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SCIENCE

A High-Resolution Orbiting Telescope

New techniques would lead to orbiting an optical telescope 25 times the diameter of Palomar's.

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A number of fundamental problems in astronomy and astrophysics could be attacked successfully by means of a high-resolution optical telescope (*1*). Such an instrument could enable us to study the outer planets and their moons, could resolve the nuclei of other galaxies, could help to unravel the problem of the quasi-stellar objects, and could provide the first direct observation of planets in other star systems, to name only a few of its uses.

Any high-resolution telescope must be located above the atmosphere, because seeing conditions normally limit ground-based telescopes to effective resolution-apertures much smaller than that of the 200-inch (5-meter) Palomar instrument. A high-resolution telescope must therefore be put in earth orbit, or in some more distant location at a corresponding sacrifice in weight for a given expenditure in energy. Space, as an environment, offers a clear advantage beyond the obvious ones of perfect seeing and unlimited spectral transmission; that advantage is the absence of stress due to gravity. An object in orbit is freely falling, and the only gravitational stress on it is due to the *gradient* of the earth's gravitational field. Even for a large object (100 meters in diameter) this stress is lower by a factor of 10^5 than the stress for the same object resting on the earth's surface. Therefore a very large object, even if necessarily mechanically weak, can, if assembled in orbit, maintain good dimensional stability. The limits on its stability probably are set by thermal conditions dependent on heat radiation from the sun, earth, and moon. We can reduce this radiation by a large factor by enclosing the telescope within a cylindrical multilayer tube of aluminum foil, open at one end and rotated about the cylinder axis to maintain the cylindrical shape, and not in contact with the telescope itself.

For some of the astronomical problems listed here, the telescope must have very high resolution; a resolution-limiting aperture of 5000 inches, 25 times that of the Palomar instrument, is used as a target figure in the following discussion. Some illustrations are given in the appendix; for orientation, I merely note here that such a telescope would resolve detail of about 300 meters on the inner planets at closest approach, or of a few kilometers on Jupiter.

Clearly, any very large telescope must be composite—that is, its mirror must be made of two or more elements filling only a small fraction of the total aperture—because a single large mirror would be far too heavy. In 1920, Michelson developed his stellar interferometer (*2*), a device by which a double-slit diffraction pattern could be made by means of slits much farther apart than the diameter of a telescope. It is much the same principle that I discuss here, but applied to the formation of a complete optical image of high quality. Rockets expected to be available by about 1970 should be able to put a 120-ton payload in low orbit in one shot. If 40 tons of such a payload were in the form of telescope mirrors, the composite mirror could be made of 200 individual glass segments, each 1 meter in diameter and 10 centimeters thick, intercepting about 1 percent of the light falling on the 5000-inch-diameter circles. The individual elements would be mounted on a light framework, and their alignment would be checked and readjusted frequently or continuously with the help of laser interferometry (*3*). Correspondingly larger arrays would be possible with lightweight reflectors.

The question of how best to arrange the mirrors is a little less obvious. With reasonable choices, clearly the resolution limiting angle η will be that of the overall array—namely, $\eta \sim \lambda/D$, where D is the diameter of the array and λ is the wavelength. I will give some examples.

The effect of the mirror array is to bring light on converging spherical wave fronts to a focus at some point P_1. Let z be the coordinate along the optic axis, and let x and y be the coordinates in the focal plane. The vector representing the electric **E** field at the point (x,y,z) can be written (see Fig. 1):

$$\mathbf{v}(x,y,z) = -\frac{ik}{2\pi}\, e^{ikC} \int\int \mathbf{U}_0(\theta, \varphi) \times \{e^{-ik[\sin\theta(x\cos\varphi + y\sin\varphi) - z\cos\theta]}\} \times \sin\theta\, d\theta d\varphi, \quad (1)$$

where k = the wave number = the number of radians per centimeter; θ = the polar angle from the optic axis; φ = the azimuthal angle; $\mathbf{U}_0$ = the vector tangent to the unit sphere; and C is a constant. Equation 1 is known as Debye's solution (*4*). The multiplicative factor before the integral is a constant. In the high-*f*-number approximation, U_0 can also be approximated by a con-

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stant, and, with the further restriction to the focal plane, Debye's solution becomes just

$$v(x,y) = \iint (\sin\theta \, d\theta d\varphi) \times e^{-ik[\sin\theta(x\cos\varphi + y\sin\varphi)]}. \quad (2)$$

