The Wide Field Cassegrain: Exploring Solution Space

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Abstract

This article illustrates the use of an internal aperture stop in a high speed, wide field Cassegrain optical system. The astrograph features a well corrected and uniformly illuminated focal plane. Opto-mechanical design and manufacturing issues are also discussed.

1. Introduction

Of all the conventional astronomical telescope designs used in amateur astronomy the Cassegrain is the least likely to be considered a candidate for wide field imaging applications. This perception is a hangover from the era of visual observing where minimizing the central obscuration was critical to preserving image fidelity. The resulting long focal length, slow telescopes did not lend themselves to photography.

The central obscuration in reflector astrographs need not be so constrained since ground based amateur instruments never achieve diffraction limited performance, primarily due to poor seeing, image sampling limitations and tracking errors. Cassegrain astrographs with a large obscuration (50% of the aperture diameter or greater) and a fast primary will permit a relatively short overall focal length, a wider field of view and more uniform focal plane illumination. While the larger obscuration does reduce system through put, the light loss can be compensated for with longer exposures.

In addition to the benefits of a larger obscuration, allowing the aperture stop position to move from the primary mirror to a more central location in the Cassegrain optical system offers the potential to achieve very wide fields of view in a fast system while still controlling off axis aberrations.

The ideas presented in this article are based on the design of an f/2.8 Cassegrain astrograph of 210mm aperture with a conic 300mm diameter primary. This astrograph was scaled to cover a 5 degree field on a commercially available 4Kx4Kx9 micron pixel CCD detector. The system features good aberration control, uniform field illumination and at 280mm long, is extremely compact.
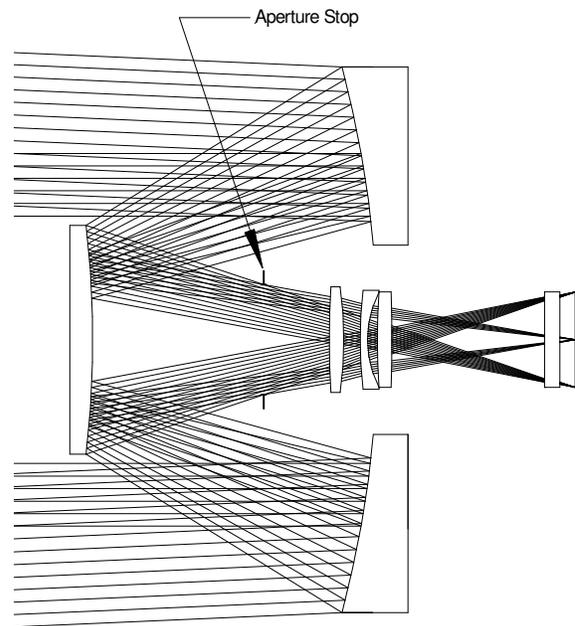
Figure 1, internal stop Cassegrain astrograph

2. The Aperture Stop

An optical system's aperture stop is located at the point on the axis where all field rays intersect, the pivot point for all the light field rays. In optical design the aperture stop location is considered a "degree of freedom". The stop can be located anywhere in an optical system and its position is typically used to control off-axis aberrations in wide field optical systems. This is well illustrated by a generic photographic lens whose aperture stop is nestled between two lens groups.
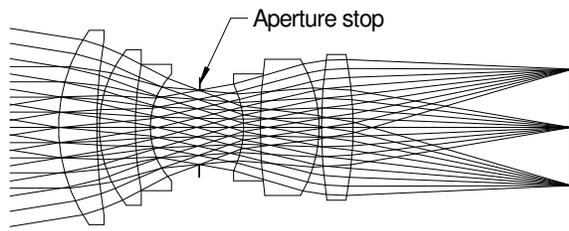
Figure 2, typical photographic lens layout

