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NAVY DEPARTMENT

Second Report

on

Daylight Observation of Stars and Planets

Some Optical Details

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

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INTRODUCTION

In the following paragraphs are discussed certain optical details concerning the design and the housing of the telescopic bubble octant for aerial daylight navigation.

NAVIGATION DOME

A plexiglass navigation dome of diameter 22 inches and height 11 inches made by Rohm & Haas Company of Bristol, Pennsylvania, was tested to determine how high power a telescope could be used through the dome. It was found impossible to use a telescope of 10 power or more through the dome. The definition with 6 power binoculars was poor. It was possible to use a 4 power binocular with the dome although the definition was impaired in many places in the dome. The two power telescope in the Pioneer Mark IV bubble octant was usable, however, showing poor definition in only a few places.

It was concluded that it would be impossible to make observations of stars and most planets in daytime through the Rohm & Haas Navigation Dome.

A second property of the plexiglass dome is its birefringence. Plane polarized light with plane neither perpendicular nor parallel to the axis of the dome in general is modified into elliptically polarized light by passage through the dome. If a plastic dome were used, it would be necessary to employ a quarter wave plate, or some equivalent device, with the polarizer in order to make the polarizer function satisfactorily at all times.

SCATTERING OF SUNLIGHT BY EXTERNAL GLASS SURFACES

If sunlight is permitted to fall on the external glass surfaces of octant considerable light may be scattered into the field of the instrument. The effect will be to increase the apparent sky brightness and reduce the contrast between star and sky.

The magnitude of the effect depends on the following considerations:

1. The condition of the glass surfaces. If the glass surfaces are kept scrupulously clean and unscratched, and if sunlight entering the instrument is well trapped by diaphragms, little decrease in star visibility will result.

2. The brightness of the sky. The lower the sky brightness, the more the scattered sunlight will decrease the star visibility. At high

altitudes dirty optical surfaces will be more objectionable than at low altitudes.

In order to investigate the magnitude of the scattered light measurements were made of the brightness of a piece of glass placed in the sunlight and of the intensity of the sunlight. Dirty glass plates were found to have brightnesses up to 100 candles/ft² in intense sunlight. Glass plates cleaned with water and a cloth gave brightnesses of about 5 candles/ft².

During a flight in a P.B.Y. plane it was observed that the plastic dome in clean but slightly scratched condition, added 50 c/ft² and so the dome made the apparent sky nearly twice as bright as the real sky.

Since the brightness of a hazeless sky at altitudes above 10000 feet is usually less than about 200 c/ft² during most of the hours of daylight, it will be important to keep clean and free from scratches those glass surfaces on which the sunlight falls. If this is done, and if all sunlight entering the instrument is well trapped, it should not be necessary to shade the telescope from the sun,

SURFACE TREATMENT WITH LOW-REFLECTING FILMS

Surface treatment with low-reflecting films improves the performance of an optical instrument in two ways. First, the light transmission is increased. Second, the image is made more brilliant because of the reduction of twice reflected light. It will be shown in the following discussion that the second consideration is of some importance, but the first is unimportant for the case of a daylight octant.

Consider the general case. The field of the instrument includes an area of brightness B_1 , which is to be distinguished from a surrounding area of brightness B_0 . B_0 is nearly equal to B_1 . These two areas can be distinguished if the quantity $\frac{B_1 - B_0}{B_0}$ is greater than the appropriate threshold for contrast perception.

This quantity, $(B_1 - B_0)/B_0$, will be called the contrast, γ , and its dependence upon reflection losses and back reflected light will be investigated.

Brightnesses B_1 and B_0 , for the case of an octant, are proportional to the brightnesses of the retinal images of the star plus sky and the sky, respectively. The contrast between them, $(B_1 - B_0)/B_0$, is not directly affected by reflection losses. If 4.5 per cent of the light is lost each time a glass-air surface is crossed, the transmission of the instrument will be 0.955^n , for n glass-air surfaces. If all the surfaces are "coated" the transmission will be 0.99^n . "Coating" will increase both B_1 and B_0 but will not change $(B_1 - B_0)/B_0$ provided all the reflected light is lost.

