APERTURE SCREENS FOR SOLAR TELESCOPES

Robert H. Hammerschlag
Zonnenburg 2, 3512 NL Utrecht, The Netherlands

ABSTRACT

A screen with many small holes reduces the amount of light with preservation of the resolution. The reduction of light prevents internal seeing and excessive heating of the secondary optics of compact telescopes.

A simpler screen with slit or cross aperture allows focussing and guiding on the rim of the sun. The screen is opened for solar observations during short times.

An imaging criterion for structures on a light background is defined, which is used for the investigation whether the screens reduce the resolution. This criterion shows also in an easy way, that annular apertures reduce the resolution inadmissibly and that multiple aperture telescopes should have only a small area between the individual apertures.

1. INTRODUCTION

The large amount of light causes heating of the air in solar telescopes. The temperature differences induce differences in the refractive index of the air, which deteriorate the image: the so-called internal seeing. Besides an inadmissible heating of the secondary optics can occur at large numerical aperture (=small f-number) of the primary optics. A compact construction is a reason to use a large numerical aperture. In that case, relative light constructions give a sufficient mechanical stability for high resolution.

Evacuated telescopes solve the problem of internal seeing (Dunn, 1964, 1969). The maximum diameter of the entrance pupil is limited by the diameter of the entrance window. The diffraction limit of the resolution is proportional to the diameter of the entrance pupil. Technical problems limit the dimensions of the window. Too large windows give too much optical aberrations. The window limits the maximum resolution, on the condition that the seeing allows such a resolution.

Telescopes with a construction which is open as much as possible, and with large numerical aperture of the primary optics for a short light path of the primary beam, also hold out a prospect of a solution for the internal seeing (Hammerschlag, 1980). A water cooled diaphragm at the primary image only transmits a small part of the solar image. In this way, one prevents an inadmissible heating of the secondary optics. Air suction around the water cooled diaphragm prevents internal seeing from air heated or cooled at this diaphragm. This telescope concept does not allow a simultaneous image of the whole sun at the present technical possibilities to manufacture lenses or mirrors for use at the secondary optics.

The whole sun can only be imaged with primary optics with small numerical aperture (=large f-number). In that case, the primary solar image becomes so large, that the light is spread over a large enough surface. Also evacuated telescopes have this problem. The requirement of mechanical stability combined with a large focal length leads to heavy and expensive constructions.

The aim of the concept which we give here, is a light weight telescope which allows a high resolution image of the whole sun.

2. PRINCIPLE OF THE SCREEN WITH HOLES

A usual concept for a stellar telescope is shown in figure 1. It is a Cassegrain telescope with large numerical aperture of the primary mirror. A screen with holes is placed in front of the telescope. Figure 2 shows a front view of this screen. The pattern of holes works as a two dimensional grating. A two dimensional array of solar images is formed in the image plane. The zero order image is used. The zero order image is separated from the higher order images if $p \leqq \lambda/q$, where p is the distance between the holes (see figure 2), λ the shortest wavelength of the light in use and q the diameter of the sun expressed in radians. The diameter of the sun is 1/107.4 radian. It follows : $p \leqq 107.4\lambda$.

If we call the diameter of the holes d (see figure 2), the intensity reduction compared to an open aperture is proportional to $(d/p)^4$. This reduction factor can be understood as the product of $(d/p)^2$ reduction of the entered light by geometrical obscuration of the screen and $(d/p)^2$ reduction of intensity by the spread out of the light caused by diffraction.

We give a numerical example. Suppose the shortest wavelength in use is 0.32 µm (atmospheric cut off). From $p \leqq 107.4\,\lambda$ it follows that $p \leqq 34$ µm. The sky brightness is high in the direct neighbourhood of the sun, see section 8. Therefore, the value of p is chosen slightly smaller and the sky near the sun of the first order images falls outside the zero order image of the sun. A safe value is $p = 25$ µm. Suppose we have a telescope with a f-ratio $f_r = 2.75$ of the primary mirror. We want a light intensity in the primary image equal to the light intensity of the direct solar light. The required attenuation is

$$(1/q\,f_r)^2 = 1525 \rightarrow (p/d)^4 = 1525 \quad \text{or} \quad p/d = 6.25$$

with $p = 25$ µm, we find $d = 4$ µm.

Coarser hole patterns can be used for observations in the infrared. For example, with $\lambda = 1.6$ µm a pattern can be used with $p = 125$ µm and $d = 20$ µm. Large aperture telescopes can be used effectively for high resolution in the infrared because the seeing disturbs less the longer wavelengths. Large apertures require low f-ratios for compact constructions. The coarser hole patterns are easier to make. Hence the screen with holes may be of special interest to infrared observations

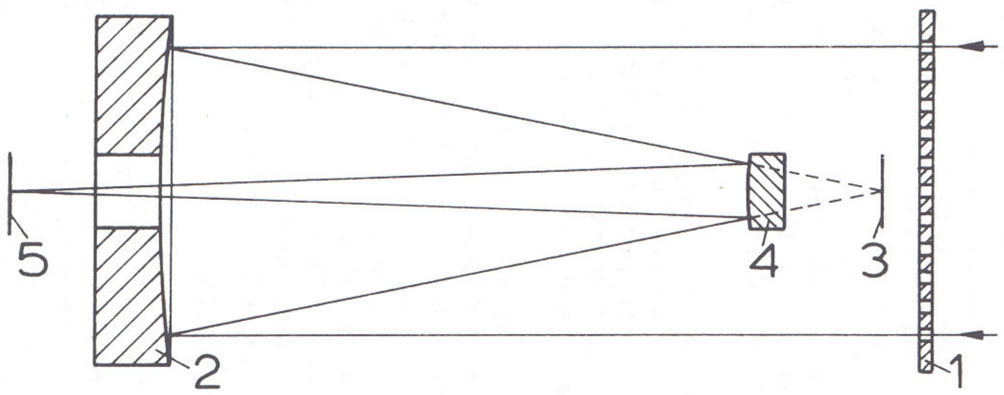


FIG. 1.— Schematic drawing of a telescope with an aperture screen
1 plate with holes, the aperture screen
2 primary mirror
3 primary image plane, virtual
4 secondary mirror
5 secondary image plane

