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First Report

on

Seeing Stars in Daylight

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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INTRODUCTION:

In the following paragraphs are given briefly results on experiments which have been carried out up to the present time on the problem of seeing stars in daylight. The experiments have dealt with measurements in the laboratory on artificial stars and skies, with observations from the ground on real stars and planets in the daylight sky, and with observations from an airplane at altitudes up to 10,000 feet. Certain experiments were not exhaustive and are to be continued. Therefore, some of the conclusions are tentative. In the last section plans for further work are mentioned.

MAGNIFICATION AND OBJECTIVE DIAMETER

In general, the higher the magnification of a telescope the weaker the stars which can be seen. More exactly, the theory of telescopes states that as the magnification M is increased the threshold of brightness contrast between star and sky decreases inversely with M^2, until M equals "normal magnification," i.e. until the exit pupil of the instrument becomes as small as the pupil of the eye. For higher magnifications the threshold remains constant.

This relation has been tested and found to be approximately true, but to be modified by physiological factors. For the purpose an artificial star and sky were observed with several objectives combined with several different eyepieces. The results for a typical objective are shown in Figure 1. The heavy line describes the theoretical relationship; the break occurs at normal magnification assuming an eye pupil of 2mm. (The curve was located as a whole by the threshold for the naked eye measured with the artificial star and sky). The experimental curve shows that this relationship is fairly well followed for magnifications less than normal. But at higher magnifications the threshold continues to drop, though more slowly. The reason is that simple theory assumes that the threshold depends only on the brightness contrast between the retinal images of the star and the sky. Actually, it is a well known physiological fact that for a given brightness contrast the threshold is lower the larger the size of the image. Since the image size increases due to diffraction for magnifications greater than normal, with no change in contrast, the star becomes easier to see. Apparently the threshold rise caused by the lower brightness of the sky image is not very important.

Another way of investigating the same effect is to keep the magnification constant and to determine the threshold as the objective is stopped down. Figure 2 shows the results of such an experiment for the objective used for Figure 1. The theoretical relation shown by the heavy curve requires a constant threshold until the exit pupil becomes reduced to the eye pupil. For smaller apertures the threshold rises as $1/d^2$, where d is the diameter of the exit pupil. The experimental curve agrees with theory fairly well down to the point for normal magnification, but below this the threshold does not rise as fast as $1/d^2$ because the increased size of the image due to diffraction makes it more easily visible.

For planets, however, the theory is more complicated because a planet, unlike a star, is not a point source and is usually perceived as a disk. In general, it can be concluded from theory that there should be less increase in brightness contrast with magnification for planets than for stars, and sometimes there may even be a decrease. However, the increased size of image comes into the problem and, as a rule, makes up for the lesser gain in brightness contrast.

Qualitative experiments on planets showed that Venus was easier to see, the greater the magnification, up to about 10 power or more. Jupiter, which is larger and is perceived as a disk for very low magnification, was made more easily visible with magnifications up to about 10, but higher magnifications seemed to make observation no easier.

It was concluded that a telescope for viewing stars in full daylight should have as large a magnification as size and other practical considerations will permit. It is most advantageous to keep the eye pupil filled; but it may be of some advantage to push the magnification to somewhat above normal if the objective diameter must be limited for practical reasons.

EFFECTS OF SKY BRIGHTNESS AND OF EYE PUPIL

Concerning the brightness of the sky, the simplest assumption is that if a given star is visible against a given sky, a weaker star should be visible against a proportionally weaker sky. This has been investigated and found to be partly true. Two factors enter; first, the threshold for brightness contrast perception is higher for lower brightness; second, the eye pupil dilates for lower brightness and this changes the size of the star image and hence the threshold.

Experiments to investigate this were performed in two ways using the artificial star and sky. First, the sky was dimmed and the threshold value of the star determined for many settings of the sky. Second, neutral density filters were placed between the eye and the eyepiece and the threshold redetermined. The results are given in Figures 3 and 4 and show that the threshold becomes higher at low brightnesses.

The application to the problem of seeing stars is simply that the visibility of a star for skies becoming weaker than 100 candles/ft^2 will not increase as much as a simple proportion would indicate. Furthermore, neutral filters are disadvantageous and hence partial dark adapting of the eye is of no advantage.

FOCAL LENGTH OF OBJECTIVE

The absolute values of the focal lengths of objective and eyepiece do not enter in the simple theory separately, it is only their ratio, the magnification, which is of importance. Thus it might seem that two telescopes, one with objective and eyepiece having half the focal lengths of a second, should be equally good. But this is not true, because spherical aberration and coma are usually not so well corrected for a short focal length large aperture objective lens and this makes a star image less sharp and hence less bright.

To investigate this,achromatic lenses of various focal lengths have been tested with the artificial star and sky. As yet no objectives of aperture larger than f/10 have been found which compare favorably with objectives of f/15 or smaller aperture. Several achromats were very poor.

It was concluded that the telescope objective should be an achromat especially computed for use with an object at infinity, and that its aperture should be no larger than about f/10.