The once reflected light now strikes other glass-air surfaces, is reflected a second time, and is sent back toward the eye where it will tend to veil over the image. The twice reflected light does reduce the contrast and its elimination, by the use of low reflecting films, will make the image more brilliant.

The reduction in contrast can be calculated if we assume that the twice reflected light is distributed uniformly over the field. This assumption is very approximate because some surfaces will be curved in such a way that the twice reflected light will not reach the eye, while others may concentrate it in the field. Only a detailed calculation for a given instrument, or, better, a test of the instrument, will tell which surfaces need coating most.

Assuming that the twice reflected light is spread over the field uniformly, the contribution to the brightnesses of all images in the field is

$$.045^2 \frac{n(n-1)}{2} B_{av}$$

for n untreated glass to air surfaces, where B_{av} is the average brightness of the field. In case all n surfaces are treated, the contribution becomes

$$.01^2 \frac{n(n-1)}{2} B_{av}$$

The contrast for the uncoated instrument is

$$\gamma_u = \frac{B_1 - B_0}{B + B_{av} \frac{.045^2}{.955^n}} \frac{n(n-1)}{2}$$

and for the coated instrument

$$\gamma_c = \frac{B_1 - B_0}{B + B_{av} \frac{.01^2}{.99^n}} \frac{n(n-1)}{2}$$

The fractional increase in contrast produced by treating the surfaces is

$$\frac{\gamma_c - \gamma_u}{\gamma_u} \approx \frac{B_{av}}{B_0} \frac{n(n-1)}{2} \left[\frac{.002}{.955^n} - \frac{.0001}{.99} \right]$$

For a bubble octant we may assume $n = 14$, neglecting the index prism. Then

$$\frac{\gamma_c - \gamma_u}{\gamma_u} \approx \frac{B_{av}}{B} \times .346$$

For use in daytime $B_{av} = B_0$, since the star makes a negligible contribution to the whole field. An increase in contrast of about 35 per cent can be expected from treating all the surfaces. If half the surfaces are treated, by setting $n = 7$ in the above relation we find

$$\frac{\gamma_c - \gamma_u}{\gamma_u} \approx \frac{B_{av}}{B_0} \times .058$$

Treating half of the surfaces produces 80 per cent of the gain which may be obtained by treating them all.

The foregoing discussion leads to the following conclusions for the case of an octant for use on stars in the daytime:

1. Coating all the surfaces will increase the light transmission from about 50 per cent to near 90 per cent. This will increase star visibilities because the brightness contrast threshold is lower for higher brightnesses. The increase, however, is slight and of little practical importance.

2. The star visibility thresholds will be lowered appreciably by coating all glass to air surfaces to reduce the twice reflected light. Most of this advantage will be realized by coating only half the surfaces.

It should be noted that the above conclusions do not apply to instruments such as prism binoculars used for viewing extended objects in daytime or nighttime. In this case, coating increases the contrast in the darker portions of the field and makes detail more easily visible. The relation derived above still applies, but now $B_0 < B_{av}$, and, therefore $\gamma_c - \delta_4 / \delta_4$ is much larger.

POLARIZATION AND THE QUARTER WAVE PLATE

The visibility of a star against the daylight sky can be increased by as much as six times by the use of a polarizer, depending on the particular sky conditions. The polarizer reduces the sky brightness more than the star intensity because the light from the sky is partially plane polarized, while the starlight is unpolarized. In order to obtain the greatest possible gain the polarizer must be so placed in the octant that it receives skylight in its original state of polarization. The index prism and other prisms may change plane polarized into elliptically polarized light which cannot be extinguished by a simple polarizer.

Full effectiveness can be had by placing the polarizer before the index prism. However, for practical reasons, it is desirable to locate the polarizer near the eyepiece. Its performance here will be satisfactory, provided a quarter wave plate is inserted just before the polarizer. The quarter wave plate and the polarizer must each be adjustable by independent rotation. The quarter wave plate changes the elliptically polarized light back to plane polarized light which the polarizer can extinguish.