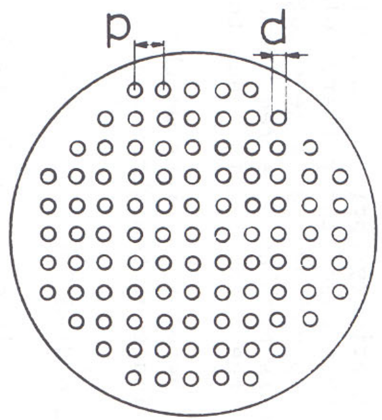


FIG. 2.— Front view of the aperture screen

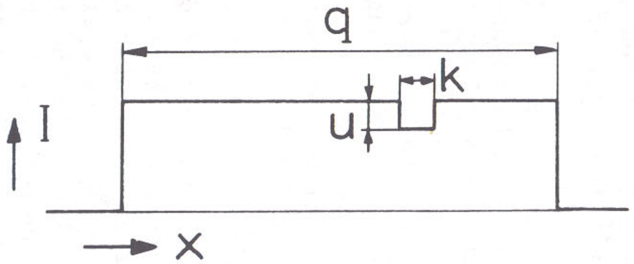


FIG. 3.— Intensity distribution of an object with limited diameter and a low contrast feature. I = intensity ; x = place

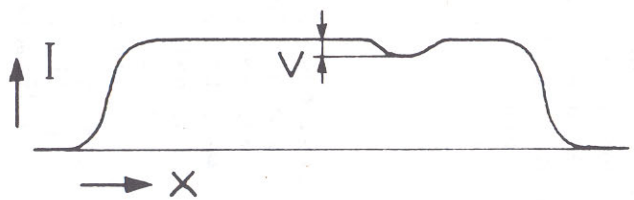


FIG. 4.— Intensity distribution of the image of the object shown in figure 3. I = intensity ; x = place

of the sun with existing large aperture telescopes.

3. THE SPOT TRANSFER FUNCTION T ON A LIMITED FIELD OF LIGHT

We want to investigate whether the screen with holes deteriorates the image quality. A usual criterion for the image quality is the optical transfer function (OTF). The OTF uses sine shaped objects with infinite dimensions. The screen with holes works for objects with limited dimensions only. This means, that the OTF is not suitable for the description of the image quality in this case.

In figures 3 and 4 we introduce an image quality criterion, which is adapted to objects with limited dimensions and low contrast features. Figure 3 shows the intensity distribution of an object with limited diameter q and a low contrast spot with diameter k and intensity deviation u. Figure 4 shows the intensity distribution in the image. The intensity deviation of the low contrast spot is v in the image. We define the spot transfer function on a limited field $T = v/u$, which is a function of the spot diameter k.

Figure 5 shows, how the function T can be found from the point-spread function. Under the intensity distribution of the object, the point-spread function is drawn centered on the middle of the low contrast spot. One has to keep in mind that one dimensional sections of the two dimensional intensity distribution and point-spread function are drawn. The volume under the point-spread function in the area of the spot is called K, shaded from top-left to bottom-right. The volume under the point-spread function in the area of the total object is called Q, shaded from bottom-left to top-right. We assume that the light distribution in the image is the convolution of the light distribution in the object with the point-spread function. This assumption is valid in a region of the image plane where the point-spread function does not change noticeably. With this assumption it can be proved, that $T = K/Q$, provided the intensity fluctuations in the point-spread function outside the central peak do not exceed certain limits. In most cases the fluctuations in the point-spread function remain within these limits.

The function T slightly depends on the location of the spot in the field of light. We will take the spot in the center of the field of light in the following discussions. The function T has the smallest values for this spot location and for most of the point-spread functions.

