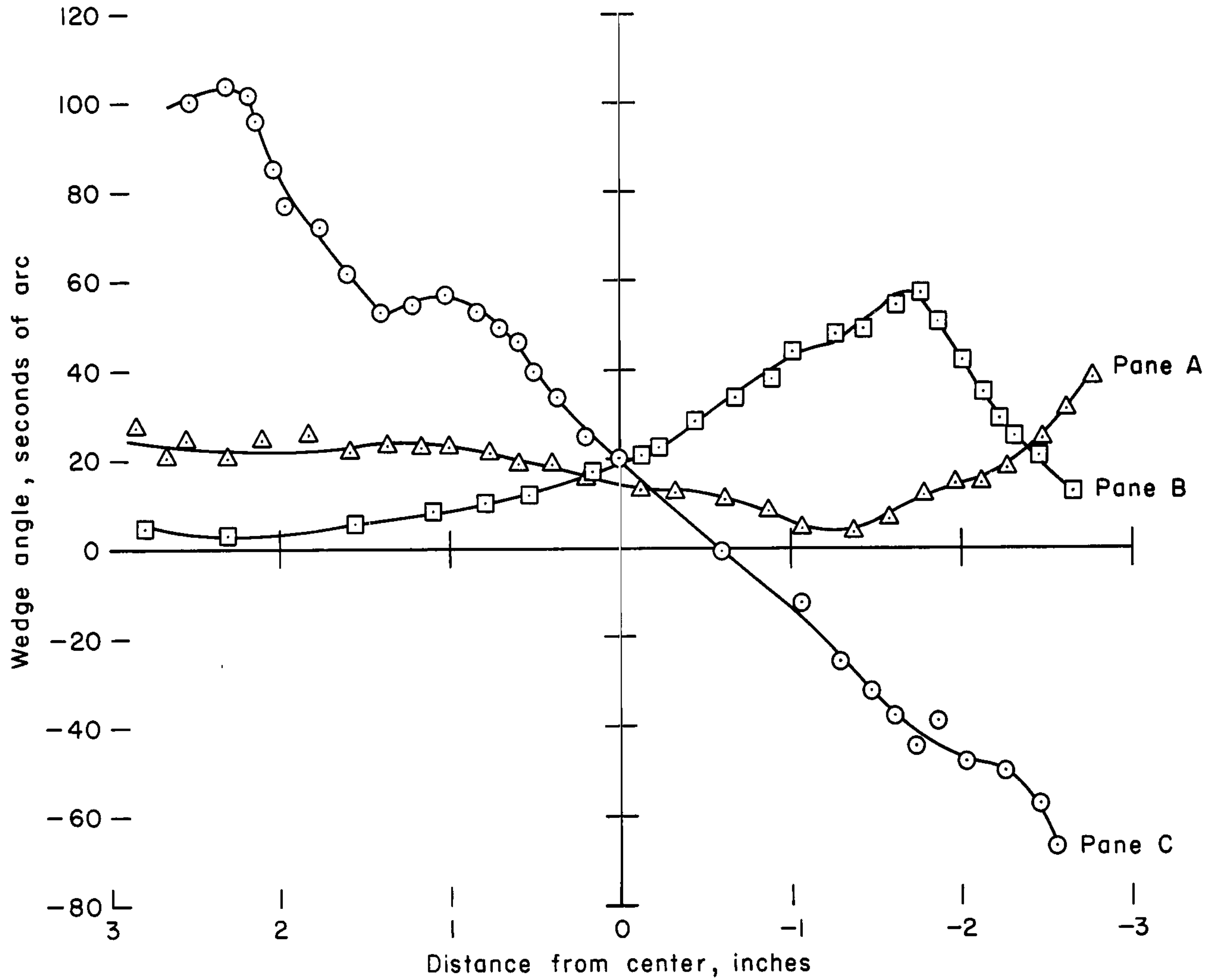


Figure 7.- Wedge angle along vertical axis.

