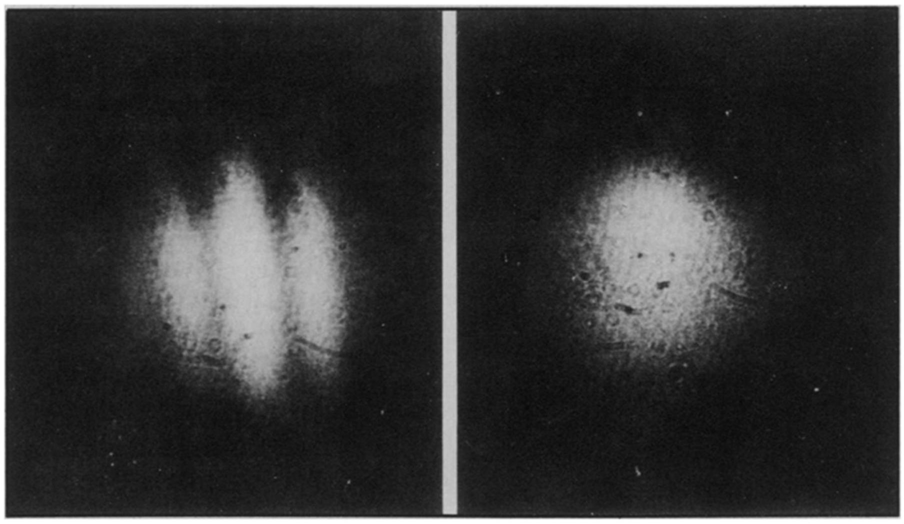
TOWARD THE DIFFRACTION LIMIT

How to see the stars as they really are, even while squinting through the atmosphere

BY DIETRICK E. THOMSEN



Photos: Lawrence Berkeley Laboratory

Comparison of flexible-mirror image (showing sidelobes) and uncompensated image.

The laws of optics say that the larger a telescope's aperture is, the better it should resolve images. The only limit optically is caused by diffraction. A plane light wave, entering a finite aperture, is bent slightly around the edges of the aperture. Bent rays and straight rays can meet at the plane where the image is formed, and destructive interference between them causes a certain fuzziness. But light waves are very short—the phenomenon depends on wavelength—so the distortion in a large aperture should be slight.

In fact, the practical limit of resolution for ground-based telescopes is reached at an aperture of about 60 inches—not big by present-day standards. The best resolution is about one or two seconds of arc, which means that the images of stars cannot be resolved to show surface detail, and details of extended objects finer than that cannot be observed—the "canals" of Mars, for example. Before spacecraft went to the planet, astronomers argued heatedly over what surface features they had actually seen as the disk shimmered and danced in the telescope objective.

The culprit in all this is, of course, the earth's atmosphere. Its turbulence makes sure that the wave presented to the telescope aperture is not a plane wave but a corrugated one with built-in phase distortions that add to the problem. The distortions vary not only from place to place across the aperture, but quite rapidly from time to time in the same place.

In recent years a number of suggestions about how to compensate for atmospheric distortion have surfaced (SN: 8/24-31/74, p. 132). Some of these involve processing multiple images of a given object recorded on film with exposure times calculated to be less than the average time over which the atmosphere's turbulence state changes. One then can look for individual shots on which the seeing was particularly good, or one can process large batches by the technique known as speckle interferometry. By the necessity of quick photography, these techniques are limited to brighter objects that can make impressions on the photographic plate in times on the order of 10 milliseconds. Nevertheless, they are proving very useful. Speckle interferometry was used in the first resolution of surface features of a star other than the sun, those of Betelgeuse (see p. 133).

The other approach is real-time correction, making adjustments in the telescope to compensate for distortion while the light is passing through and producing a resolved image at first recording. There are several such concepts, which go together generally under the name "rubber mirror" because they involve some scheme of altering the surface of the mirror to compensate for the distortions in the incoming light under the direction of some kind of servomechanism. A good part of the recent conference on Imaging in Astronomy held at Harvard University was devoted to them.

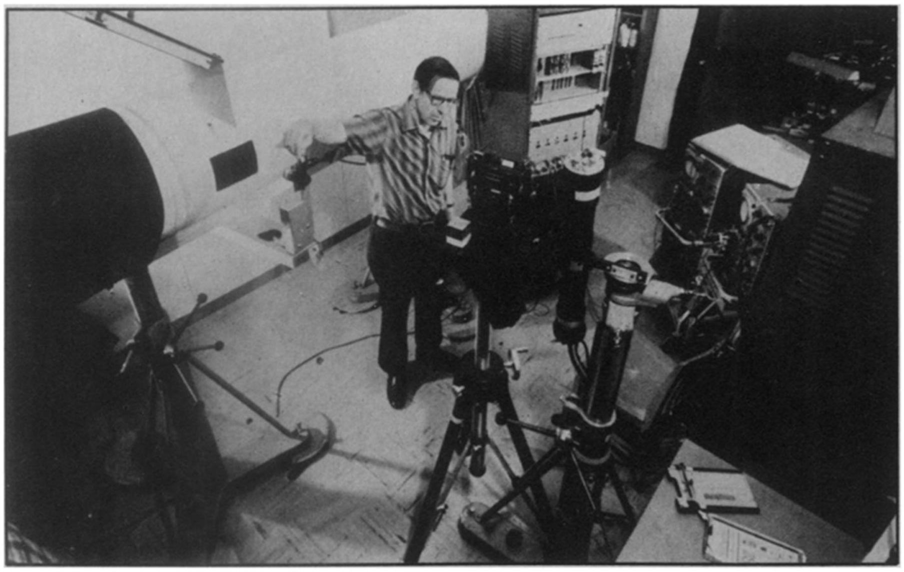
These ideas surface now—astronomers would always have been grateful for them—because advances in understanding the detailed behavior of the atmosphere and in the design of computerized servomechanisms give hope of practical results. A lot of the work is being done in military-related laboratories because that is where a lot of the atmosphere work has been done, and also because success would benefit more than astronomy.