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BINOCULAR AND MONOCULAR VISION

Experiments were carried out with the artificial star and sky with 8 and 10 power binoculars to determine whether the thresholds for star perception for monocular and for binocular vision are the same. The results for the case of the writer's eyes, seem to be that the threshold is somewhat lower for binocular vision, on one occasion by as much as a factor of three. Furthermore, it was found immaterial whether one or two eyes actually perceive the star as long as both are more or less equally illuminated by the sky. This point was tested by throwing one eyepiece out of focus so that this eye could not possibly see the star.

A similar advantage was attained with a monocular by exposing the second eye to an approximately equally bright and uniform field by means of a flashlight. However, it was found that the field for the second eye must be uniform so that the first eye has nothing to distract its attention. It will be of interest to make further tests of these effects with several observers.

If this is true, it means that it is necessary only to provide an artificial field for the second eye, which is easier and cheaper to do than to make a true binocular instrument.

FILTERS

A variety of Wratten filters were tested, first in the laboratory on the artificial star and sky, and then on both Sirius and Arcturus, as examples of blue and orange stars. Dark red filters, such as No. 70, rendered the stars invisible. Light red filters, Nos. 23 and 24A, neither helped nor hindered. An orange filter, No. 22, transmitting wave-lengths shorter than 5500A, seemed with Arcturus to be of some advantage, but

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never reduced the threshold by more than a factor of 2. Yellow, yellow-green, green, blue-green and light blue filters, (Nos. 8, 40A, 40, 44 and 38), made no perceptible difference, while dark blue and purple filters, Nos. 49A and 32, made stars less visible.

FIELD OF VIEW

The field of view is a matter of importance in locating a star. The opinion has often been expressed that the greater the total field of view of the telescope, the easier it will be to locate the star. This appears to indicate that stars will be much harder to locate in a higher power instrument. The following discussion and experiments indicate that this is not necessarily true.

A distinction must be made between the useful field, the field of perception and the total field. In most wide angle instruments it is impossible to see a weak star across the total field. By the useful field is meant the angular radius of the circle over which the star can be seen if the eye is fixated on it, i.e. if the star image falls on the fovea. By the field of perception is meant the angular radius of the circle throughout which the star will be perceived if the eye is fixated at the center and the star is seen out of the corner of the eye, i.e. the star image does not fall on the fovea. It is the field of perception which determines whether a star will be seen or not at a given fixation of the eye. A large useful field of view is an advantage in that it permits the eye to roam from point to point until the star happens to fall within the field of perception. However, the searching could be done at least as quickly, and perhaps more so, by fixating the eye on the center of the field and turning the telescope systematically until the star image falls within the field of perception.

Experiments showed that the field of perception was fully as large for a 20 power as for a 5 power telescope. Furthermore the 20 power telescope yielded the much more easily perceived star over most of the field of perception. This fact eliminates one strong objection to the use of a high power instrument.

Proof of this is given by the curves of Figure 5. These show for three typical telescopes the threshold for perceiving the star plotted against the angle in the object space between the star and the point of fixation of the eye. Each point is the average of four taken for positions to the left, right, above, and below the star. The curves are for the writer's eye, but they do not differ greatly from published curves for related experiments. The dotted curves show for comparison the useful fields of the three telescopes, the star lying at various distances from the axis and the eye fixated upon it. The brightness contrast levels for certain stars as observed here on a haze-free day appear on the diagram.

To illustrate the meaning of the curves of Figure 5 Sirius could be perceived over circles of radii 0.27°, 0.46° and 0.56°, with telescopes of powers 5, 10, and 20, respectively. Furthermore, Sirius was much easier to see, angle for angle, through the highest power telescope since its level lay furthest above the threshold for this instrument. Since the area is proportional to the radius squared, the area of perception for the 20 power telescope was 4 times that of the 5 power. These fields of perception were verified by actual observations of Sirius.

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From the curves it can be seen that it will be rare indeed to perceive a star in full daylight over a circle of more than one degree radius and that 1/2 degree will probably be more generally the value. Thus it will be necessary to set and maintain telescope orientations to $\pm$ 1/2° to keep the star within the field of perception. However, it should not be very difficult to arrange for adjusting the telescope to this accuracy easily and quickly and it should be possible to locate or relocate a star as quickly, or more so, by turning the telescope than by searching with the eye over a large field much of which may be inferior.

OBSERVATIONS OF ACTUAL STARS FROM GROUND

Observations of actual stars during daylight were carried out from the laboratory roof using various telescopes. The brightness and polarization of the sky were measured in each case. The star was observed with various powers, with polarizer set to help and also to hinder, and under different atmospheric conditions. The ease of observation, the useful field, and the field of perception were estimated.

A comparison between these data and the observations made on the artificial star and sky shows that telescope performance can be predicted satisfactorily in case there is no haze. Table I gives data on certain stars observed from ground on August 13, the most haze-free day since the investigation was commenced. In order to estimate the effectiveness of the telescope in each case the following ratio was calculated: the actual contrast between the star and the sky divided by the threshold value for that particular telescope and polarizer setting.

This ratio gives a measure of the ease with which one can observe a star in a particular case if one is looking exactly at it. The threshold value was measured with the artificial star and sky, while the actual value was calculated from the star magnitude and the measured sky brightness and polarization in its direction.

From the cases recorded in Table I it can be seen that it was just possible to see a star when this ratio was about unity, i.e. when the actual contrast was about equal to the threshold contrast. The threshold value for a given telescope, therefore, will tell whether or not a given star can be seen with a given telescope on a particular date at a certain time if there is no haze.