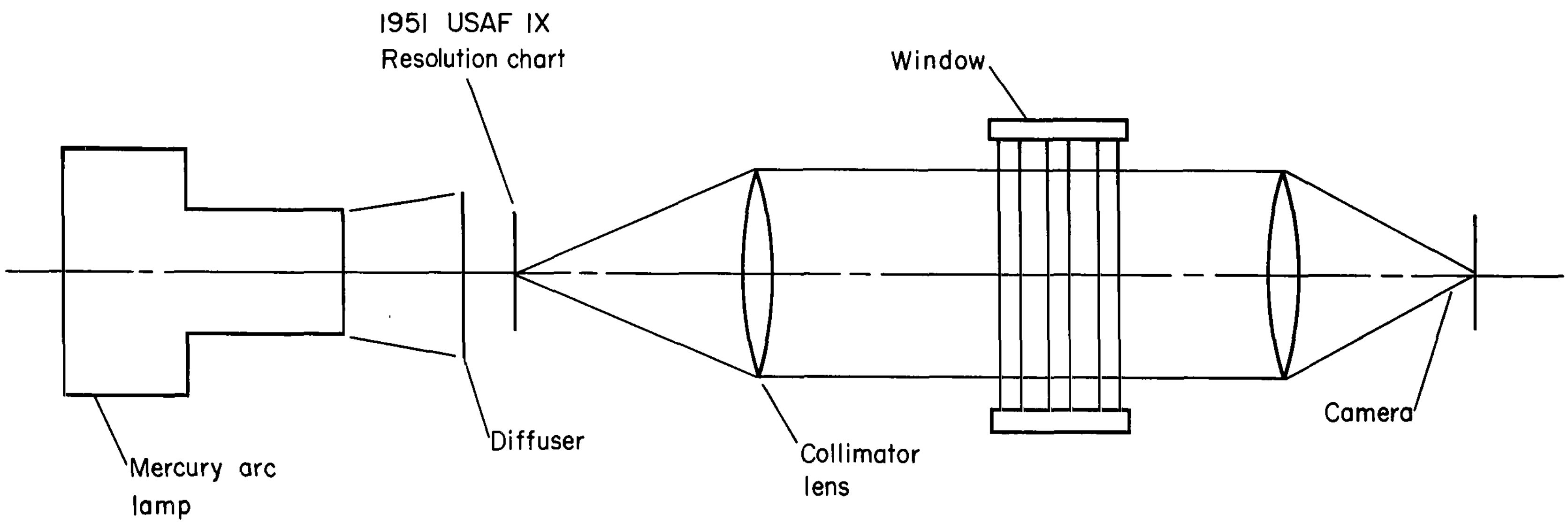


Figure 8.- Resolution measurement.