The magnitude of the gain in star to sky contrast provided by the quarter wave plate has been calculated and is shown in Table I. The gain depends on the inclination of the plane of polarization of the skylight to the vertical. When the plane is vertical or horizontal, the quarter wave plate is unnecessary. When the plane is at 45° the gain is greatest and Table I applies to this case. The gain depends also on the degree to which the skylight is polarized and upon the altitude of the point in the sky under observation.

This table has been checked qualitatively for the case of 100 per cent polarization. For the purpose the beam of light was passed through a 90° prism arranged in the manner of the telescopic octant index prism. A polaroid disc was placed before the prism and set at 45° to the plane of incidence. A second polaroid was placed after the prism. Some light was transmitted regardless of the orientation of the second polaroid. A mica quarter-wave plate inserted just before the second polaroid permitted one color to be completely extinguished. The field then appeared very dark blue or red depending on the exact adjustment.

It is seen from Table I that the gain in star to sky contrast obtained with a polarizer located in the eyepiece may be increased by as much as a factor of two by the use of a quarter wave plate. Two simple adjustments are required. The polaroid and the quarter wave plate must be rotated until minimum sky brightness is attained.

REFLECTED BUBBLE

It seems desirable to introduce the bubble into the field of view by reflection. To make the bubble image visible against a bright daylight sky requires more illumination than is needed for use at night. Figure 1 shows an arrangement which has been found suitable for projecting the bubble image into the daylight sky.

Light from the frosted 3.8 volt flashlight bulb F, is reflected from the conical mirrors M_1 and M_2 onto the sides of the bubble. Lens L_B and reflector M_3 produce an image of the bubble, B' , in the focal plane of the eyepiece. The result is that the bubble appears as a fine bright yellow ring against a blue sky of brightness 400 c/ft^2 . A red filter placed near L_B made the bubble a red ring and very pretty against the blue sky, though perhaps no more easily visible.

The bubble cell itself was a standard Mark III pioneer cell with all luminous material removed and M_2 was a part of this cell. A stop, S, served to keep the background dark. Two lenses were tried, at L_B , a 7 power Coddington magnifier, which reduced the bubble image to $1/3$ the actual bubble size, and an $f/2, 50 \text{ mm}$ Leitz Summar producing a 1:1 image. The bubble was still visible with the $f/2$ lens stopped to $f/6$, though less bright. M_3 was a platinized glass reflector reflecting 11 per cent and transmitting 50 per cent. Better than platinum which absorbs some light, would be a high reflecting layer of Titanium dioxide.

It was concluded that it is practicable to use a reflected bubble with an octant for daylight star sights.

TWO EYE BUBBLE OCTANT

It has been suggested that a bubble octant be constructed using one eye to observe the star and the other to observe the bubble.

This design has a number of advantages:

1. Star visibilities may be improved somewhat since no bubble cell or partial reflector need be introduced into the telescope.

2. The illumination system for the bubble can be made more flexible and will have no direct effect on the star visibility.

3. Any increase in star visibility to be obtained from illuminating the second eye will be realized.

Possible disadvantages are:

1. Accuracy. It would be necessary that the axes of the two eyes remain parallel to within a minute of angle in the plane perpendicular to the line connecting them. (At least the angle between them should remain constant.) The eyes could converge somewhat without serious effect. If this condition could not be met with the unaided eyes a pair of crosshairs could be placed in each eyepiece to cause the eyes to stay aligned.

2. Workability. It is questionable whether it would be comfortable and practicable for the two eyes to superimpose different images.

The following experiment was carried out to test the two eye bubble octant. A 6 power monocular was set up to view an artificial star and sky with the right eye. Before the left eye an eyepiece from a similar instrument was placed and into the focal plane of the eyepiece the image of a Mark III bubble cell was projected. The cell was illuminated by means of a 100 watt frosted lamp below a piece of ground glass. The bubble appeared as a dark ring on a bright yellow field.