Replacement of the constants by numeral 1 is equivalent to a choice of phase and amplitude for the incoming wave, and will not affect the diffraction patterns we wish to calculate. Using only the real part, we obtain

$$v(x,y) = \iint [\cos k \times (x\sin\theta\cos\varphi + y\sin\theta\sin\varphi)] \times \sin\theta \, d\theta d\varphi. \quad (3)$$

The integral in θ and φ is over the solid angle subtended by mirrors, the regions in solid angle from which the spherical waves are actually returning. For simplicity we consider Eq. 3 on a particular line from the central focus: the x axis. Making use of the high-f-number approximation again, we obtain

$$v(x,0) = \iint [\cos(kx\,\theta\cos\varphi)]\,\theta\, d\theta d\varphi = \frac{1}{(kx)^2}\iint [\cos(u\cos\varphi)]\, u du d\varphi, \quad (4)$$

where $u \equiv kx\theta$. With l the focal length of the mirror array, $d/2$ the distance from the optic axis to a point on the paraboloid, θ the polar angle of that point, and η the angle subtended at a distance l by x, u can be rewritten

$$u = \frac{x\theta}{ƛ} = \frac{1}{ƛ}\frac{x}{l}(l\theta) = \frac{1}{ƛ}\eta\frac{d}{2} = \frac{\eta d}{2ƛ}. \quad (5)$$

where lambda-bar = $(\lambda/2\pi)$.

Inspecting the integral in Eq. 4, one can see that for large values of x the integral will be small, because the integrand will go through many oscillations; at large x, $v(x,o)$ will be further reduced by the factor $1/(kx)^2$.

For mirror arrays symmetric about the plane containing the optic and y axes, equal contributions will come from points of given x and θ, with $\varphi = \varphi_0$ and $\varphi = \pi - \varphi_0$. The range of φ can therefore be restricted to $-\pi/2 < \varphi < \pi/2$. With symmetry about the plane containing the optic and x axes as well, the range of φ can be further restricted to $0 < \varphi < \pi/2$. We consider, for simplicity, only mirrors with these symmetries.

Four geometries are discussed: (A) one-piece mirror with small $\Delta\varphi$ ["bow-tie" geometry (Fig. 2)]; (B) annular ring mirror (Fig. 3); (C) conventional parabolic disk (Fig. 4); and (D) symmetric eight-element array approximating an annular ring (Fig. 5).

These illustrate two points:

1) The angular resolution of a composite array is characterized by its largest dimension, not by the element size.

2) With a small number of elements in a regular pattern, side-lobes become significant.

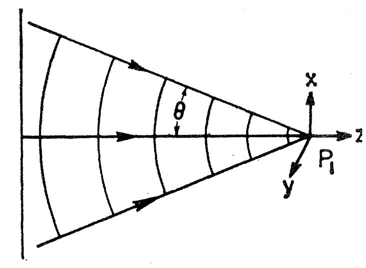


Fig. 1. Wave fronts converging on a focal point $(x,y,z,)$ from an optical system of angular aperture 2θ, where θ is the polar angle of the array-circle; x is the displacement from the center of the diffraction pattern. The calculation is along one direction only.

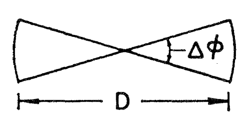


Fig. 2. Geometry A.

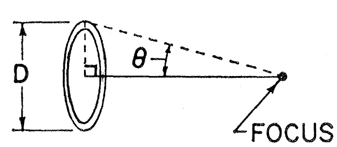


Fig. 3. Annular ring mirror (geometry B).

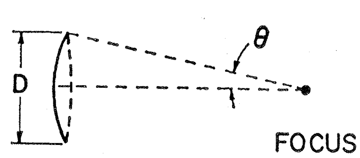


Fig. 4. Conventional parabolic disk (geometry C).

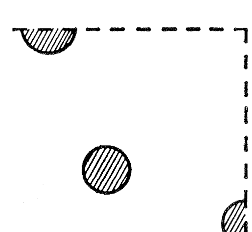


Fig. 5. Symmetric eight-element array approximating an annular ring (geometry D).