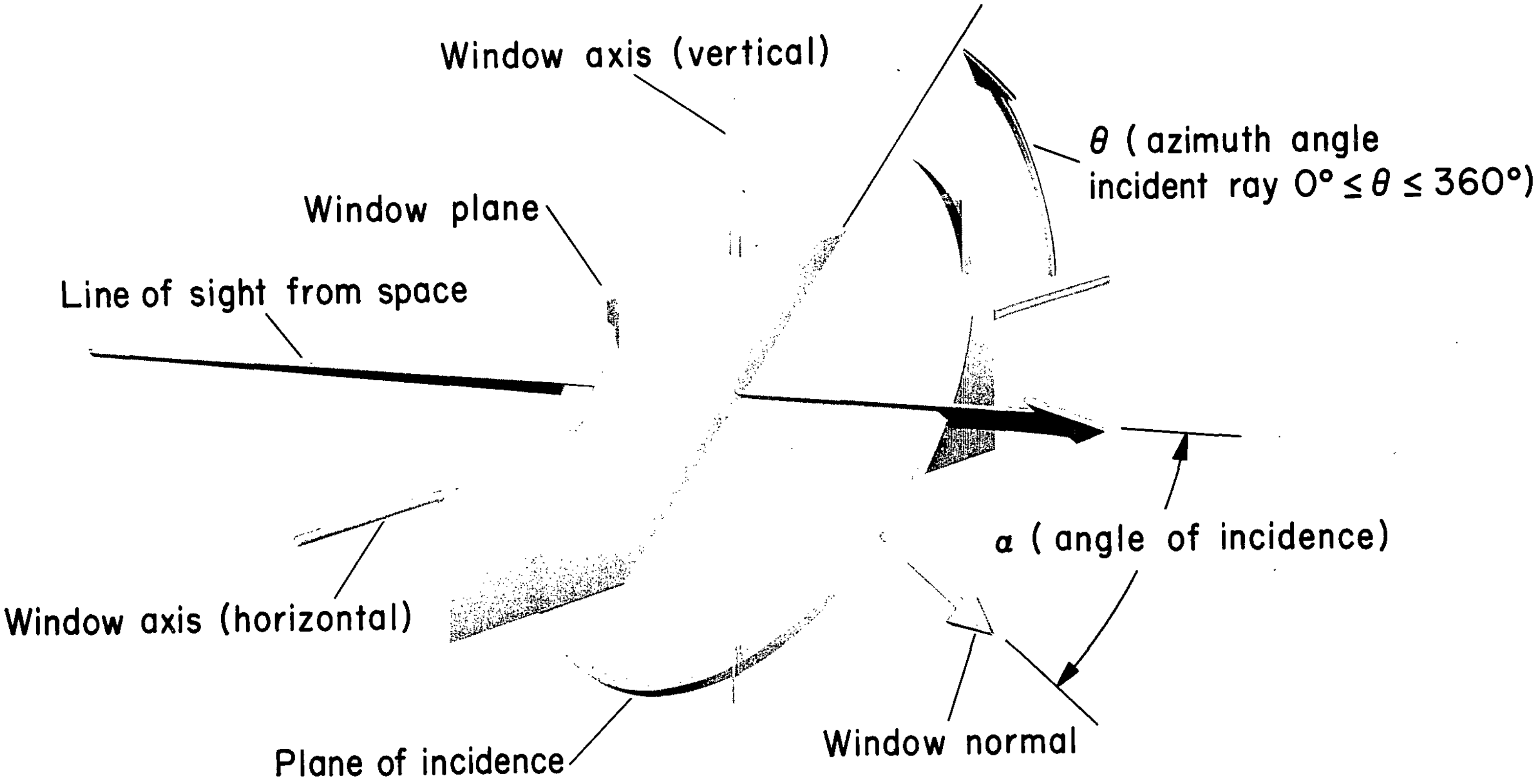
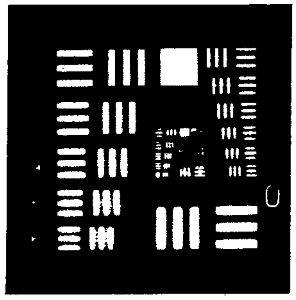
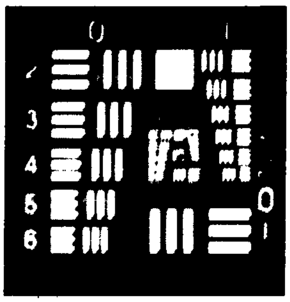


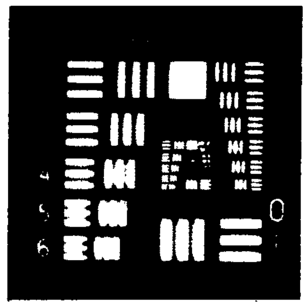
Figure 9.- Gemini window reference system.



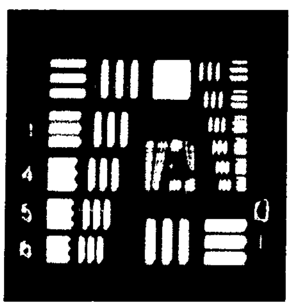
Collimator with no windows.



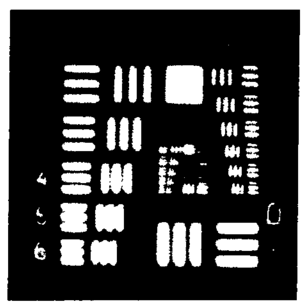
Window normal to collimator axis before refocusing.



Window normal after refocusing.