No difficulty was encountered in focussing the eye on the star image, in concentrating on the star, or in superimposing the yellow bubble field on the blue sky. Difficulty was had, however, in keeping the angle between the axes of the eyes constant to within the required very few minutes. Crosshairs were placed in both eyepieces to force the eyes to stay aligned but this had the effect of distracting the right eye from the star. By removing the central portion of the crosshairs in the left eyepiece, the distracting influence was eliminated and enough of the crosshairs were left to allow the alignment of the eyes to be checked.

It is concluded that the possible advantages of such a design over the method in which the bubble is introduced by reflection are probably not great enough to justify it at the present time.

MECHANICS OF BUBBLE

In this section is given a theoretical discussion of the mechanics of the bubble in its chamber in the case of a telescopic octant.

The conditions which must be met are as follows:

1. The bubble must follow the star as the instrument is rotated about an axis perpendicular to the vertical plane containing the star.
2. The bubble image must occupy less than the whole field of the instrument.
3. The bubble itself must be large enough so that its motion is not greatly damped.
4. The bubble period should be as short as possible.

Figure 1 shows a schematic diagram of a telescopic bubble octant with a reflected bubble. The condition to be met to make the bubble image follow the star image for rotations in the vertical plane containing the star is

$$R = f_o \frac{u}{v}$$

where R is the radius of curvature of the bubble cell, f_o the focal length of the objective, L_o , and u and v are the object and image distances for lens L_B which produces the bubble image in the focal plane of the eyepiece.

The angle subtended by the bubble image, referred to the object space is

$$\theta = d_B \frac{v}{u} \frac{1}{f_o}$$

where d is the actual bubble diameter,

Because of the first condition we can write

$$\theta = d_B/R$$

The period of the bubble is given approximately by

$$T = 2\pi \sqrt{\frac{R}{g}}$$

where g is the acceleration due to gravity, since the bubble acts like a simple pendulum of length R.

As an example consider the Mark IV octant $f_o = R = 9.5$ cm.
Let $d_B = 0.6$ cm.

$$T = 2\pi \sqrt{\frac{9.5}{980}} = 0.6 \text{ sec.}$$

$$\theta = \frac{0.6}{9.5} = 0.63 \text{ radians} = 3.6^\circ = 1/3 \text{ total field.}$$

A 6 mm. bubble is not greatly damped and is quite satisfactory.

Consider next a telescopic octant. For an 18 inch, (45.5 cm), objective the bubble characteristics have been computed for various choices of v/u , the magnification of the bubble projection system, and are shown in Table II. It can be seen that a longer period requires a larger bubble image, for a given bubble diameter.

It is concluded that a 1:1, or slightly greater, projection magnification should be satisfactory. For this case the bubble period is about 1.3 seconds. Because the motion of a large plane is fairly slow a 1.3 second period should not be too long, nor will a 6 mm. bubble too sluggish.

The bubble will subtend 0.75° which is about $1/3$ of the whole field of the instrument.

TABLE 1

Increase in Star Visibility Produced by Polarizer

Percent Polarization	Increase if polarizer is located before prism, or if quarter wave plate is used.	Increase if polarizer is located just after prism. Values for altitude range 16° to 70° .
100 (never occurs)	00	2.95 - 4.0
82	5.5	2.2 - 3.2
67	3.0	1.8 - 2.3
54	2.16	1.55 - 1.87
43	1.75	1.38 - 1.56
33	1.50	1.28 - 1.36
11	1.125	1.08 - 1.10
0	1.00	1.00

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TABLE II

Characteristics of a 6 mm. Bubble for
a Telescopic Octant with 18 inch Objective

$\frac{v}{u}$	3	2	1	$\frac{1}{2}$	$\frac{1}{3}$
R (cm)	15.2	22.8	45.5	91.0	136
θ	2.26°	1.51°	0.75°	0.38°	0.25°
T (Sec)	0.78	0.95	1.9	1.9	2.3

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STAR AND SKY

INDEX PRISM

L_0

M_3

BUBBLE AND STAR IMAGES

EYEPIECE

EYE

L_B

μ

BUBBLE

RADIUS OF CURVATURE R

M_2

M_2

S

M_1

M_1



DIAGRAM OF OCTANT SHOWING METHOD OF BUBBLE ILLUMINATION BY REFLECTION.

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PLATE 1