To rubberize a telescope one divides its surface into a number of small segments that can be independently moved by the servomechanism. Making the mirror flexible is not the major technological problem. Frank Crawford of the Lawrence Berkeley Laboratory describes how his group did it for their experimental model. The boundaries of the segments are etched into a single glass flat until the glass is almost cut through. This provides sufficient flexibility. A metal pin is mounted on the back of each segment, and the pins are pulled by the magnetic fields from solenoid coils taken from loudspeakers. This experimental arrangement does not provide the sophisticated motions a working rubber telescope would require, but it demonstrates the basic technology.

The motions can be divided grossly into two kinds, "piston" or straight in-and-out, and tilt, says Raymond P. Urtz Jr. of the Rome Air Development Center, Griffiss Air Force Base, N.Y. The wave comes in at an angle with a gross tilt and variations in phase. Piston correction is for phase variation; tilt is for angular deviation. Urtz describes an experimental system with 49 segments that produces a "dramatic improvement" in the image with piston correction only. Taking piston and tilt together nine segments do as well as 49 with piston only.

This kind of work is closely correlated with atmospheric research. Darryl P. Greenwood of the Rome Air Development Center's Environmental Studies Section discussed how the theory of mirror tilt is being based on studies aimed at deriving a phenomenological model of atmospheric turbulence for the Advanced Research Projects Agency's Maui Optical Station on Mt. Haleakala in Hawaii. Fine-wire probes, acoustic sounders, regular radiosonde runs, meteorological instruments and a Hartmann test (see below) of the light entering the telescope are all used to determine which layers of the atmosphere contribute how much to the turbulence problem, and what are the optimum combinations of mirror operation, time and angle of viewing to get the best pictures.

More of a problem is defining image sharpness and translating it into terms that can be sensed by a physical system. It might be thought easy: The eye sees, and the brain records. But the human brain does not work like a digital computer, and translating its judgments into terms acceptable to a servomechanism takes ingenuity.



Robert G. Smits adjusts 12-inch telescope used at Berkeley for flexible-mirror tests.

Crawford and his group have chosen a mathematical approach. In a paper written more than a year ago, Richard A. Muller and Andrew Buffington derived a formula, an image sharpness function that takes into account the criteria by which the brain would judge, such as brightness and geometric definition, and yields a single value that is maximized when the image is at its optimum. A sensor can then monitor the image formed by the mirror, and when that sharpness value slides off its maximum, the computer, which likes to work with single comprehensive values, can apply the necessary correction.

Other approaches tend to be more physical and rely on sensing, not the image formed by the mirror but the state of the light as it enters the telescope. J. C. Wyant of the University of Arizona listed the approaches in addition to a general description of the qualities such a sensor should have. The sensor should be speedy, able to sense changes at rates between 100 and 1,000 a second. It must sense the same wavefront distortion as that experienced by the light from the object of interest, which means that it usually must use the light from that object rather than being able to calibrate itself by the light from a bright nearby object. It must provide about 300 measuring points for an aperture one meter in diameter.

The methods suggested include, besides the sharpness function measurement, a simple knife edge, Zernike phase contrast, a radial shear interferometer, a lateral shear interferometer, and the Hartmann test. Wyant thinks the lateral shear interferometer and the Hartmann test will probably be the best fitted, and he proceeds to describe those in detail.

The Hartmann test depends on the relation of image displacement to slope errors in the shape of the wavefront. A plane wave will image a regular square array of points as a regular square array, but the corrugated atmospherically distorted wave front displaces the points into an irregular array. The point of the Hartmann test is to sense this displacement for each of the 300 or so image points and correct it.

The lateral shear interferometer is a "black box" with a turning optical element that uses images of the entrance pupil to get interference fringes that give the wavefront slope. At the same time, heterodyne detection techniques are used to get the phase differences, and shaking the diffraction grating sideways causes a Doppler shift that yields the frequency difference between beams. Such a system, Wyant figures, could be useful for objects as faint as sixth magnitude for the usual criterion of wavefront measurement accuracy, which is the wavelength of the incoming light divided by 20. Under less rigorous conditions it might be useful to 11½ magnitude.

Other technology is in hand. In addition to Crawford's style of mirror, Urtz points out that a piezoelectrically driven mirror has been built and can be driven at kilohertz rates. (The distortions in a piezoelectric mirror are made by changes in the shape of certain kinds of crystals that occur when electric fields are applied to them.) A system using a Hartmann sensor is being built. It has a high signal-to-noise ratio, he says, and seems to have a good prospect of success. If the phase changes can be sensed, the corrections in the mirror can be made, he says, and he quotes Freeman J. Dyson as saying that these systems may be able to reach 14th magnitude objects. Success of the rubber telescopes will be the fulfillment of an age-old astronomers' dream. □