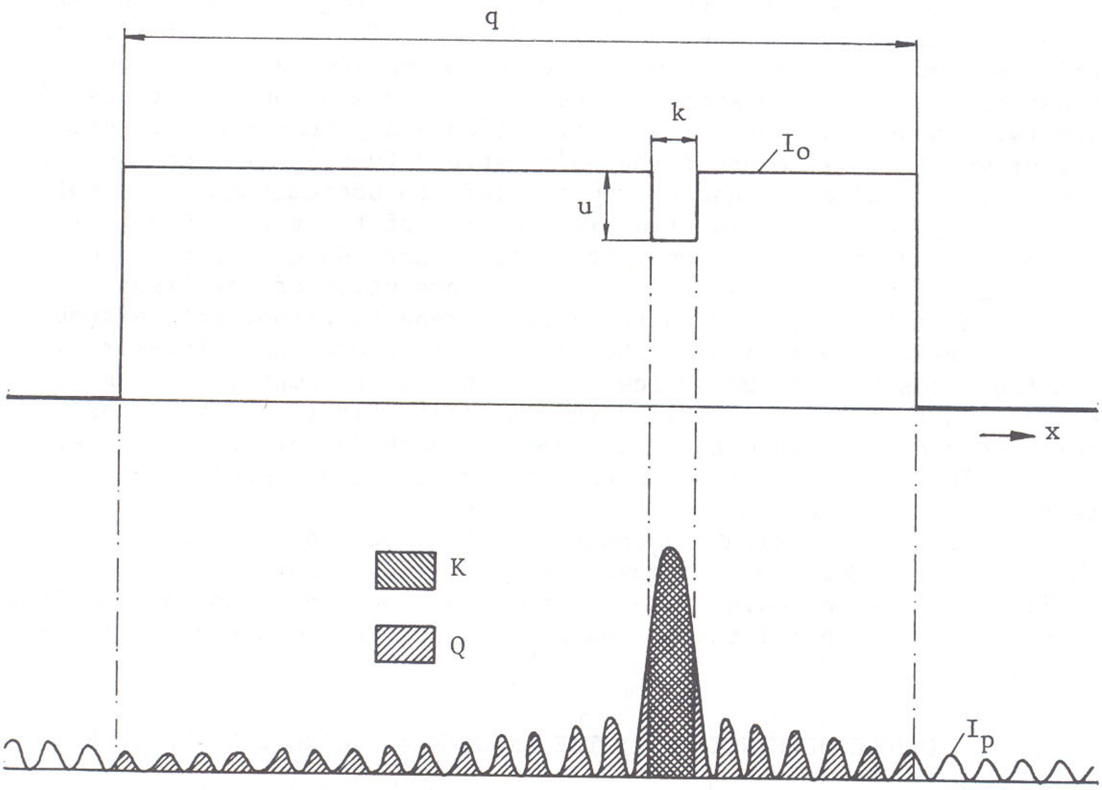
4. EXAMPLE OF FUNCTION T: THE ANNULAR AND CIRCULAR APERTURE

Figure 6 shows an example how the function T can be plotted against the spot diameter k. Two curves for interesting cases are drawn:

1. an aberration free annular aperture with outside diameter b_1 and inside diameter b_2
2. an aberration free circular aperture with diameter $b_1 - b_2$.

k is expressed in units of $\lambda/(b_1-b_2)$, where λ is the wavelength of the light. To the right, the curves go to 1 for $k = q$. A logarithmic scale for k is useful for the right-hand side of the graph, if one wants to show the complete curve. The curves are calculated with the assumption that $b_1 - b_2 << b_2$.

The question rises: above which value of T do we obtain a usable image of a spot. This depends on the structure of the object. A spot on an object with many more or less random distributed features on short distances, like on the sun, will need a larger T than a single spot on a neighbourhood with uniform light distribution. A minimum distance between neighbouring spots is required for separation of these spots in the image, like it is the case in the Rayleigh criterion for light spots on a dark background. A larger T gives a smaller image of a spot because the integrated light change caused by a spot



$$T = \frac{v}{u} = \frac{K}{Q} \quad \text{follows from} \quad I_i = I_p * I_o \quad (I_i = \text{image intensity})$$

FIG. 5.— The figure shows how the transfer function T is found from the point-spread function

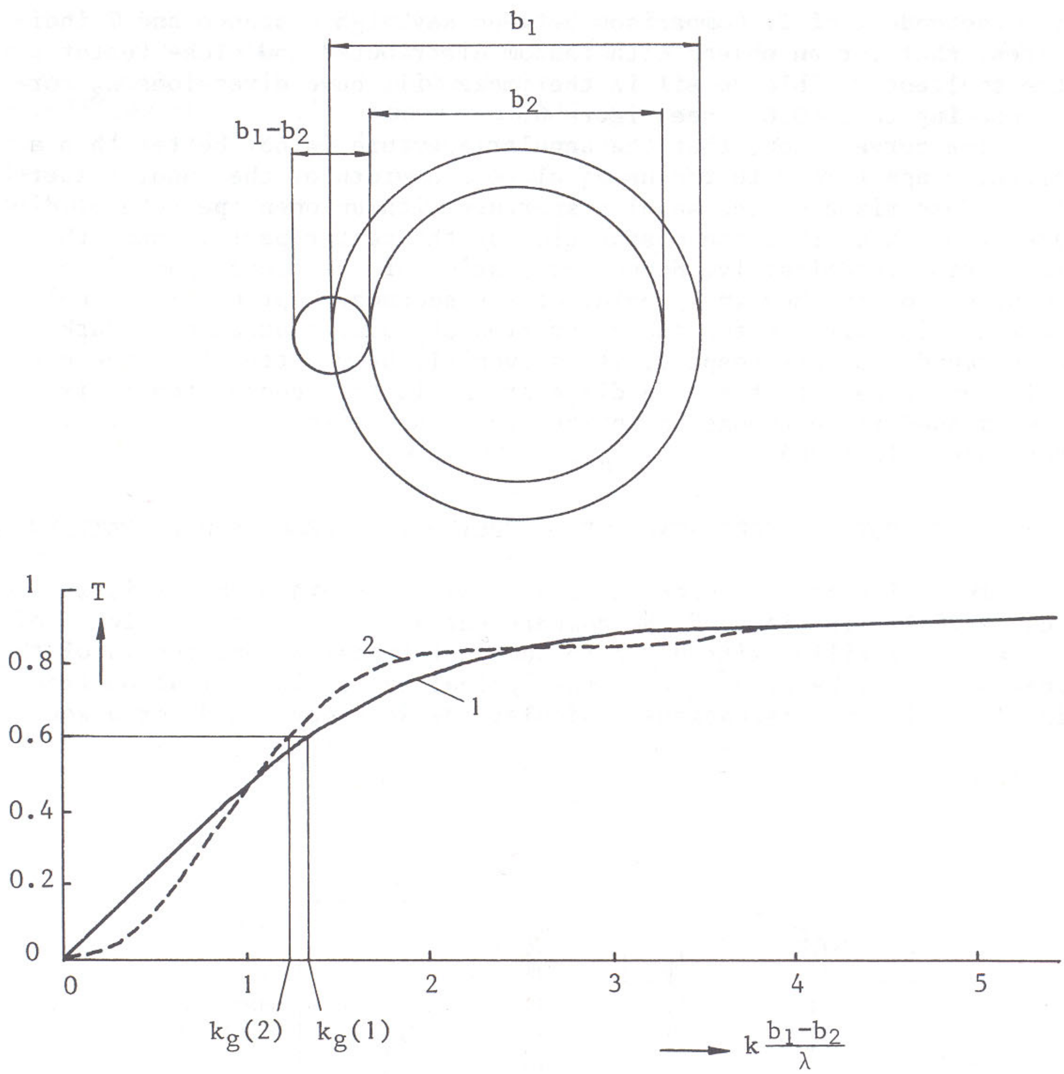


FIG. 6.— Example of how the function T can be plotted against the feature diameter k.
1 annular aperture with outside diameter b_1 and inside diameter b_2
2 circular aperture with diameter $b_1 - b_2$
With the assumption $b_1 - b_2 << b_2$ and in the region of $k << q$, we find the following equations for the curves:

$$1 \quad T \simeq 1 - \frac{4}{\pi^2} \frac{\lambda}{(b_1 - b_2)k} + \frac{4}{\pi} \frac{\sqrt{b_1 b_2}}{b_1 + b_2} \left\{ \frac{\cos[\pi k(b_1 - b_2)/2\lambda]}{\pi k(b_1 - b_2)/2\lambda} + \mathrm{Si}[\pi k(b_1 - b_2)/2\lambda] - \frac{\pi}{2} \right\}$$

$$2 \quad T \simeq 1 - J_0^2[\pi k(b_1 - b_2)/2\lambda] - J_1^2[\pi k(b_1 - b_2)/2\lambda]$$

This is equal to the formula for the fraction of the total energy contained within circles of diameter k, see section 8.5.2 in Born and Wolf (1965) is independent of T. Comparison between Rayleigh distance and T indicates, that for an object with random distributed and close features the smallest visible detail in the image will have dimensions k_g corresponding to $T = 0.6$, see figure 6.

The curves show, that the annular aperture is not better than a circular aperture with radius equal to the width of the annular aperture. Comparison of the annular aperture with an open aperture of diameter b_1 shows that the obscuration of the center part reduces the resolution inadmissibly. Hence obscuration of the center part is no solution for the heating problem of the secondary optics. The annular aperture is suitable for the separation of point sources on a dark background. In this respect, it is even slightly better than the circular aperture with the same diameter and in this connection it is recommended in textbooks on optics, for example in section 8.6.2 in Born and Wolf (1965).

5. THE SPOT TRANSFER FUNCTION T APPLIED TO A REGULAR HOLE PATTERN

The point-spread function of a regular pattern of holes is shown schematically in figure 7. We compare the spot transfer function T of the aperture filled with holes to the spot transfer function T_0 of the open aperture. We assume, that the optical system is aberration free in all following discussions. Calculations were performed for a square

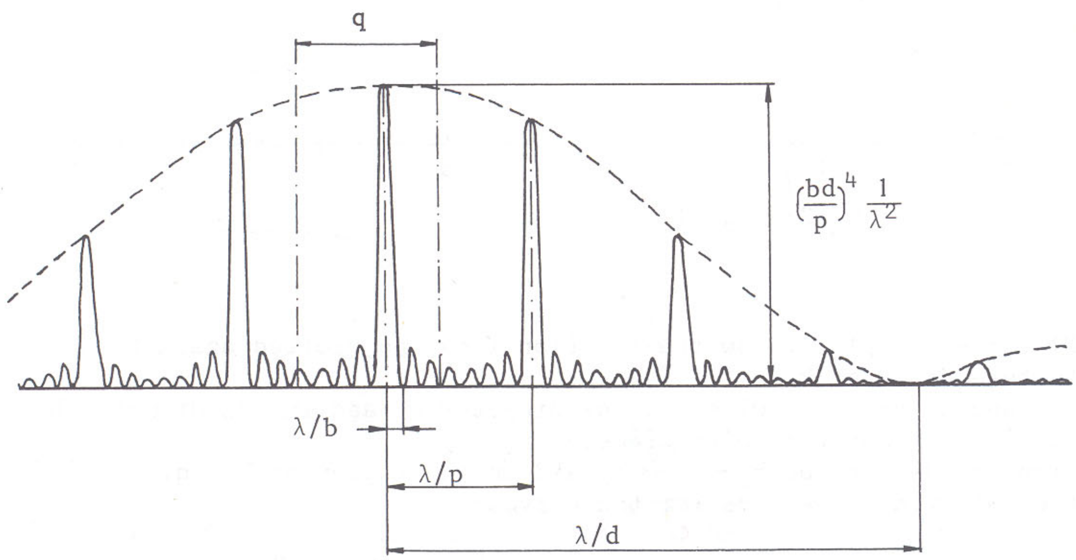


FIG. 7.— Point-spread function of a regular pattern of holes.
b = diameter of aperture

aperture with a regular pattern of holes. The shape of the holes is arbitrary but equal for all holes. The shape of the sun was assumed square with sides equal to the diameter of the sun. This assumption simplifies the calculations and is allowed because the calculated value of T will not be larger than the real value of T (the area of the real sun lies inside the assumed area). For the maximum allowed distance between the holes $p = \lambda/q$ (see section 2) we find:

$T > (1 - p/b)\, T_0$, where b is the diameter of the aperture.

A further specialized case with square holes gives

$T \gtrapprox (1 - 4p/\pi^2 b)\, T_0$, where = is a usable approximation for the region $k \ll q$

This last formula is remarkable, because

$T_0(q{=}\infty) = (1 - 4p/\pi^2 b)\, T_0$ with $p = \lambda/q_{sun}$

where $T_0(q{=}\infty)$ is the transfer function for a light object with infinite dimensions imaged by an open aperture. Normally $p/b \ll 1$, hence the decrease of T compared to T_0 will not be significant. Suppose we want a telescope with a resolution limit by diffraction of r. The diameter of the aperture becomes $b = \lambda/r$. From this relation and the relation $p = \lambda/q$ we find $b/p = q/r$. The value b/p is the same as the number of holes in one row and the value of q/r can be interpreted as the number of image elements in one row. We see, that these numbers are equal and we will define them by N. The diameter of the sun is 1920". If we want a diffraction limit of 0.1" then we find N = 19200 and the decrease of T compared to T_0 becomes negligible.