Window at 35° before refocusing.



Window at 35° after refocusing.

Figure 10.- Resolution test photographs.

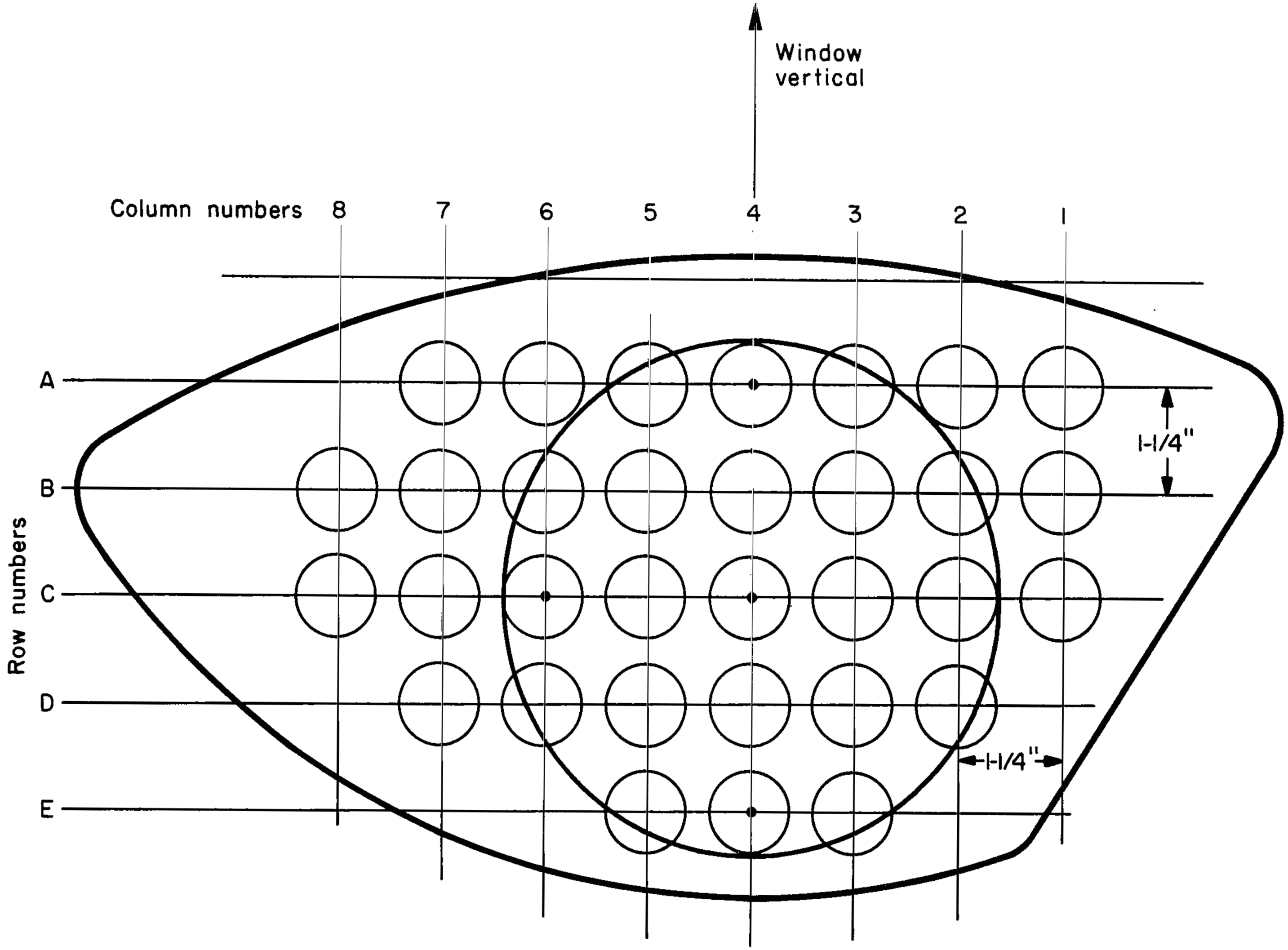


Figure 11.- Aperture spacing, Gemini inner window.