Geometry A. With φ close to zero, $\cos\varphi \approx 1$, and Eq. 4 becomes

$$v(x,0) = \frac{\Delta\varphi}{(kx)^2}\int_0^{u_m} u(\cos u)du = \frac{\Delta\varphi\theta_m^2}{u_m^2}[\cos u_m + u_m\sin u_m - 1], \quad (6)$$

with $u_m \equiv kx\theta_{max}$. The first zero is at $u_m \approx 3\pi/4 = \eta_0 D/2ƛ$, with D the long dimension of the mirror. In angle, this is

$$\eta = 0.75\frac{\lambda}{D}, \ (u_m = 2.37). \quad (7)$$

The second zero is near

$$\eta = 2\frac{\lambda}{D}, \quad (8)$$

and successive intensity maxima for large u_m are bounded by the envelope

$$\left|\frac{u_m + 1}{u_m^2}\right|^2 \approx \left|\frac{1}{u_m}\right|^2 = \frac{1}{u_m^2}.$$

For other values, see Fig. 6. Away from the y-axis, the intensity pattern is approximately that of Fig. 6, multiplied by an envelope function whose width in angle is of the order $\eta_x = \lambda/D\Delta\varphi$. A similar statement can be made without approximation for the closely related case of reflector elements of diameter d, distributed along the y-axis with a number density proportional to y. The multiplying envelope function is in that case that of a single element of diameter d (discussed under "geometry C" below).

Geometry B. In polar angle the annular ring mirror subtends a small $\Delta\theta$, but covers 2π in φ; $\theta = \theta_0 =$ a constant, and Eq. 4 becomes

$$v(x,0) = \frac{\theta_0^2}{u_0^2}u_0\Delta u\int_0^{\pi/2}[\cos(u_0\cos\varphi)]\,d\varphi$$

$$\Delta\theta = \int_0^{\pi/2}[\cos(u_0\cos\varphi)]d\varphi \equiv \Delta\theta\, G(u_0). \quad (9)$$

$u_0 \equiv kx\theta_0$, and $\Delta u \equiv kx\Delta\theta$. The intensity $v^2\,(x,0)$ is shown graphically in Fig. 7.

The first zero is near $u_0 = 2.5$, close to its value for geometry A. In geometry B, however, the diffraction pattern is symmetric about the optic axis.

Geometry C. From Eq. 4 we obtain

$$v(x,0) = \frac{1}{(kx)^2}\iint [\cos(u\cos\varphi)]\,u du d\varphi = \frac{1}{(kx)^2}\int_0^{u_{max}}[G(u)]\,u du. \quad (10)$$

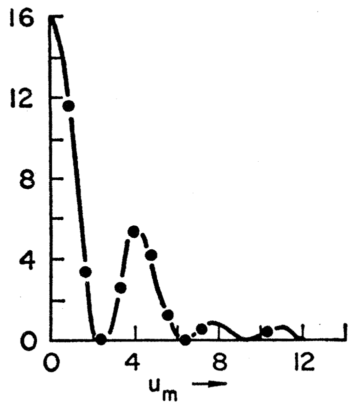


Fig. 6. Intensity pattern for the geometry of Fig. 2.

The integral in Eq. 10 has as its integrand the integral carried out for geometry B. For fixed $\theta_{\max}$ the functional dependence on x enters through the factor $1/(kx)^2$ and through the limit on the u-integral. The resulting intensity is shown graphically in Fig. 8. Note that the central maximum is wider than in the earlier cases, but that the side-lobes are much reduced. The first zero occurs at

$$u_{\mathrm{m}} = kx\theta_{\max} = 3.8 = \eta D/2\lambda\!\!\!^{-}, \quad (11)$$

so the angular resolution

$$\eta = 7.8\ \lambda\!\!\!^{-}/D = 1.22\ (\lambda/D), \quad (12)$$

a result well-known in elementary physical optics as the Rayleigh criterion (*2, 5*).

Geometry D. This example is chosen to illustrate the dangers of using a composite array with a small number of regularly spaced elements. The eight elements are equally spaced on a circle; Fig. 5 shows the view along the optic axis. The size of the elements is exaggerated to make clear the proper weighting of the terms in the sum which replaces Eq. 9. That integral becomes

$$v(x,0) = \cos u_0 + 2 \cos \frac{u_0}{\sqrt{2}} + 1 \quad (13)$$

The intensity pattern (Fig. 9) is quite similar to that of case B out to $u_0 = kx\theta_0 = 6$, but there is a large second maximum near $u_0 = 8$. According to Eq. 13, similar maxima will occur whenever u_0 and $u_0/(2)^{1/2}$ simultaneously approach multiples of 2π. Along lines other than the y-axis, the intensity pattern of this array is in general worse than that of Fig. 9.