It is interesting to note that the objective's aperture stop is significantly smaller than most of the lens elements. The difference in size is more pronounced with very wide field lenses where the lens elements need to be enlarged significantly to catch the off axis light rays, otherwise vignetting will be induced.
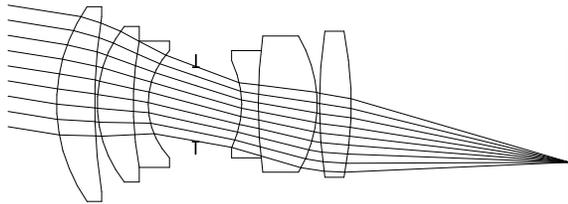
Figure 3, off axis beam effect on element size

Also note that the physical size of the aperture stop in this type of lens does not define the system's effective light gathering aperture or entrance pupil. The entrance pupil is larger since the optics ahead of the aperture stop magnifies its size.
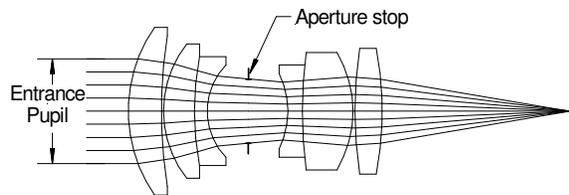
Figure 4, entrance pupil and aperture stop

The entrance pupil migrates to the edge of the first surface as the source moves off axis (Fig. 3). Aspheric surfaces in such systems principally affect off axis aberrations like astigmatism the most. The surface's departure from sphericity and its influence on imaging rays is at its maximum at its edge. Aspheric surfaces in traditional telescopes are usually located at the aperture stop, thus they affect axial and off axis rays uniformly. The reflecting telescope's aspheric (parabolic) primary's principal function is the correction of spherical aberration.

A telescope's aperture is usually defined by the largest element in the optical system; the primary mirror or refractor objective. The only telescope that deviates significantly from this norm is the Schmidt camera. The Schmidt camera's aperture stop is coincident with the corrector plate located at the primary mirror's center of curvature. In order to catch all the off-axis rays the primary must be larger than the Schmidt corrector.

Removing the constraint on the aperture stop's location is one of the last options in the telescope designer's tool kit to make a substantive change in the telescopes imaging characteristics.

3. The ideal telescope design form

Many optical designs are easily cooked up on the computer, but the predicted performance can be difficult to realize once the optics and mounting hardware are fabricated. Often the problem is collimation, lenses and mirrors can be difficult to mount and locate precisely in stress free cells. The problem is exacerbated in telescopes because optics critical to performance are often widely spaced, quite massive and subject to large variations in gravity loading.

Ideally the telescope's optics will be arranged to better facilitate collimation by design. Some telescope design forms are better suited to this ideal than others. While any optical system can be made to work, the Cassegrain is one of the more friendly design forms because of the ability to mount the primary mirror, field corrector lenses and the heavy CCD camera/filter in a single cell.

The typical telescope, reflective or refractive, naturally produces a curved focal surface. To effectively use a large format flat CCD, wide field telescopes require the use of corrector lenses close to focus to flatten the field and minimize off axis aberration. As important as image quality is, the minimizing of ghost images produced by spurious reflections off the CCD detector and within the field corrector group is just as critical. Of particular importance is the pupil ghost because it is additive and its effects cannot be easily calibrated out without adding noise to the image. An optical system's design is incomplete without a thorough ghost image analysis.

The typical telescope optical tube assembly will have collimation provisions for all the optical components. This approach is suitable for the average optically slow and long telescope built to loose

mechanical tolerances, i.e. a Newtonian reflector. A compact optical system is always more desirable, but compactness breeds complexity and the tolerances usually tighten exponentially. The more adjustments incorporated in the mechanics the greater the number of headaches one is likely to encounter trying to collimate the system. Ideally collimation should be primarily achieved by design and careful manufacture rather than adjustment.

The special case of the Cassegrain with a spherical secondary (Wynne, Rosin, Harmer) further facilitates ease of collimation by design. An aspheric secondary has an optical axis that must be carefully lined up with the primary's axis while simultaneously adjusted in tip and tilt. All this must be accomplished with the secondary mounted on a thin vane spider and often flexible tube.