Table II, taken from the data in Table I, gives some idea of how easy it was to see a star for different values of the contrast ratio. It was very difficult indeed to find a star if its contrast level lay near the threshold. Usually several minutes intensive scrutinizing the field were required before it was perceived, even though it was squarely in the center. In order to be very easy to see, a contrast value five or ten times greater than the threshold was required.

The numbers of Table II are related to areas of perception derived from the data of Figure 5. The relation will be investigated further.

For planets the values in Table II do not hold. Table I contains figures for Jupiter and Venus. All that can be said at this time is that increasing the magnification did help with planets, but that the advantage was not as great as with stars.

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HAZE

The haze generally prevalent in Washington decreased tremendously the visibilities of stars and made prediction of their visibilities very uncertain. The sky brightness was usually more than twice that of a haze-free sky and it was impossible to predict from this sky brightness just how much the light from a star was attenuated in passing through this haze. Even on those days which seemed to be clear, with horizontal visibilities 5 or 10 miles, stars whose levels lay several times above the threshold were often invisible.

STAR OBSERVATIONS FROM THE AIR

Observations of Venus, Jupiter and Sirius were made from a plane at 10,000 feet for solar altitudes 40° and greater. It was found; first, that a 20 power telescope can probably be mounted satisfactorily in a plane; second, that a 20 power telescope makes stars easier to see than a 10 power; third, that further investigation is required to determine whether air turbulence may sometimes impair the definition.

The plane used was a medium sized amphibian, Type JRF. The two telescopes of 10 and 20 power, with polarizing eyepieces, were arranged for altitude and azimuth location of the stars and mounted on a table just aft of the wing. Removal of the top section of the door provided a port through which to sight.

In order to reduce mechanical vibration, it was necessary to mount the telescopes on rubber. This was successfully accomplished so that with the 20 power telescope little trace of vibration was evident. However, elimination of vibration will always be important, and may often be difficult.

Venus was exceedingly easy to locate and follow in both the 10 and 20 power telescopes. Jupiter, also, was easily seen in both telescopes; in this case the 20 power seemed little better than the 10 power. Sirius was located at once in the 20 power telescope and was also seen satisfactorily but less easily in the 10 power.

To keep Sirius in the field of perception with the 20 power telescope offered little trouble. The gyro-pilot maintained the plane's course within about a degree, and the plane remained approximately level. Changes in course and level were rather slow, and little difficulty was encountered in keeping the 20 power telescope on the star even though the diameter of the total field of view was 1.8°.

On several occasions the image of Jupiter or Venus in the 20 power telescope was diffuse. It was suspected that for certain lines of sight the air may have been so turbulent as to impair the telescope definition.

A five minute search for Capella was without success.

SKY BRIGHTNESS AND POLARIZATION

Series of measurements of the brightness of the sky were made from sea level to 10,000 feet. Complete measurements of the brightness and polarization of the sky were made at 10,000 feet for the sun at about 40° altitude. These will be continued and the results from them organized.

BUBBLE OCTANT

Tests in the air were made with a standard bubble octant, Pioneer Instrument Company, Mark IV. The optical arrangement of the instrument is such that the image of the celestial object is obstructed by the bubble. Therefore, the star must be seen either through the bubble or to one side of the bubble. The octant was modified by the addition of eyepieces giving magnifications from 2 to 6 power, by the removal of diaphragms, and by the addition of a polarizer.

Although it was possible to see a bright star through the bubble, properly adjusted, the optical arrangement was unsatisfactory. The bubble should not be placed in the light path from the star; its image should be introduced into the light path by reflection. This, of course, has been known for a long time.

With the standard 2 power eyepiece a series of altitude observations on Venus were made at 10,000 feet near noon. They are plotted in Figure 6. The image of Venus was lined up outside the bubble since it was not visible through the bubble. The instrument was hand held. The straight line through the points has a slope determined by the plane's speed and by the computed altitudes of Venus. It can be seen that no points fell more than 15' from this line and that this line should give the plane's position to within ± 3 miles.

Jupiter was observed from the ground at about 9 A.M. using eyepieces providing from 2 power up to 6 power magnification. It is believed that it would be practicable to make sights on Jupiter from a plane using the present octant if an eyepiece providing 4 or 5 power magnification were provided.

Sirius was observed from the ground with difficulty using the eyepiece providing 6 power magnification. It is possible that such an eyepiece would make practicable high altitude sights on Sirius. However, it is doubtful if any weaker stars and planets could be used.

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PLANS FOR FURTHER WORK

The following tentative plans for further experiments are in mind:

1. Test present rather crude telescopes on a larger plane to determine effects of vibration and air streaming.
2. Test further telescope lenses and eyepiece combinations. Difficulty is being encountered in obtaining such equipment. At this date none of our orders have been filled.
3. Continue tests of star finding and measurements of sky brightness and polarization at altitudes above 10,000 feet.
4. Build a telescopic bubble octant suitable for tests on a plane. The first design to be essentially simple and for test purposes only. A final design will depend on the type of window or viewing arrangements of the plane.