The problem illustrated by cases A and D—the appreciable side-lobe introduced by a mirror which does not average over a complete disk—suggests that one good design for a general-purpose telescope would be an array of many elements having uniform density over a parabolic disk. Given a sufficiently large number of small reflectors, the intensity pattern would then approach that of case C. The problem illustrated by case D—the "diffraction-grating" effect of a small number of regularly spaced reflectors—could best be studied by computing two cases: a regular pattern and a random pattern of reflectors.

In the case of randomly located reflectors whose average density is constant over the telescope aperture, the central maximum would be of the same width as that in case C. Far from the central maximum in the diffraction pattern, the average wave amplitude would be obtained from the fluctuation in the cancellation of positive and negative amplitude contributions. Typically the difference between N_+ (the number of positive contributions) and N_- (the number of negative ones) would be

$$\left| N_+ - N_- \right|_{\mathrm{av}} = \sqrt{(\sqrt{N_+})^2 + (\sqrt{N_-})^2} = \sqrt{N_+ + N_-} = \sqrt{N}, \quad (14)$$

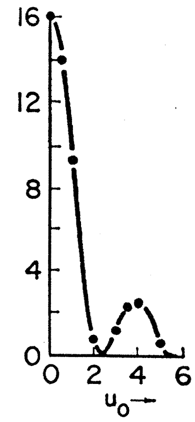
where N is the total number of reflectors. The average background intensity I', in terms of the central peak intensity I_N, would be

$$\frac{I'}{I_N} = \frac{\left|N_+ - N_-\right|_{\mathrm{av}}^2}{N^2} = \frac{|\sqrt{N}|^2}{N^2} = \frac{1}{N} \quad (15)$$

This approximation applies to the region away from the central image in the diffraction pattern of the array but *within* the central maximum of the pattern which would be produced by a single element.

A more rigorous argument, not restricted to dispersed arrays, is one based on the law of conservation of energy. If a mirror of dimension D is divided into N close-packed elements of equal size d (for example, a hexagonal mirror made up of N hexagonal segments close-packed), and if each element contributes amplitude A_1 at the central focus, the central intensity for one element is $I_1 = A_1^2$, and that for the entire array is $I_N = (NA_1)^2 = N^2 I_1$. If r_1 is the radius to the first diffraction minimum in the pattern from one element, the total energy U_1 in the central peak, with one element acting alone, is

$$U_1 = g\pi r_1^2 I_1 = g\pi r_1^2 A_1^2, \quad (16)$$



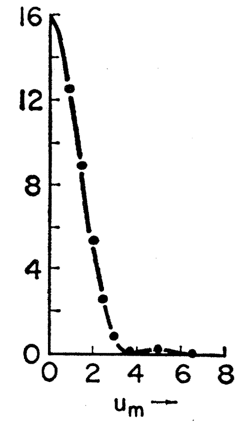


Fig. 7 (left). Intensity pattern for continuous annular mirror. Fig. 8 (right). Intensity pattern for continuous paraboloidal mirror.

where g is a constant, of order 1, which depends on the shape of the element. With N elements acting, the diffraction peak from the array is narrower, its width being $r_1/(N)^{1/2}$, because $(D/d) = (N)^{1/2}$. The total energy in the peak is

$$U_N = g\pi \left(\frac{r_1}{\sqrt{N}}\right)^2 I_N$$

$$U_N = g\pi \frac{r_1^2}{N} A_1^2 N^2 = NU_1, \quad (17)$$

as it must be; the N elements collect N times the energy of one element alone.