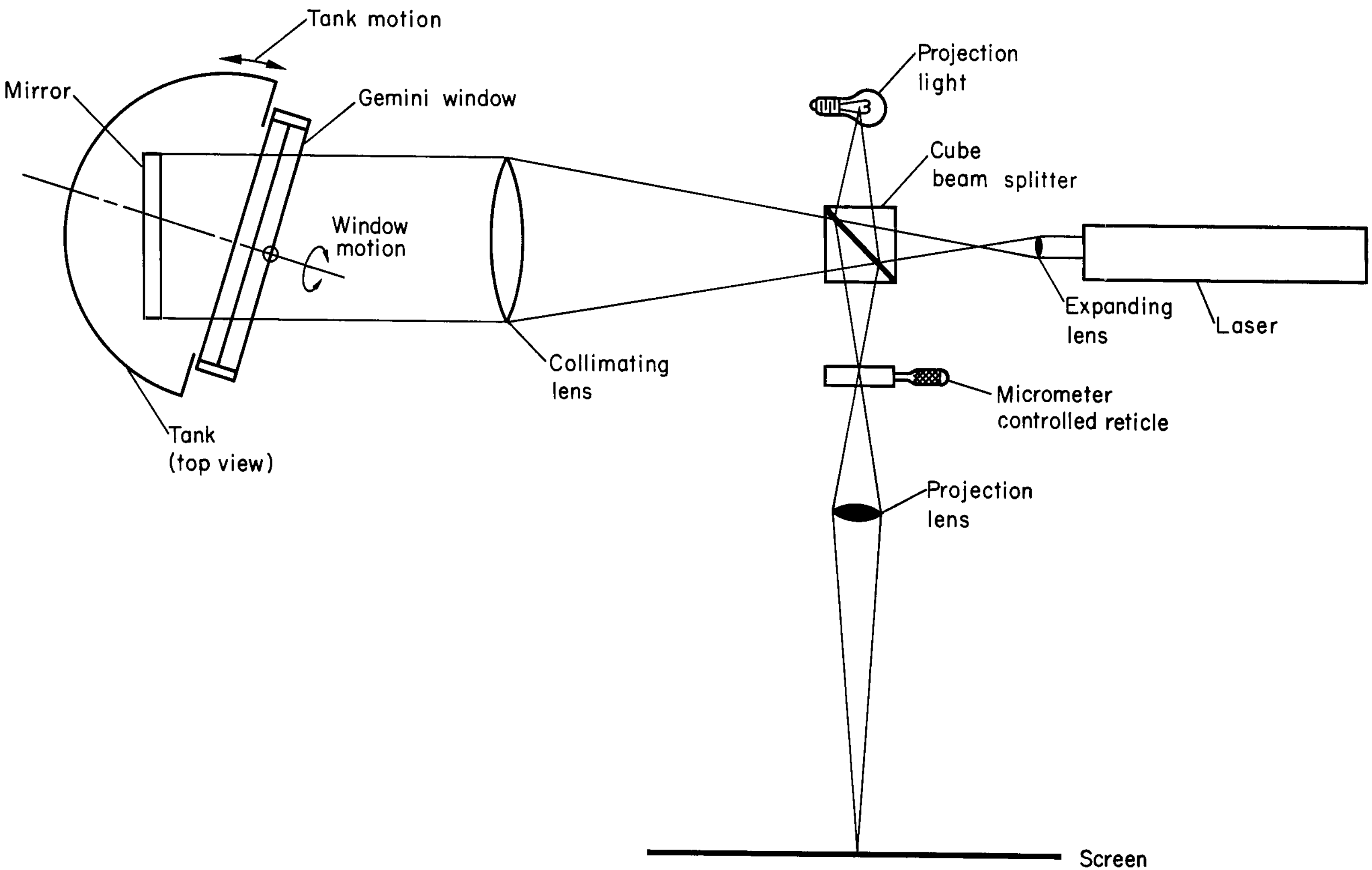