6. PATTERN OF RANDOM DISTRIBUTED HOLES

In practice a pattern of holes will never be completely regular. We want to know how the spot transfer function T is influenced by irregularities in the hole pattern. To this end we study first the pattern of completely random distributed holes.

Figure 8 shows schematically the point-spread function of a pattern of random distributed holes. p is now the mean value of the varying distances between the holes. This point-spread function is discussed by Born and Wolf (1965) in section 8.5.3. However, they ignore the central peak with width $2\lambda/b$ in their equation (25). If one looks carefully at their figure 8.15(a), one can recognize the central peak. A photograph, which shows the central peak clearly, is plate 16-1 in Harburn, Taylor and Welberry (1975). The central peak is also shown in figure 7 of Martin and Aime (1978, 1979).

The central peak is essential for the image formation with a random pattern of holes. In the calculation of $T = K/Q$ (see section 3) the value of T is reduced by the part of the diffraction light in the area with diameter q and outside the central peak. This diffraction light can be reduced with respect to the light in the central peak by using a small p and d. The diffraction light is spread out over a large area with diameter λ/d, hence the part of the diffraction light in area q decreases, whereas the light in the central peak remains constant.

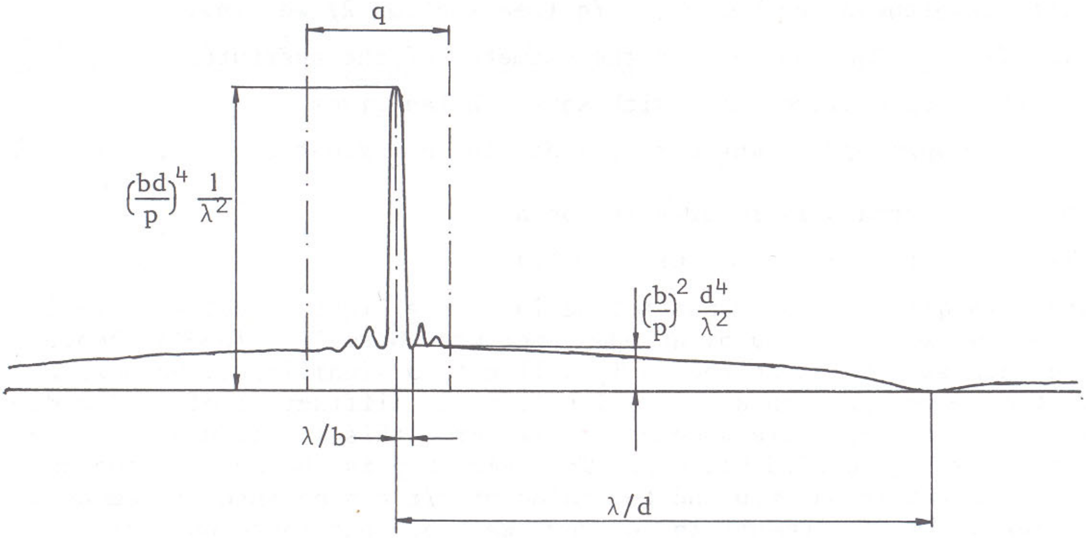


FIG. 8.— Point-spread function of a pattern with random distributed holes. p = mean value of the distances between the holes

After some calculations it is found, that

$T \gtrapprox T_0/[1 + (qp/\lambda)^2]$, where = is a usable approximation for the region $k \ll q$

Some numerical values of this equation are:

p =	λ/q	$\lambda/2q$	$\lambda/3q$	$\lambda/10q$
T =	$0.5T_0$	$0.8T_0$	$0.9T_0$	$0.99T_0$

Even a pattern of random distributed holes will give an image without significant loss of contrast, provided the holes are close enough to each other.

7. TRANSITION PATTERNS BETWEEN REGULAR AND RANDOM ONES

A hole pattern with some deviations from regularity will have a spot transmission which lies between the spot transmissions of the regular pattern and the random pattern. It is remarkable, that deviations in the position of the holes do not give much diffraction light around the zero order of the point-spread function. There is a dark area around the central peak. Consequently, small deviations of the holes from the regular positions do not decrease much the spot transmission.

The dark area around the zero order can be understood by forming the fourier series of a hole pattern with (slow) periodic change of the hole distance. The slow periodic change gives side bands to the Fourier terms of the regular hole pattern. It is found, that the amplitudes of the side bands of the zero order term are small. The photographs of plate 20 in Harburn, Taylor and Welberry (1975) demonstrate this effect. The side bands are visible around many orders, but the zero order is always free of side bands. The side bands do not have discrete frequencies any more, if the position deviations of the holes are arbitrary. The side bands contain a continuous range of frequencies and form patches of light around the orders or, in case of large position deviations, the orders are smeared out to broad spots. The photographs of plate 15 in Harburn, Taylor and Welberry (1975) show the point-spread functions of hole patterns with increasing arbitrary position deviations. The area around the zero order again remains free of patches of light.

Discussions of the dark area around the central peak from statistical viewpoints are given by Stark (1977, 1978) and by Martin and Aimes (1978, 1979).

8. STRAY LIGHT FROM THE SKY

In section 2 it was shown, that the light reduction of the sun is $(d/p)^4$. If we assume, that the sky is half a sphere with constant brightness, then the reduction of the sky light is $(d/p)^2$ caused by geometrical obscuration of the screen. Hence the sky light is enhanced by a factor $(p/d)^2$ compared to the sun.

However, the sky brightness is not constant, it depends on the distance to the solar limb. We find the following table in Mehltretter (1978):

D	10"	30"	1'	5'	20'
$10^6 i/i_\odot$	6500	64	28	16	10

where D is the distance to the solar limb, i is the brightness of the sky and $i_\odot$ is the brightness of the sun.

