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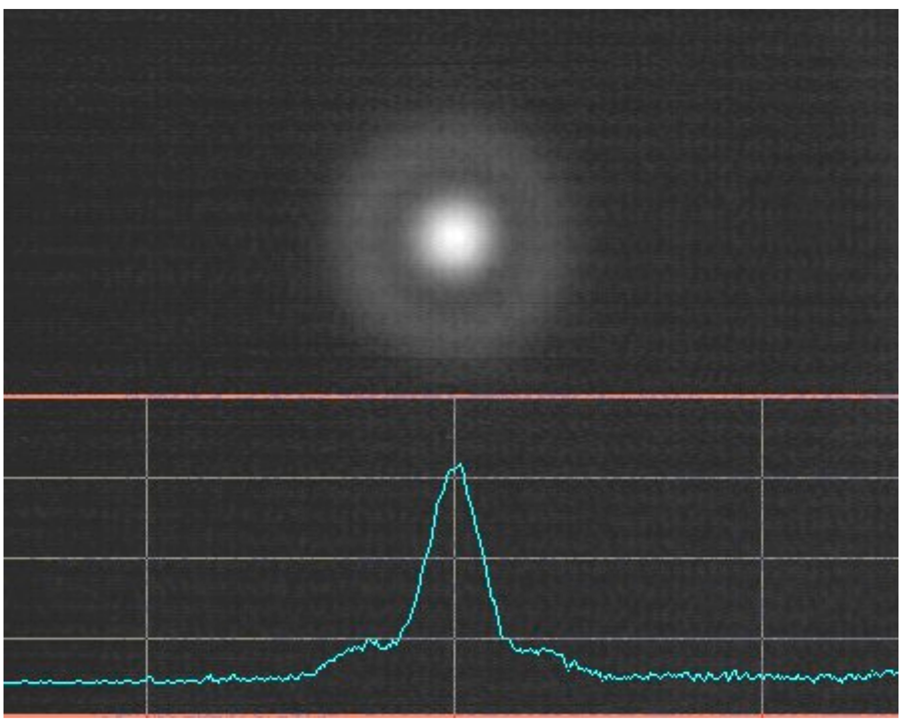
TELESCOPE OPTICS DISCUSSION:

We recently responded to a Request For Proposal (RFP) for a 24-inch (610-mm) aperture telescope. The optical specifications specified an optical quality encircled energy (EE80) value of 80% within 0.6 to 0.8 arc seconds over the entire Field Of View (FOV) of 90-mm (1.2-degrees).

From the excellent book, "Astronomical Optics" page 185 by Daniel J. Schroeder, we find the definition of "Encircled Energy" as "The fraction of the total energy E enclosed within a circle of radius r centered on the Point Spread Function peak". I want to emphasize the "radius r" as we will see this come up again later in another expression.

The first problem with this specification is no wavelength has been specified. Perfect optics will produce an Airy disk whose "radius r" is a function of the wavelength and the aperture of the optic. The aperture in this case is 24-inches (610-mm). A typical Airy disk is shown below. This Airy disk was obtained in the DFM Engineering optical shop.



Actual Airy disk of an unobstructed aperture with an intensity scan through the center in blue.

Perfect optics produce an Airy disk composed of a central spot with alternating dark and bright rings due to diffraction. The Airy disk above only shows the central spot and the first bright ring, the next ring is too faint to be recorded. The first bright ring (seen above) is 63 times fainter than the peak intensity. The second bright ring is 360 times fainter than the peak intensity so cannot be detected with the 8-bit (256 levels of intensity) CCD camera and frame grabber used to obtain the above image.

The radius (not the diameter) of the first dark ring is the familiar equation:

$\alpha = 1.22\ \lambda/D$ — α is the radius of the first dark ring in radians
λ is the operating wavelength in the same units as D
D is the aperture of the telescope optic in the same units as λ

Many people forget that α is the angular radius and they think of this as the diameter. Also, the value 1.22 is for an unobstructed aperture. The central obscuration for an optic causes the energy in the central spot to be reduced and re-distributed out among the rings. Schroeder presents a table on page 183 showing the effect of a central obscuration. The telescope requested in the RFP has a central obscuration ratio of about 50% (central obscuration / aperture). The value 1.22 in the above equation becomes about 1. This means that the central spot diameter actually gets smaller.