A spherical Cassegrain secondary has no optical axis, it needs only simple tip/tilt adjustments. The practical advantages of a spherical secondary in a fast, wide field, highly corrected Cassegrain cannot be over emphasized. The collimation tolerance envelope drastically shrinks as the field widens and the system's speed increases.

4. Internal aperture stop Cassegrain

In optical design the aperture stop is treated as a plano, single surface "element". Since the aperture stop is essentially a machined metal rim, its refractive index is equal to 1, that of air. The stop's position in the system is allowed to vary during optimization, but constrained so as not to interfere with imaging rays.

For the initial design a fast Cassegrain mirror system with field correctors was laid out. The stop was placed forward of the primary, anticipating it would migrate farther from the primary and the final system would converge on "Schmidt camera" type of telescope. However during computer optimization runs, the stop would immediately snap back against the primary. The stop was then placed against the secondary mirror, the next practical location, with encouraging results. After further exploration of solution space it was allowed to wander farther down stream between the field corrector lens group and the anticipated end of the primary's baffle tube.

It may not be obvious, but this Cassegrain resembles, in function at least, the photographic lens mentioned earlier (Fig. 2) with the stop in the middle of the system. In the Cassegrain astrograph the positive and negative elements ahead of the stop are now mirrors instead of lens elements.

As in the case of the photographic lens, the astrograph's 210 mm diameter entrance pupil migrates around the 300mm diameter primary mirror. This pupil movement has an interesting effect on field illumination; rather than the typical vignetting encountered in conventional telescopes, this Cassegrain astrograph's illumination actually increases slightly off axis. As the entrance pupil migrates off axis it leaves the secondary behind, obscuring less of the incident light.
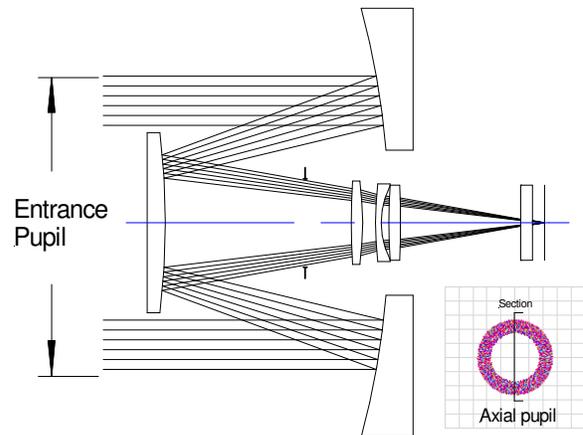
Figure 5, axial beam with large obscuration
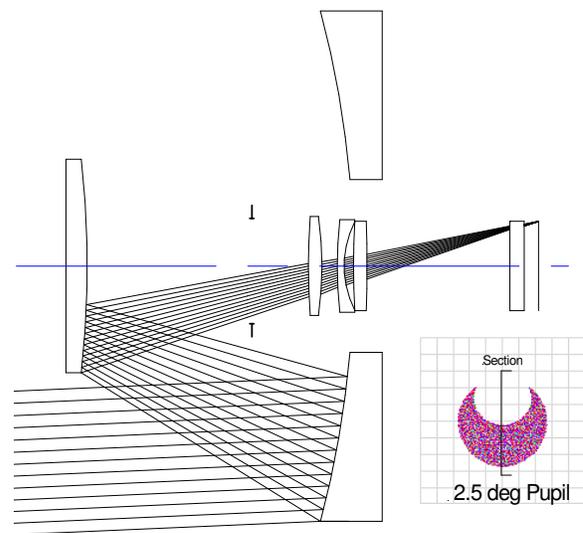
Figure 6, off axis beam and displaced obscuration

This special case of the Cassegrain where the secondary is constrained to be spherical requires the primary's conic constant to vary along with the field corrector group parameters in order to balance spherical aberration while controlling off axis image

quality. The primary's conic constant in this type of system is usually less than 1, or an ellipse.