A bright ring of sky light is located near the solar limb. One should avoid, that the rings from the first order images fall over the solar image in the zero order. The value of the hole distances p has to be slightly smaller than calculated from $p = \lambda/q$. In the example of section 2, p = 25 μm instead of 34 μm. Around the first order solar images we can draw rings, which fall outside the solar image in the zero order. The width of the rings is 12' for the example. Consequently, the bright sky near the solar limb does not disturb the solar image in the zero order. The stray light only comes from the sky region outside the circle with D = 12'. The given table allows a rough calculation of the stray light. The result for the example is $4 \times 10^{-4} i_\odot$.

9. TECHNICAL REALISATION OF THE HOLE PATTERNS

The screen with holes can be manufactured by etching and/or electroplating techniques. Photoresist films are used for printing the pattern of holes on foils. Hill and Rigby (1969) describe a method for the manufacture of patterns with these techniques.

In the last few years, these techniques are successfully applied to lattice patterns for astronomical instruments. Open transmission gratings with 500 and 1000 lines per mm are used for soft X-rays (Dijkstra, 1976; Dijkstra et al., 1978; Schnopper et al., 1977). Grid plates with square holes of 46×46 µm and pitch 104 µm are used in a hard X-ray imaging spectrometer (Van Beek et al., 1980).

Both applications require a highly regular pattern. In sections 6 and 7 we have seen, that the regularity requirement is not so strict for our application and we expect easier manufacture in this respect.

New is, that we need screens with much larger dimensions. Small holes require a thin foil and a supporting grid may be necessary. In this respect a screen for infrared observations (see section 2) is easier to make because of the larger holes. The supporting grid also allows the screen to be composed of pieces.

The form of the holes in the screen is not important. Any form will work, also line and ring shaped holes, provided the distance p between the lines or rings is equal to or smaller than λ/q. However, holes with about the same dimensions in both directions like circles or squares are preferred because of the higher mechanical rigidity of such a screen, which can be attached to a coarser supporting grid.

If the width of the beams of the supporting grid is smaller than λ/q there is of course little influence on the spot transfer function T. But in practice broader beams may be necessary. Broader beams reduce the spot transfer function:

$$T_G = (1-w)\,T ,$$

where T_G is the spot transfer function with supporting grid and T without supporting grid, and w is the part of the aperture surface obscured by the beams of the supporting grid.

The cause for the transfer reduction is diffracted light from the beams, which does not fall outside the zero order image. The diffracted light is collected in a bright dash perpendicular to the beam direction if many beams of the supporting grid have the same direction. This can lead to false interpretation of the image.

It is better to distribute the beam directions as much as possible over all directions. The diffracted light is spread out over a larger disk shaped surface, which reduces the intensity and prevents false interpretation. Figure 9 shows a regular supporting grid with equal distribution of the directions of the beam pieces. A random beam pattern has also an equal distribution of the directions of the beam pieces. But a regular beam pattern like the one of figure 9 has more mechanical rigidity than a random beam pattern, which obscures the same part w of the aperture. The beam pattern of figure 9 is particularly rigid because it consists of triangles only.

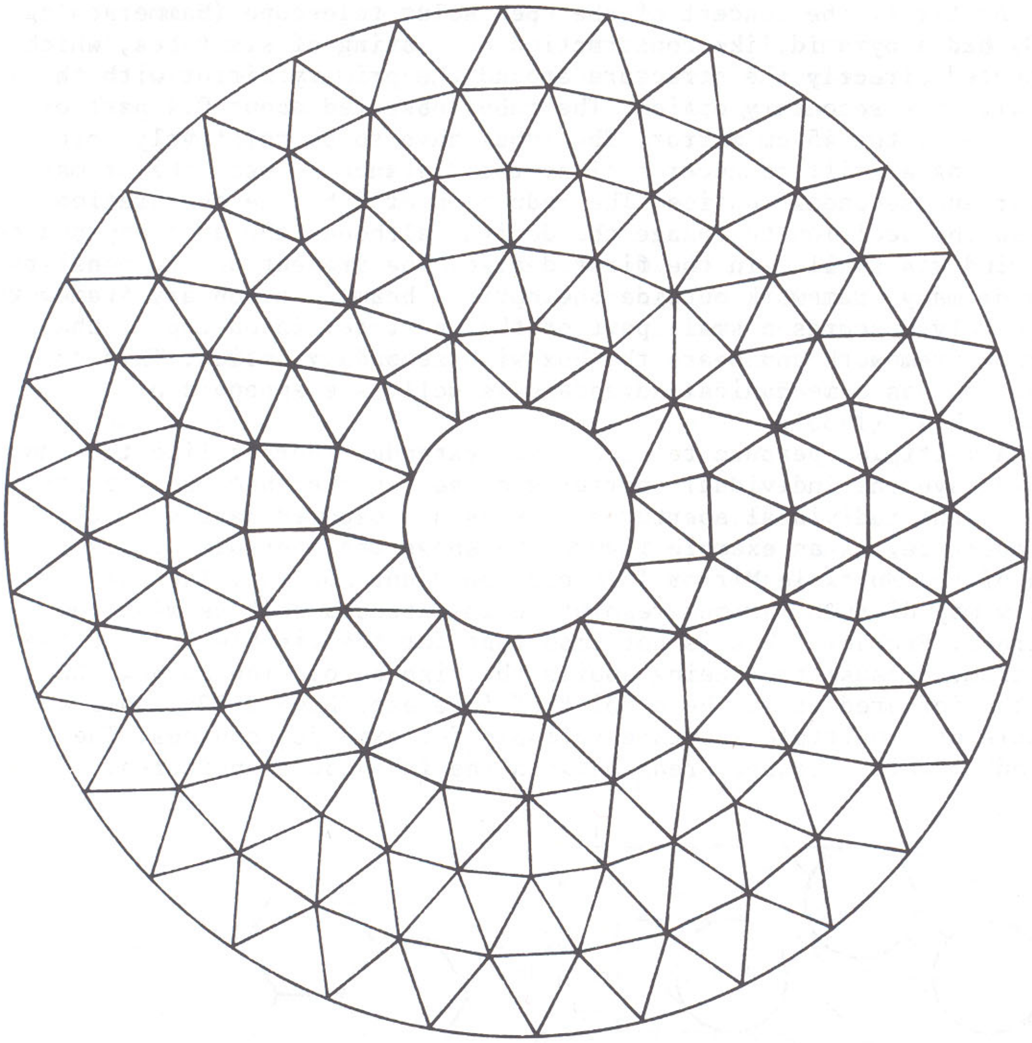


FIG. 9.— Regular supporting grid with equal distribution of the directions of the beam pieces