However, the energy contained in the central spot is greatly reduced. The table on page 186 of Schroeder shows the encircled energy within the Airy dark rings. For a central obscuration ratio of about 0.5, the energy is reduced to about 48% (compared to 84% for the unobstructed case). Schroeder's table only goes up to a central obscuration of 0.4, so the value for the constant was extrapolated for a central obscuration of 0.5.

With a central obscuration ratio of about 0.5, one must encircle the second dark ring to get >80% of the energy. The radius of the second ring for this obscuration is about:

$$\alpha = 2.5\ \lambda/D$$

The encircled energy including the second bright ring contains about 85% of the energy.

At 0.58 µm (580-nm) wave length, the resulting encircled spot radius is:
α = 2.5 x 0.00058-mm /610-mm x 206,265 (There are 206,265 arc seconds in a radian)
α = 0.49 arc seconds radius or 1 arc second diameter

At 2.5 µm wave length, the resulting encircled spot radius is:
α = 2.5 x 0.0025-mm /610-mm x 206,265
α = 2.1 arc seconds radius or 4.2 arc seconds diameter

From the above, the customer specified encircled energy (EE80) value of 80% within 0.6 to 0.8 arc seconds radius, can not be achieved for wavelengths longer than about 1 µm. However, the customer specified the telescope operating wavelength range as 350 nm to 2.5 µm.

Our many decades of experience has shown us that most astronomers forget that the equation:

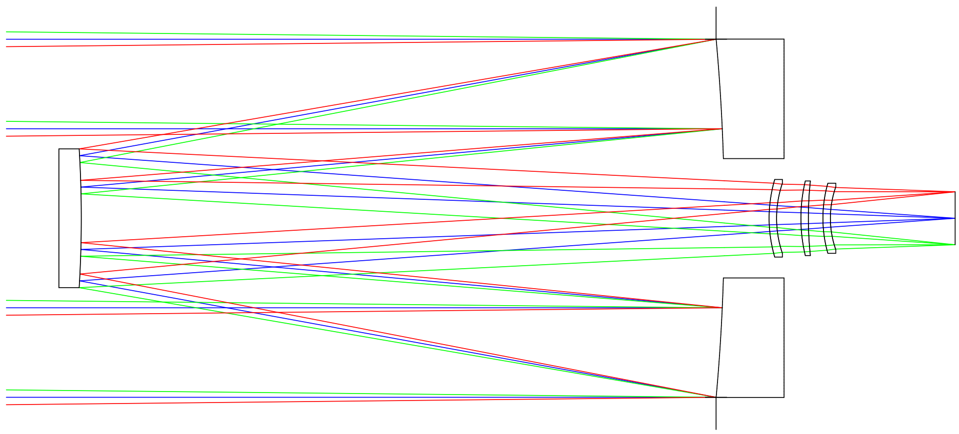
$$\alpha = 1.22\ \lambda/D$$

specifies the radius and not the diameter and is only for an unobstructed aperture. They are then disappointed when the images are more than twice as large as they think they should be.

The off axis images are degraded due to the optical aberrations; coma, field curvature, and astigmatism. The next section discusses how the off axis image quality is improved using a field corrector.

FIELD CORRECTOR DISCUSSION:

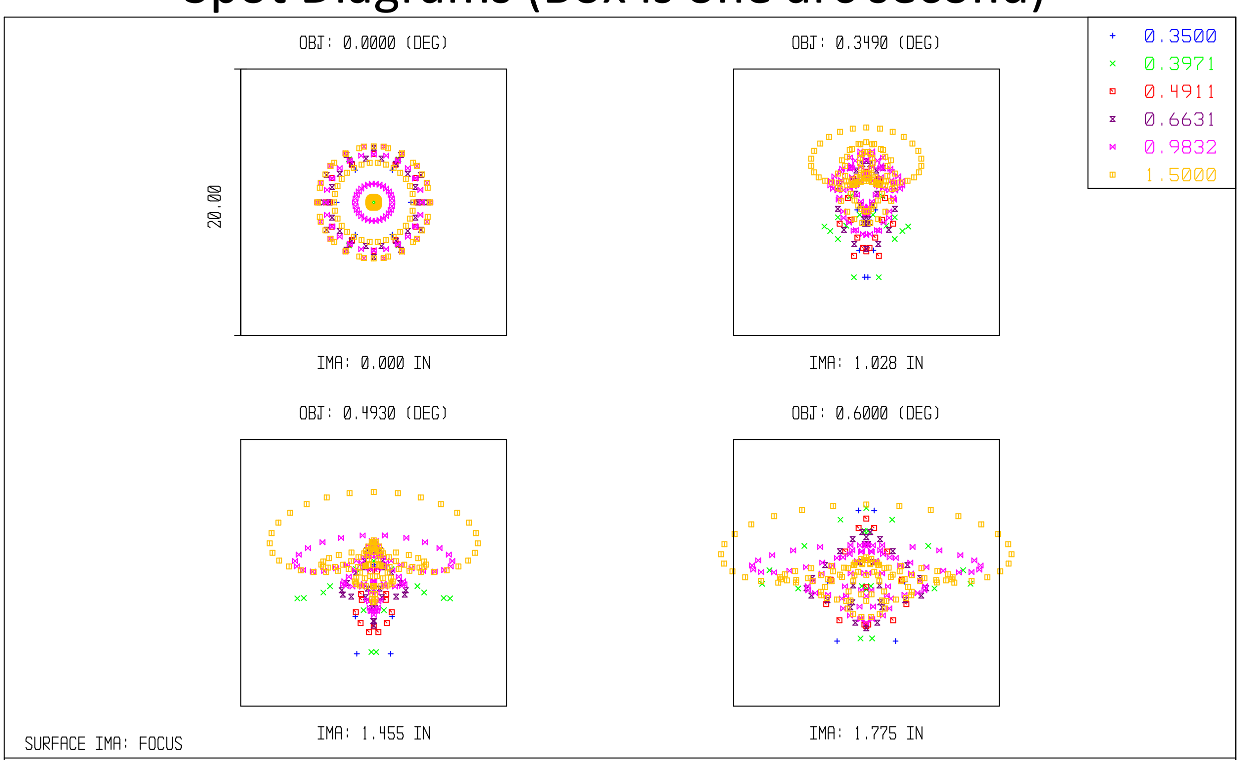
A Ritchey-Chrétien optical system is free from coma, but has astigmatism and field curvature. The field curvature is dependent only upon the difference in the radii of the primary and secondary mirrors and is independent of the prescription (classical Cassegrain, Ritchey-Chrétien, or Dall-Kirkham). The astigmatism and the field curvature can be corrected by a 2 element or 3 element field corrector depending upon how large the field is. The preliminary field corrector design for the 24-inch F/7 telescope with a 1.2-degree FOV is shown below.



Optical System Layout

Chromatic problems are minimized if the field corrector has nearly zero power (the focal ratio is unchanged by the field corrector). The chromatic aberration is shown within the spot diagrams below for 6 colors ranging in wavelength from 350-nm to 1.5-µm. The boxes are 1-arc second on a side.

Spot Diagrams (Box is one arc second)



Geometrical Spot Diagrams 6 colors and 4 field angles (Does not include diffraction)

The wavelength range (the band pass) is from 350-nm to 1.5-µm. The preliminary design uses fused silica (quartz) for the 3 elements. This material is expensive, but is needed to include the near IR.

Field correctors are expensive to build due of the number of optical surfaces and the number of tools required for grinding and polishing the surfaces. The above field corrector has 6 surfaces. To fabricate the individual elements requires, as a minimum, 1 tool for each surface (6 tools). The 3 convex surfaces will each require a concave test plate which requires 3 more tools. A test plate is required because only concave (or flat, or small diameter convex) surfaces can be tested directly with an interferometer.

A test plate has a concave surface on one side and a flat surface on the other side. The concave surface must have the same radius as the radius of the surface to be tested. The test plate is set on the surface to be tested, and interference fringes are developed between the two surfaces. Typically the test plates are made 6-inches in diameter to test optics of this size.

There are a total of 12 surfaces that need to be polished (6 for the actual elements, 3 test surfaces, and 3 flat surfaces). Only 9 tools are required because 3 surfaces are flat and flat tools are a standard tool in the optical shop.

We find that each field corrector is unique to the specific telescope requirements, so new tools and test plates need to be made every time. In production, there would be (2) tools for every surface, one for grinding and one for polishing (18 tools plus the flat tools).