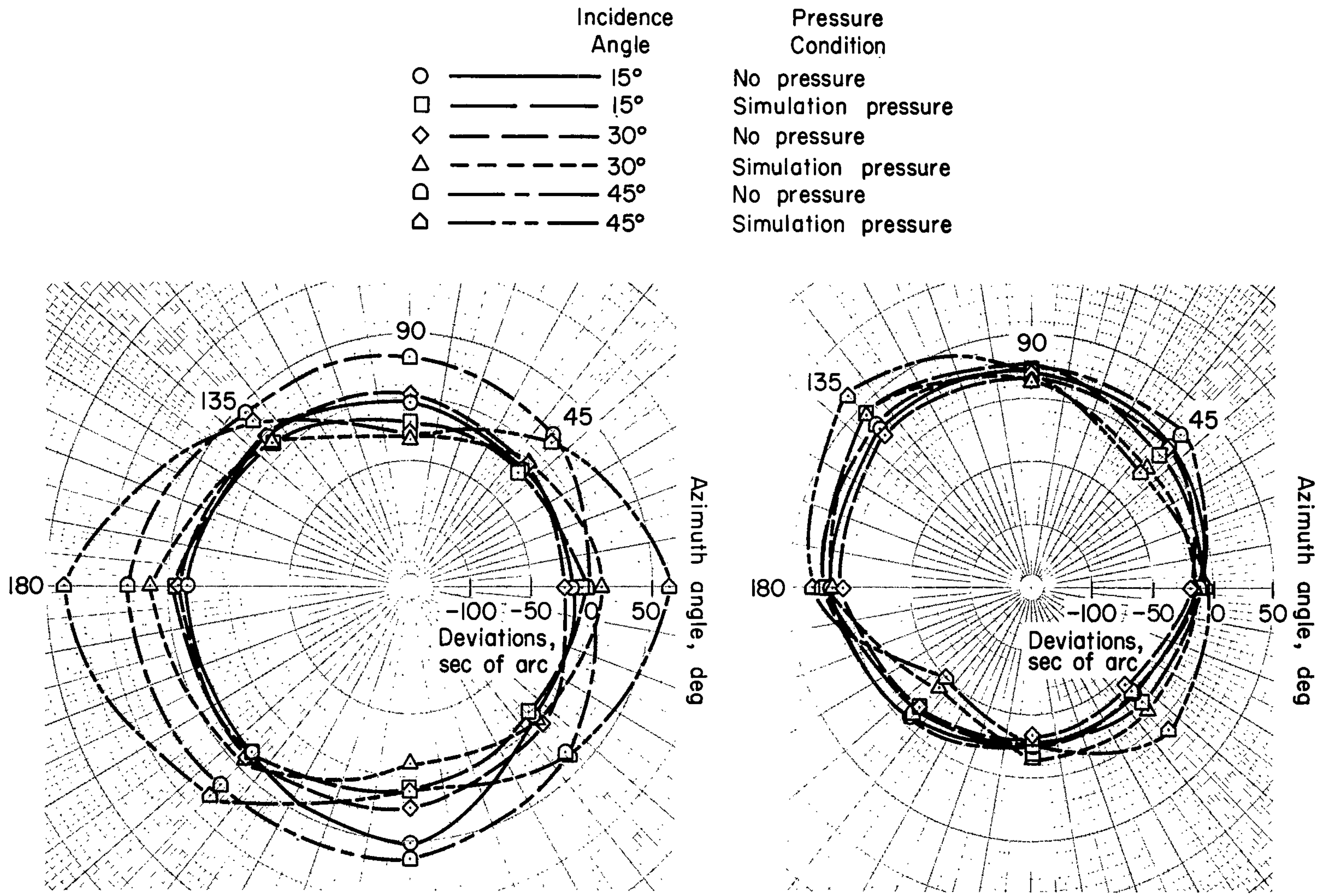