10. FUNCTION T FOR TELESCOPES WITH OBSCURATIONS AND FOR MULTIPLE APERTURE TELESCOPES

The equation $T_G = (1-w)\,T$, given in section 9, is not only valid for supporting grids in telescopes with screens. The equation is also valid for obscurations larger than λ/q in telescopes without screens. In the latter case, T and T_G are the spot transfer functions of the open aperture and of the aperture with obscuration, respectively. The part of the area, which is obscured, is indicated by w. The equation holds for spot diameters $k \ll \lambda/c$, where c is the dimension of the remaining open parts between the obscurations. The equation is found for regular and irregular grids and arrays of patches. The telescope is supposed to be aberration free, as already assumed in section 5.

At first, the concept of the open solar telescope (Hammerschlag, 1980) had a pyramid like construction consisting of six tubes, which connected directly the structure around the primary mirror with the box with the secondary optics. The tubes obscured about 0.4 part of the area of the 45 cm mirror. The tubes have to be relatively thick for making a stiff connection along the distance between the primary mirror and secondary optics. The reduction of T by the obscuration caused the decision to change the design, although the area exposed to the wind was smaller in the first design. The present design consists of a primary framework outside the optical beam. A secondary framework which only obscures a small part of the aperture, is on top of the primary framework and bears the box with secondary optics. This construction has a mechanical advantage as well, see appendix of Hammerschlag (1980).

A multiple aperture telescope for extended sources like the sun should have the individual apertures close together because the area between the individual apertures acts as an obscured part w of the total aperture. As an example figure 10a shows the aperture configuration of the Multiple Mirror Telescope on Mount Hopkins. The large area part w may disturb maximum resolution in extended sources with low contrast. Probably this is not important for the visible part of the spectrum, because the seeing spoils the high resolution anyhow. But for the infrared it may be a point of interest. Figure 10b shows an example of a multiple aperture suitable for extended sources. There are only small obscured areas between the individual apertures.

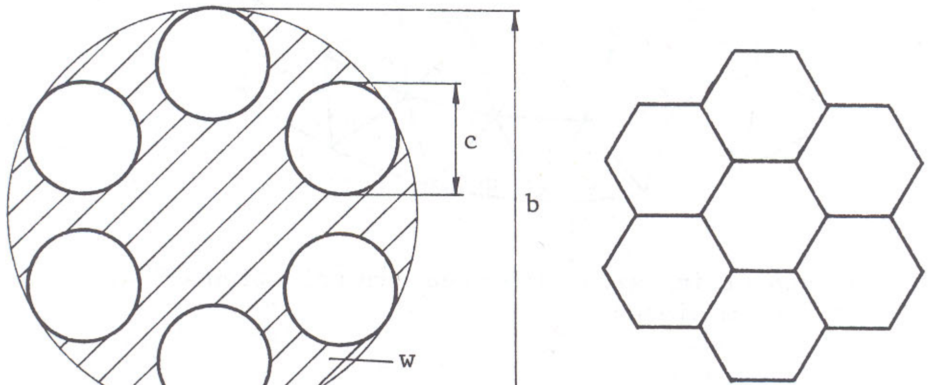


FIG. 10.— Multiple aperture configurations

a. the Multiple Mirror Telescope on Mount Hopkins

$$T_G(k) = (1-w)\,T(k) \quad \text{for} \quad k \ll \lambda/c$$

b. an example with 7 apertures, suitable for extended sources with low contrast

11. REMOVABLE APERTURES

Another solution, which avoids the heating of the secondary optics, is a removable screen with a slit or cross aperture in front of the telescope. During the exposures the screen is removed for a short time. The slit aperture gives two points with a sharp image of the solar limb, see figure 11a. These two points allow focussing.

Guiding requires four points on the limb. Also finding the average focus in case of astigmatism requires four points. A cross aperture gives four points on the limb with a sharp edge of 50% modulation, see figure 11b. The disadvantage of the 50% modulation can be removed by an optical system at the secondary optics of the telescope. The secondary beam has to be divided into two beams and two images of the telescope aperture are formed, see figure 11c. Screens in the aperture images select one of the two arms of the cross aperture, in each aperture image another arm. Solar images are formed behind the aperture images. These two solar images have a sharp limb on crossed pairs of points.

The removable apertures have some disadvantages. Only short exposures are possible. No continuous observation of a feature can be done. The secondary optics come in danger if the closing system of the aperture sticks.

12. CONCLUSIONS

The diffraction theory permits the application of a screen with holes without reducing the resolution. The present-day developments in the technology of producing sheets with fine structures bring the realization more nearby. In this way, existing stable stellar telescopes can be used for solar observations. The whole sun will be visible in high resolution. The method may be of interest to high resolution infrared observations, which require large telescope apertures.

A solar telescope in space will be constructed by preference with a small f-number because of its compact construction and the low weight. One can use then, with the given limited space and weight, a primary mirror with large diameter and with corresponding large resolution. The heating of the secondary optics can become too large for a small f-number. The screen with holes gives here a solution with preservation of resolution. Longer exposure times are possible from space than from the earth, because no seeing is present in space. The longer exposure times may compensate the light attenuation by the screen.

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I thank Prof. F. Roddier for the discussion during the meeting in which he drew my attention to the work of Martin and Aime (1978, 1979).