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TABLE I

STAR VISIBILITY OBSERVATIONS

Actual Contrast ÷ Threshold Contrast for Polarizer

Celestial Object	M	Helping		None		Hindering	
Sirius	20	34:	Vy. easy	27:	Vy. easy	21:	Vy. easy
8:40 A.M.	10	8:	Easy	6:	Easy	5:	Easy
8/13/41	5	3:	Mod. easy	2.2:		1.7:	Hard
Rigel	20	14:	Vy. easy	8:	Easy	4.4:	Easy
9:05 A.M.	10	3.2:	Mod. easy.	1.8:	Hard	1.0:	Vy. hard
8/13/41	5	1.1:	Vy. hard	.6:	Not seen	.35:	Not seen
Capella	20	21:	Vy. easy	9:	Easy	4:	Easy
11:30 A.M.	10	4.6:	Easy	2:		1.0:	Hard
8/13/41	5	(1.7:	Not tried)	(.8:	Not tried)	(.35:	Not tried)
Aldebaran	20	7:	Not found	3:	Not found	1.5:	Not found
11:45 A.M.	10	1.5:	Not found	.7		13	
8/13/41							
Arcturus	20	53:	Vy. easy	21:	Vy. easy	8:	Vy. easy
2:00 P.M.	10	12:	Vy. easy	5:	Easy	2:	Mod. hard
8/13/41	5	4.3:	Not tried	1.7:	Not tried	.7:	Not tried
Vega	20	28:	Vy. easy	13:	Vy easy	6:	Easy
3:35 P.M.	10	6:	Easy	3:	Mod. easy	1.3:	Hard
8/13/41	5	2.2:	Not tried	1.0:	Not tried	.5:	Not tried
Spica	20	10:	Easy	6:	Mod. easy	3.4:	Mod. easy
3:15 P.M.	10	2.3:	Hard	1.3:	Vy. hard	.8:	Not seen
8/13/41							
Jupiter	20			20:	Vy. easy		
10:15 A.M.	10			30:	Easy		
9/13/41	8			20:	Mod. easy		
8:45 A.M.	6			9:	Mod. hard		
9/26/41	6			22:	Mod. easy		
	2			2.2:	Hard		
Venus	20			300:	Exc. easy		
2:20 P.M.	10			70:	Vy. easy		
8/28/41	6			30:	Easy		
	2			3:	Easy		

[redacted]

TABLE II

ARBITRARY SCALE OF EASE OF SEEING STARS

The numbers give the actual star to sky contrast ÷ threshold contrast.

>10 - - - - - - - - - - - very easy

5 - 10 - - - - - - - - - - - - - - easy

2.5 - 5 - - - - - - - - - - moderately easy

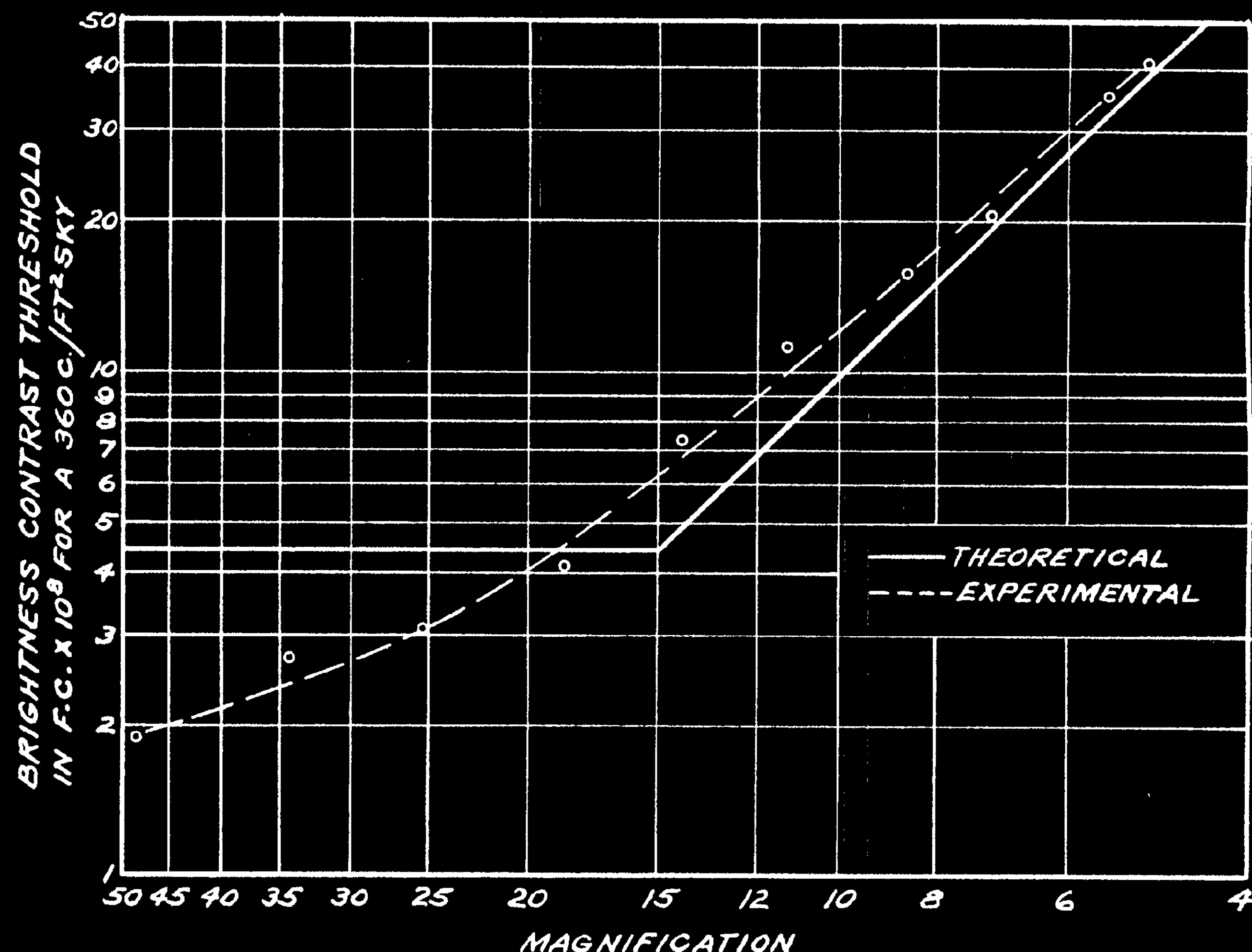
2 - 2.5 - - - - - - - - - - moderately difficult