If, now, the N elements are separated by a uniform expansion of the array, the central amplitude must remain NA_1, and the central intensity, $N^2A_1^2$. The diffraction pattern narrows, however. If F is the fraction of the array area which is covered by mirrors, the pattern is narrower by the factor $(F)^{1/2}$ and the

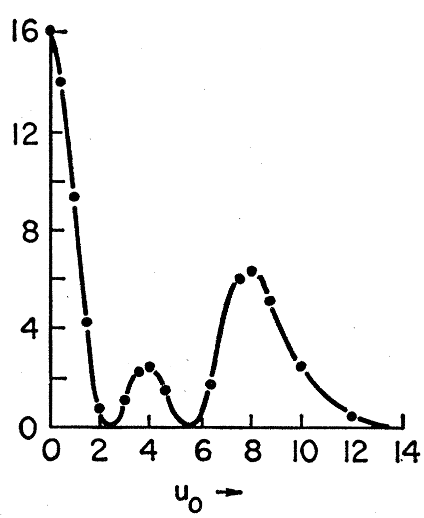


Fig. 9. Intensity pattern for eight-element composite array.

total energy in the central peak, U_{NC}, is less by a factor F:

$$U_{NC} = NU_1F \quad (18)$$

The total energy in the diffraction pattern is unchanged, however, so the energy going into background radiation must be

$$U' = NU_1(1 - F). \quad (19)$$

That energy is distributed over the diffraction peak of a *single* element, so Eq. 19 can be written

$$I' = NI_1(1-F), \quad (20)$$

with I' the average background intensity.

The area packing-fraction F is

$$F = N\left(\frac{d}{D}\right)^2 \quad (21)$$

so

$$I' = I_N \cdot \frac{I}{N}\left[1 - N\left(\frac{d}{D}\right)^2\right] \quad (22)$$

with I_N the intensity at the central focus. For $F \ll 1$, Eq. 22 approaches Eq. 15. Numerically, the design quoted at the beginning of this article has $N = 200$, $(D/d) = 125$; for that case, Eq. 15 is an excellent approximation to Eq. 22, and the background near the central image is reduced in intensity by a factor of 200, relative to the center of the pattern.

For detailed design of the pattern of reflectors it might be appropriate to study, by computer, the interference pattern of a randomly chosen array, and then to make "ordered" changes in the array to minimize the maximum fluctuations in the resulting diffraction pattern.

There are some purposes, notably the resolution of a planet from its primary star, for which extremely high side-lobe-suppression factors are needed. To obtain them it is necessary that the noise source be outside the diffraction peak of the individual element. That is one reason for making the individual elements moderately large (in the case of the instrument described, about 1/100 the diameter of the array) rather than very small.

In this article only a few applications of a high-resolution telescope have been mentioned, and those very briefly. It is fascinating to calculate in detail what could be accomplished for specific astronomical problems by a telescope with an angular resolution of 4 nanoradians, but the main point needing emphasis is that it is possible to build a telescope of very large aperture without having to fill that aperture with mirrors. In radio astronomy such an idea is very old (see appendix, part 3, and references *6–11*), but it has not so far been applied to an optical telescope.

The construction and launching of such an instrument would pose ethical and political questions; it would be in orbit a few hundred kilometers above the earth, and its atmosphere-limited resolution would be good enough to detect considerable detail on the ground. Possibly the first requirement would be a guarantee by its builders, before it was made, that it would never be pointed toward the earth.

In closing it should be emphasized that, although the work described here is original, a number of people have worked on the idea of nonrigid optical systems (*12, 13*). Studies have been made (*3*) of the problems of aligning composite mirrors with $F = 1$, and the physics on which Eq. 1 is based was developed more than a century ago. An effort has been made to search for and list those articles and reports (*3, 14*) which might have bearing on the problem.

Appendix: Resolution, Contrast, Relevant Studies in Radio Astronomy

Part 1: Resolution. As shown in the discussion of case C, the angular resolution η of an array of diameter D is

$$\eta = 1.22\frac{\lambda}{D}, \quad (23)$$

where λ is the wavelength. For an array with diameter $D = 125$ meters and blue-violet light of wavelength $\lambda = 4000$ angstroms,

$$\eta = 1.22\ (4 \times 10^{-5}\ \text{cm})(1.25 \times 10^4\ \text{cm})^{-1}$$
$$= 0.4 \times 10^{-8}\ \text{m} = 4\ \text{nanoradians} \quad (24)$$

Table 1 indicates what such resolution would mean in terms of distance. The resolution available at the distance of Jupiter and its moons would be comparable to that with which our own moon can be seen by an earth-based telescope of 3-inch aperture.