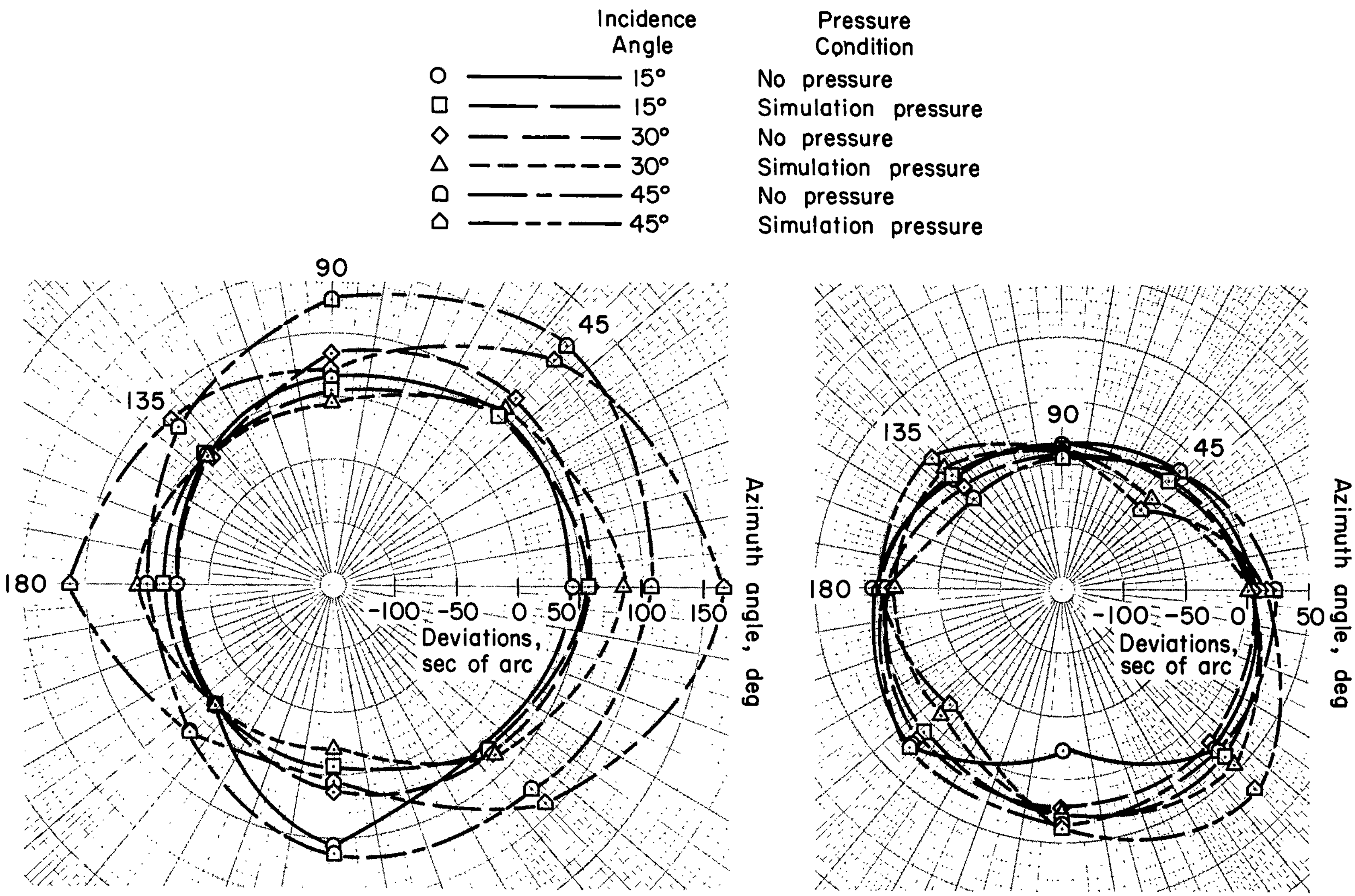
Figure 12.- Deviation measurements.



(a) Deviation in plane of measurement.

(b) Deviation perpendicular to plane of measurement.

Figure 13.- Line-of-sight deviations, aperture C-4.



(a) Deviation in plane of measurement.

(b) Deviation perpendicular to plane of measurement.

Figure 14.- Line-of-sight deviations, aperture C-6.

NASA-Langley, 1966 A-2340

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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