1 - 2 - - - - - - - - - - - difficult - (Requires several minutes looking to see, even though it is in field)

1 - - - - - - - - - - - very difficult - (Can be seen if one looks long enough at exact place in field)

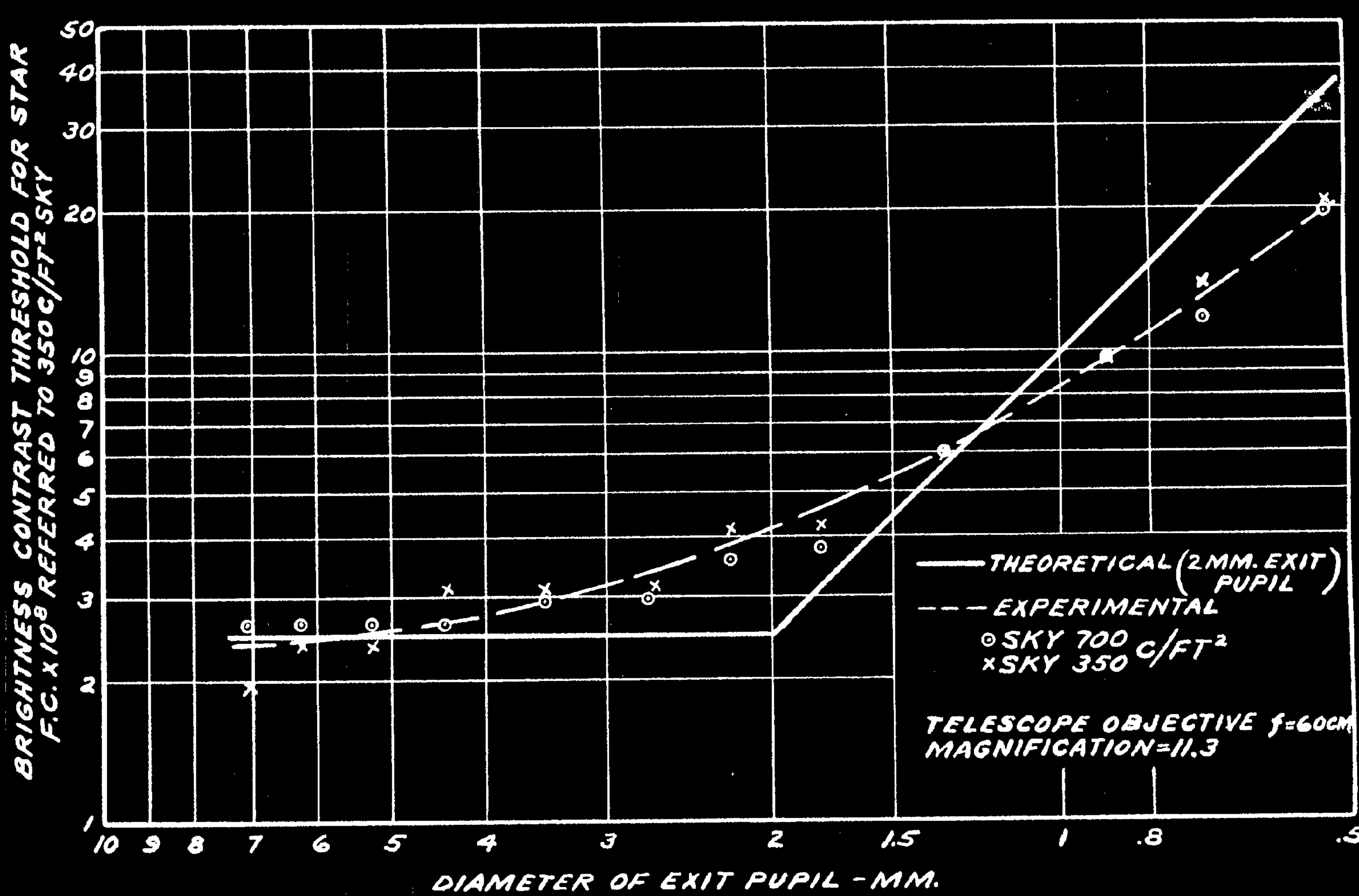
<1 - - - - - - - - - - - cannot be seen

[redacted]