Table 1. Spatial resolution of a composite telescope with an aperture of 5000 inches.

Spatial resolution (m)	Distance	Object
0.001	250 km	Satellite in orbit
1.6	4×10^5 km	Surface of the moon
240	6×10^7 km	Mars and its moons
350	9×10^7 km	Mercury; comets near the sun
2.6×10^3	6.3×10^8 km	Jupiter and its moons
24×10^3	5.8×10^9 km	Pluto
0.4×10^9	10 light-years	Planets of another star

The resolution at a distance of 10 light-years is sufficient for detecting a planet the size of Jupiter in at least three ways. The planet would have an orbit radius corresponding to an angle of 6 microradians, which is about the 14th band in the single-element diffraction pattern of the primary. The interval between maxima would be about 400 nanoradians, so a search could be conducted in an angular region 10 or more nanoradians wide, centered on a dark band. A planet crossing the band would appear as a point of light about 4 nanoradians in size. Alternatively, a region several hundred nanoradians in width, covering one or more light and dark bands, would be scanned. In that case one would not have to wait for a planet to cross a dark band, but would be looking for a signal change of less than 1 percent. As a third alternative, occasional photographs, taken over a period of years, of the primary star seen against the star field would show a motion (about 1 stellar diameter, 10^6 kilometers) of the star about the system's mass center (*15*). That motion, about 10 nanoradians, would be resolved by the telescope described here, with which in fact a sun-size star at a distance of 10 light-years would appear as a disk rather than as a point of light. The discovery of earth-size planets about other stars is possible in principle by means of the first two methods, but presumably would occur only after techniques had been refined for extracting the maximum amount of information from the high-resolution image the telescope would provide.

Part 2: Contrast. On the principle that "nothing comes free" one should expect that high resolution obtained cheaply must carry with it some disadvantage. That is so, and the disadvantage is a loss of contrast. For many astronomical objects (a star, for example) there is extremely high contrast between the object and its background, and therefore no contrast problem. For others (for example, a planetary surface), contrast is not high, and a high-quality image would have to be reconstructed from the image sensor with the help of a computer.

The resolution function of the telescope can be measured through observation of the diffraction pattern from a distant small star (one more than 100 light-years away). We will approximate it by the response function R:

$$R(r,\theta) = R(r) = I_0 \text{ for } r < r_0$$
$$I' \text{ for } r_0 < r < r_1$$
$$0 \text{ for } r > r_1$$

Suppose that the source at which the telescope is pointed is a planetary surface, on which a surface detail (equal in size to the resolution of the telescope) exists having a brightness C times that of its surroundings. C we may call the contrast of the detail. The source brightness function is then

$$S(r,\theta) = S(r) = 1 + C \text{ for } r < r_0$$
$$1 \quad \text{for } r_0 < r.$$

The intensity received at the center of the diffraction pattern is then

$$I_S = \int\int S(r)\, R(r)\, r dr d\theta$$
$$= 2\pi \left\{ (1 + C)\, I_0 \frac{r_0^2}{2} + I' \cdot \left(\frac{r_1'^2 - r_0^2}{2} \right) \right\}.$$

The ratio of the first term to the second is a measure of the contrast, C_F, of the final image. Using the formulas derived earlier, and in the approximation that $F \ll 1$, we have

$$C_F + 1 \approx \frac{NF(1 + C)}{(1 - F)\,(N - F)} \approx F(1 + C)$$

for small F and large N. The contrast, therefore, is reduced by just the same factor F by which the total mirror area is reduced for a given aperture. It would be an interesting and quite practical exercise to model the response function of the telescope and to study test pictures taken by the model. There are additional tricks by which low-contrast information can be recovered; for example, the individual mirrors could be moved synchronously along their axes by a few wavelengths of light; in this way the figure of the overall paraboloid could be deliberately destroyed and recreated, and thus the central maximum could be modulated from I' to its full value of NI'.

Part 3: Relevant studies in radio astronomy. The concept which has concerned us—the achievement of a large effective aperture only a small fraction of which contains detectors—has been the subject of intense study by radio astronomers for many years. Their (*6*) descriptive title *aperture synthesis* has been carried over to the optical field in a recent symposium (*13*).