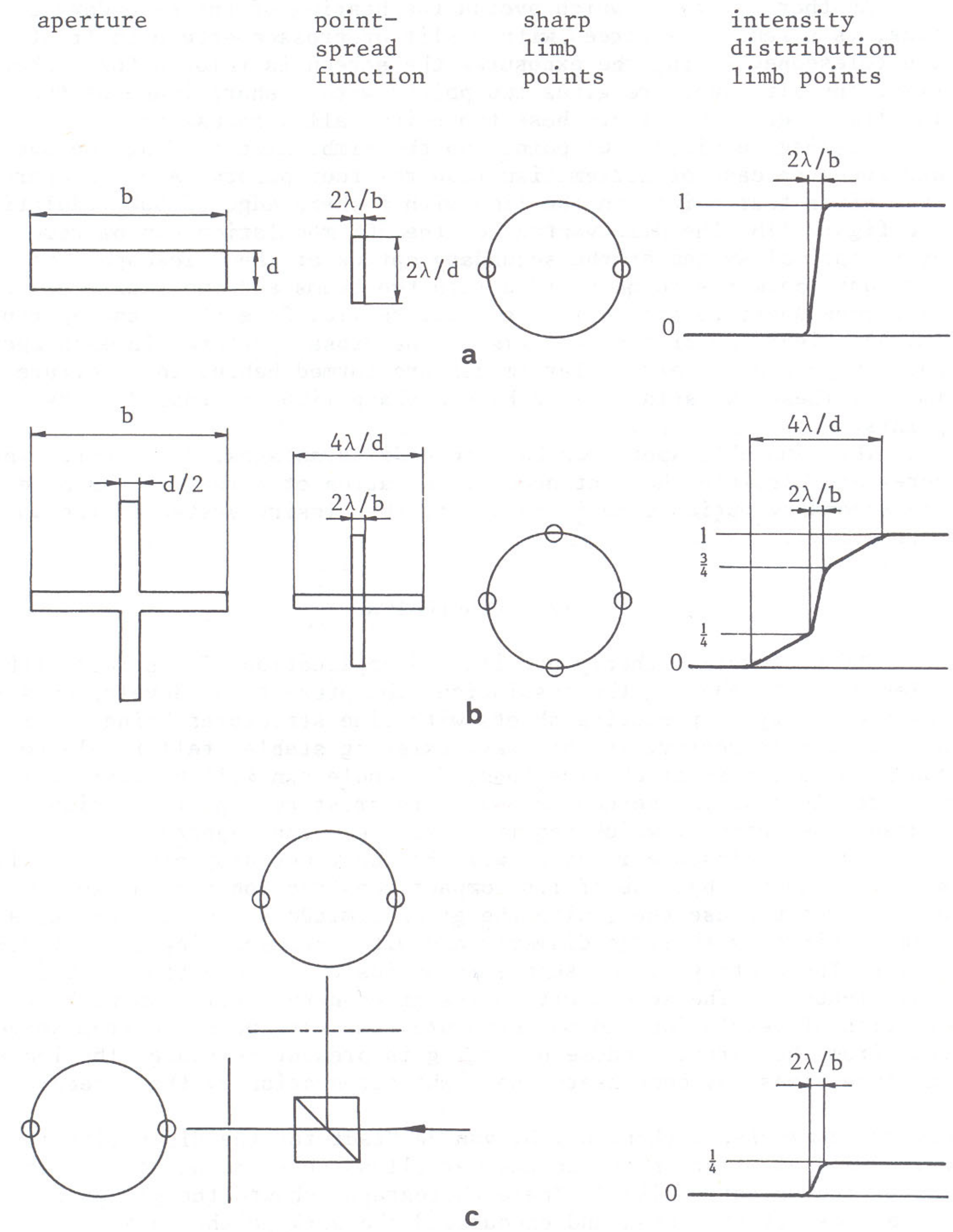

FIG. 11.— Removable apertures
a. slit
b. cross
c. cross with selection slits in aperture images

REFERENCES

Born, M., and Wolf, E. 1965, *Principles of Optics*, third edition, (Oxford: Pergamon Press).

Dijkstra, J.H. 1976, *Space Science Instrumentation*, 2, 363.

Dijkstra, J.H., Lantwaard, L.J., and Timmerman, C. 1978, in Cospar: *New Instrumentation for Space Astronomy*, ed. K. van der Hucht and G.S. Vaiana (Oxford: Pergamon Press), p.257.

Dunn, R.B. 1964, *Applied Optics*, 3, 1353.

———. 1969, *Sky and Telescope*, 38, no.6.

Hammerschlag, R.H. 1980, *Construction Outlines of the Utrecht Open Solar Telescope*, in *Solar Instrumentation: What's Next?*, to be published in this volume.

Harburn, G., Taylor, C.A., and Welberry, T.R. 1975, *Atlas of Optical Transforms* (London: G. Bell & Sons Ltd).

Hill, A.E., and Rigby, P.A. 1969, *Journal of Scientific Instruments (Journal of Physics E)*, Series 2, 2, 1084.

Martin, F., and Aime, C. 1978, 1979, *J. Opt. Soc. Am.*, 69, 1315 (without figures 68, 1782).

Mehltretter, J.P. 1978, *Calibration of the Visual Photometer for Aureole Measurements, Joint Organization for Solar Observations*, report no.1978/2.

Schnopper, H.W., Van Speybroeck, L.P., Delvaille, J.P., Epstein, A., Källne, E., Bachrach, R.Z., Dijkstra, J., and Lantwaard, L. 1977, *Applied Optics*, 16, 1088.

Stark, H. 1977, *J. Opt. Soc. Am.*, 67, 700.

———. 1978, *ibid.*, 68, 1785.

Van Beek, H.F., Hoyng, P., Lafleur, B., and Simnett, G.M. 1980, *Solar Physics*, 65, 39.