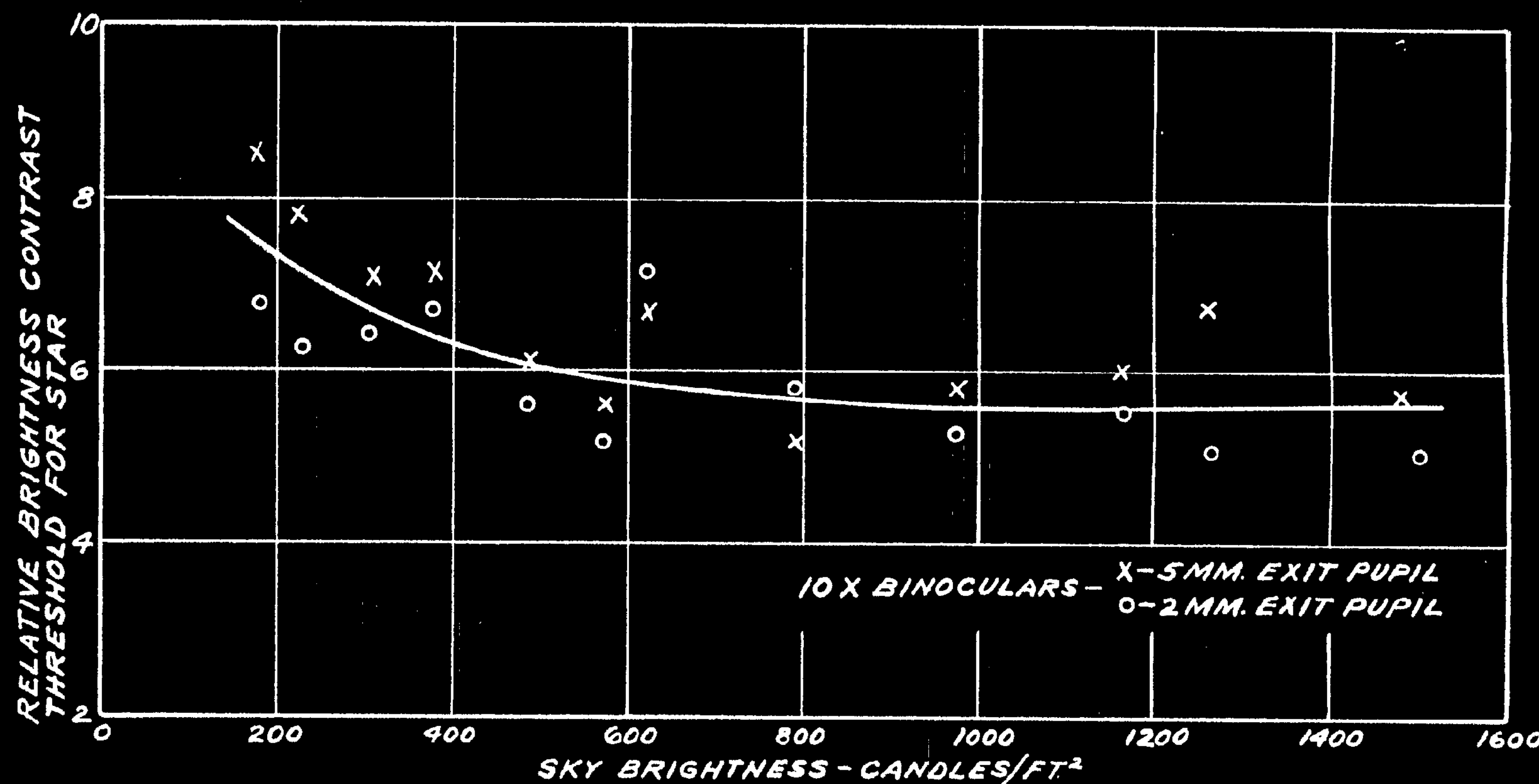
THRESHOLDS FOR A TELESCOPE WITH A 60 CM., f/20 OBJECTIVE

PLATE 1



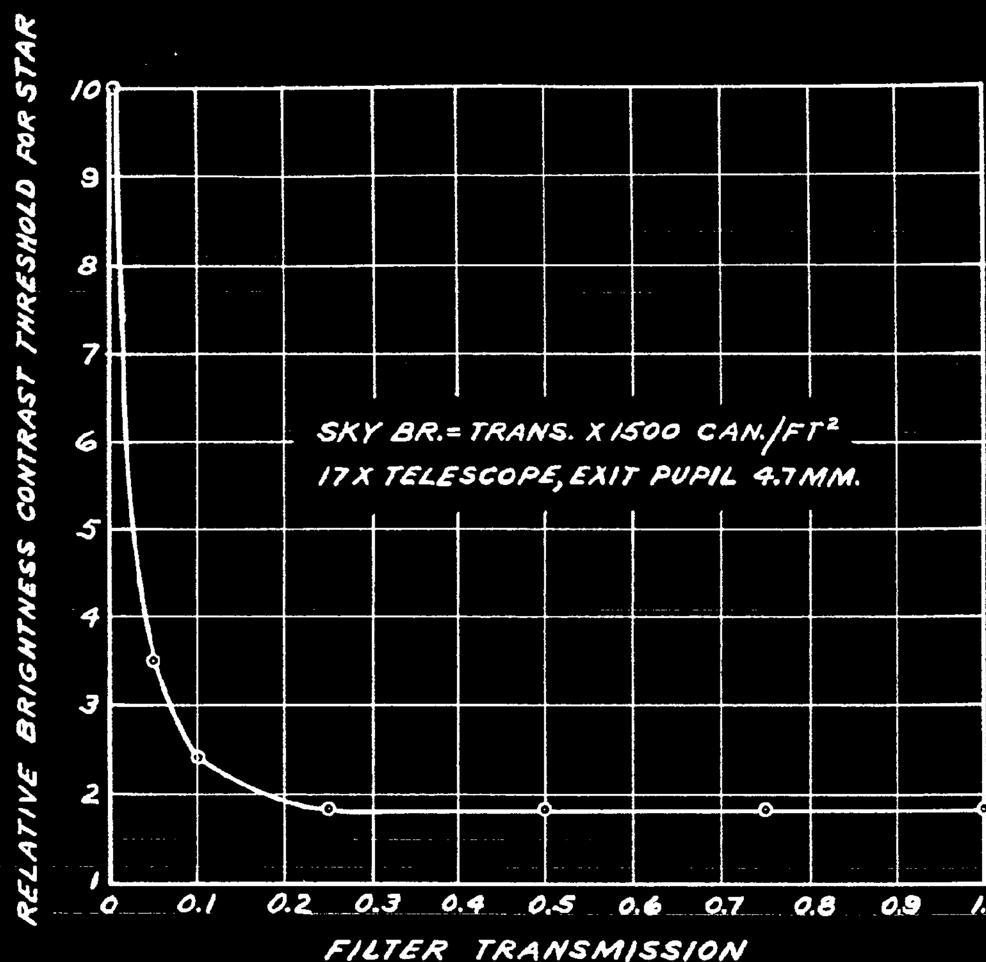
BRIGHTNESS CONTRAST THRESHOLD FOR STAR