Bracewell, in two review articles (*7*), discussed many of the ideas which radio astronomers have developed for aperture synthesis. The most extreme version of a synthetic-aperture system is a variable-spacing two-element interferometer. Ryle pointed out (*6*) that construction of a complete image by such a system is possible in principle if information is collected at many spacings and angles. One can neglect phase information only if the observed object is symmetrical.

The Christiansen interferometer (*8*) is a linear spaced array with element separation of many wavelengths, somewhat analogous to case A of this discussion. The Mills cross (*9*) achieves high resolution in both dimensions through the use of a cross-shaped array of elements in combination with a phase-switching scheme. Phase switching is equivalent to modulation of the overall paraboloid, as suggested for the optical case (C).

For a static linear array in one dimension, Arsac noted (*10*) that four elements located at the 1's in the sequence 1100101 sample equally all spatial Fourier components from 1 to 6 in units of the lowest component other than zero. There is no equivalent choice for two dimensions.

The Brown-Twiss phase-independent radio interferometer (*11*) was developed for study of the sizes of very small radio sources. Its principles were also applied to optical interferometry. More recently, two-element interferometry has been extended to long-baseline interferometry and, in special cases, to lunar occultation.

In transferring the ideas of radio astronomy to optical astronomy one should keep in mind the fact that aperture synthesis pursued to extremes leads to very low rates of light collection. Even with 1-micron spatial resolution of the detector at the focal plane, a 125-meter complete paraboloid could not operate at less than *f*:2.5, to use optical language; with 1-percent aperture filling, the effective *f*-number would be 25, and an interferometer with a 125-meter base line and two 1-meter mirrors would have a speed equivalent to that of a camera of *f*:250. The rotation, (practical only in space) of any such asymmetrical array could produce a time-averaged symmetrical diffraction pattern.

References and Notes

1. National Academy of Sciences Space Science Board, *Space Research—Directions for the Future* (National Academy of Sciences, Washington, D.C., 1966), pt. 2.
2. F. A. Jenkins and H. E. White, *Fundamentals of Optics* (McGraw-Hill, New York, ed. 2, 1950), pp. 279–377.
3. "Active Optical System for Spaceborne Telescopes—Final Report," *Perkin-Elmer Eng. Rep. No. 8525* (1966) (contract No. NAS-1-5198, Langley Research Center, Hampton, Va.).
4. R. K. Lundeberg, *Mathematical Theory of Optics* (Brown Univ. Press, Providence, R.I., 1944), vol. 2, pp. 361–64.
5. P. Drude, *Theory of Optics* (Dover, New York, 1959), pp. 185–228.
6. M. Ryle, "The Mullard Radio Astronomy Observatory, Cambridge," *Nature* **180**, 110 (1957).
7. R. N. Bracewell, "Radio astronomy techniques," in *Handbuch der Physik*, S. Flügge, Ed. (Springer, Berlin, 1962), vol. 54, p. 42; *IRE (Inst. Radio Engrs.) Trans. Antennas Propagation* **9**, 59 (1961).
8. W. N. Christiansen and J. A. Warburton, "The distribution of radio brightness over the solar disk at a wavelength of 21 centimeters," *Australian J. Phys.* **6**, 262 (1953).
9. B. Y. Mills and A. G. Little, "A high-resolution aerial system of a new type," *ibid.*, p. 272.
10. J. Arsac, "Radio-astronomie—nouveau réseau pour l'observation radioastronomique de la brilliance sur le soleil à 9350 mc/s," *Compt. Rend.* **240**, 942 (1955).
11. R. H. Brown and R. Q. Twiss, "A new type of interferometer for use in radio astronomy," *Phil. Mag.* **45**, 663 (1954).
12. Symposium, International Astronomical Union, Tucson, Ariz.; Pasadena and Mt. Hamilton, Calif., Apr. 1965.
13. "Proceedings, 1967 Summer Study on Synthetic Aperture Optics" (National Academy of Sciences, Washington, D.C., in press).
14. "A System Study of a Manned Orbital Telescope," *Study No. D2-84042-1* (1965), prepared by the Aerospace Group of the Boeing Company, Seattle, for Langley Research Center, under contract NAS-1-3968.
15. P. Van de Kamp, "Planetary companions of stars," *Vistas Astron.* **2**, 1040 (1956); "Astrometric study of Barnard's star from plates taken with the 24 inch Sproul refractor," *Astron. J.* **68**, 515 (1963).

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