EFFECT OF CHANGING OBJECTIVE DIAMETER

PLATE 2

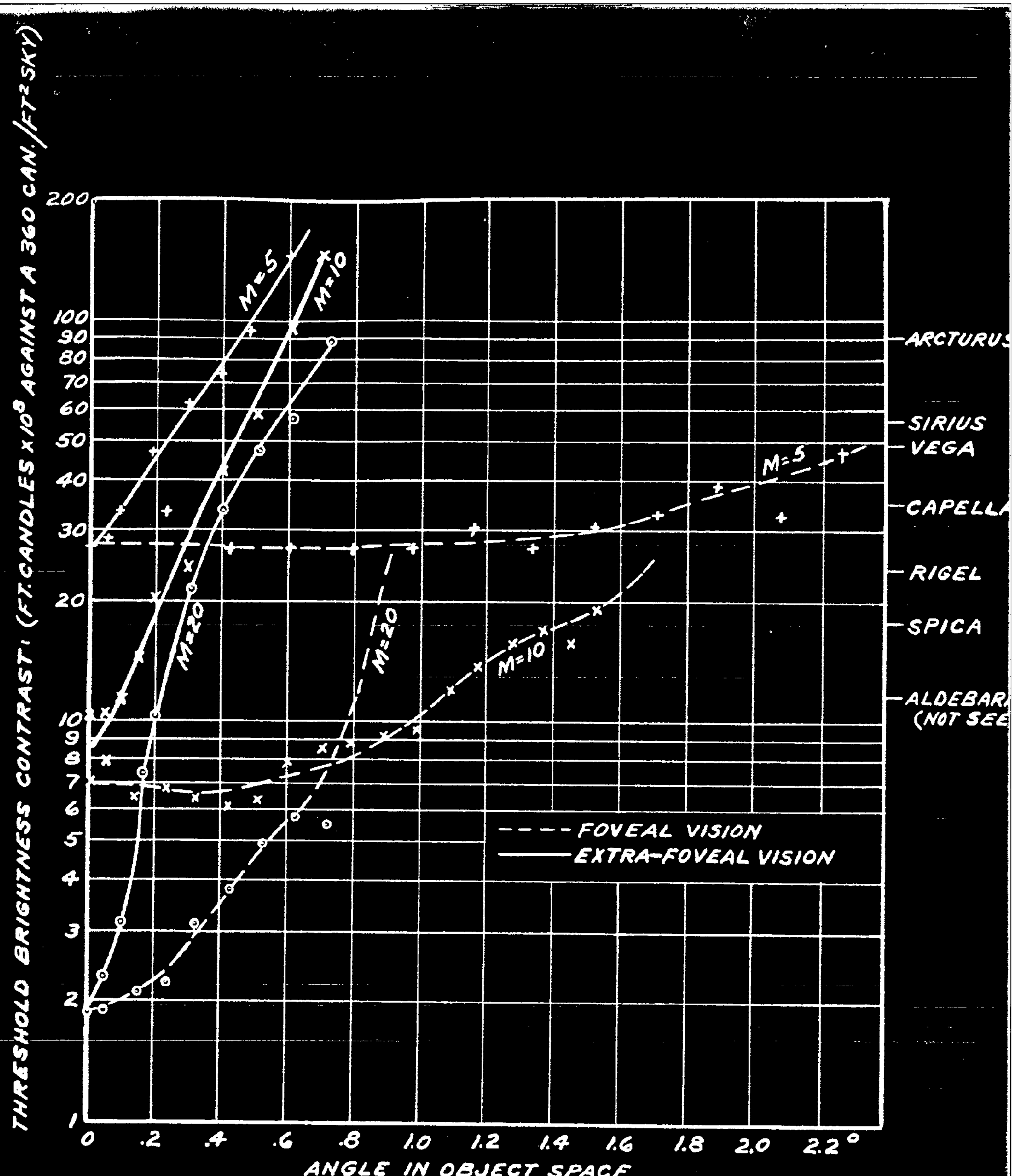


STAR VISIBILITY—EFFECT OF DIMMING SKY

PLATE 3

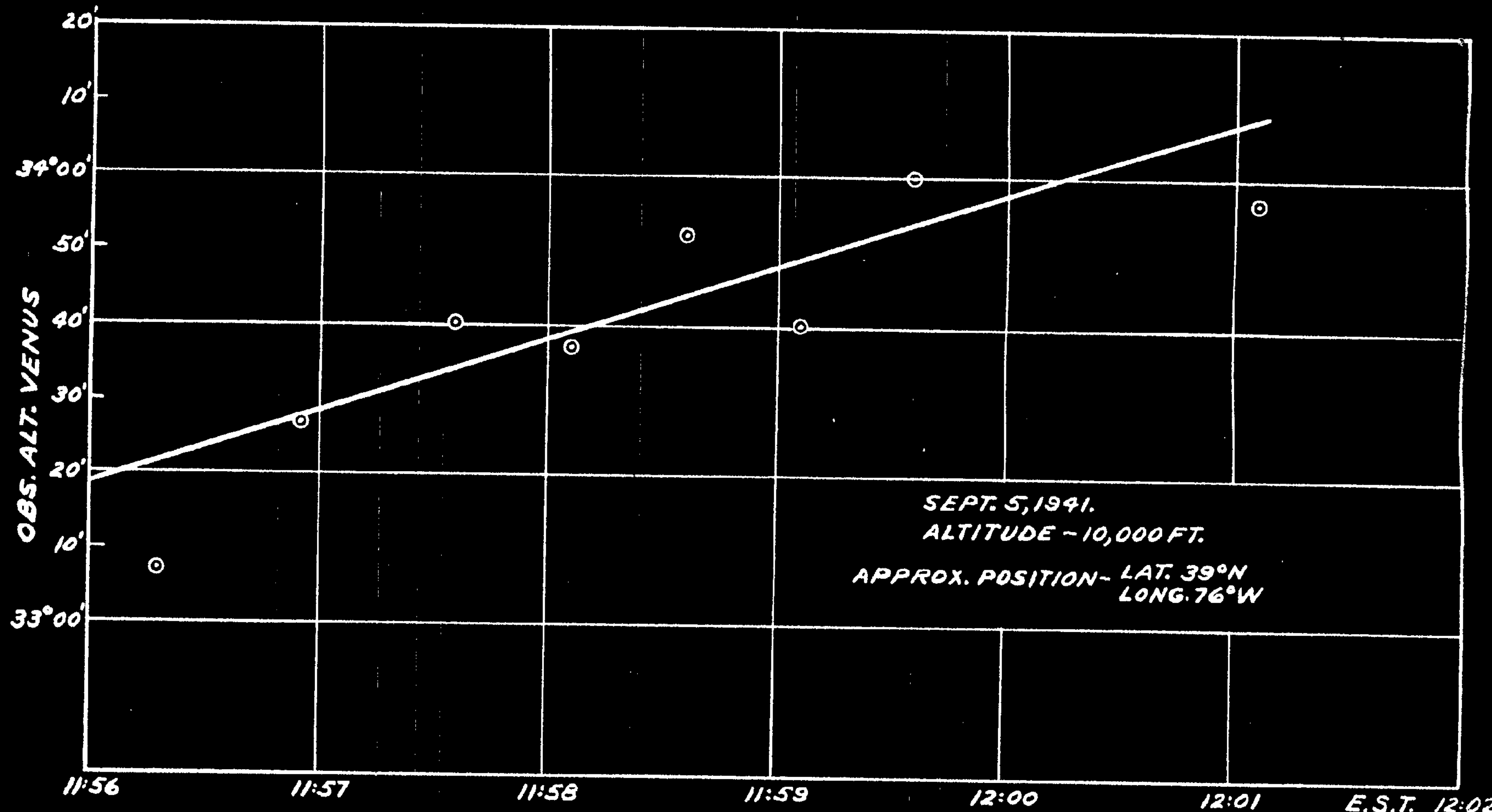


STAR VISIBILITY
EFFECT OF NEUTRAL FILTERS



FIELD TESTS – THRESHOLDS FOR THREE TELESCOPES

PLATE 5



OBSERVED ALTITUDE OF VENUS - MARK IV PIONEER BUBBLE OCTANT

PLATE 6