The combination of a spherical secondary and elliptical primary resembles the classic Dall-Kirkham Cassegrain telescope. The similarities are entirely superficial since the relationship between the spherical secondary and elliptical primary's conic constant required to achieve spherical aberration correction characteristic of the Dall-Kirkham does not exist. The astrograph will not function without the field corrector optics, they are an integral part of the optical system; they are not optional.

The f/1 aspheric primary's role in this astrograph is very different from that normally encountered in conventional telescopes. As mentioned earlier, aspheric surfaces on either side of the aperture stop principally affect off axis aberration correction, and the aspheric surface's departure from sphericity is at its maximum at the edge. The off axis light ray bundle's sagittal and tangential light rays see a different "shape" on the mirror, aiding the correction of off axis aberrations like astigmatism.

The field corrector group has nearly zero net power, thus there are no significant chromatic aberrations. All required correction may be achieved using the same substrate for the three elements, permitting solutions with fused silica to encompass a broader section of the spectrum.
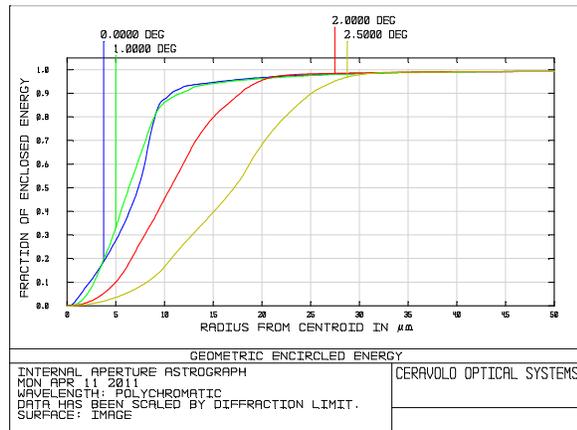
Figure 7, image quality: 320nm – 1 micron wavelength range

Because the system is relatively fast, and the imaging ray's incident angle on the CCD is high, the optical influence of the typical CCD camera window and filter thicknesses were included in the layout during optimization via one thick parallel plate. Not

allowing for filter and window thickness would induce lateral color.
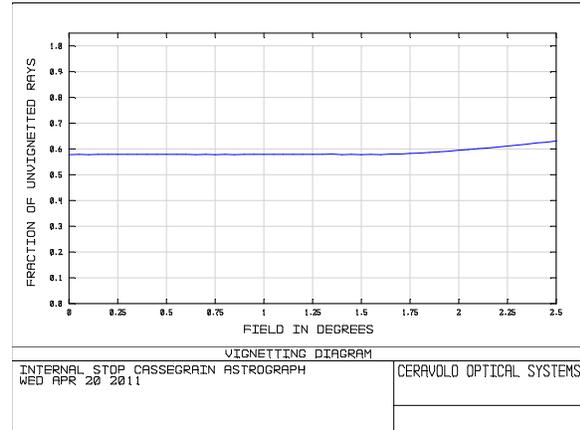
Figure 8, field illumination

4.1 Collimation

This high speed, wide field and compact astrograph design will be a challenge to fabricate. The only optical manufacturing challenge is the f/1 conic primary, but it does not need be as precise as the typical primary mirror. A one wave or so error in the aspheric profile will not cause significant change in image quality. Most image degradation will likely arise from optic mounting and collimation issues.

The field corrector lens group is positioned close to the primary's central hole. The lenses and primary can be mounted in a common carefully machined cell to mitigate centration and tilt problems.

The secondary mirror collimation will be very sensitive; it will call for a highly refined secondary cell. The typical tip/tilt cell found in most telescopes will not work. The cell design found in optics labs, with their orthogonal adjustments and very fine pitch screws will be required. Better still is a cell design that will not induce focus change with adjustment. In this type of cell the pivot point is coincident with the secondary vertex.

Large format CCD cameras and fast optical systems present severe alignment challenges. Collimation will be impossible with a tilted CCD detector. Large CCD detectors must be considered a part of the optical system, not just an add on. The detectors collimation, or orthoganality to be precise, is vital to system performance. Special attention needs to be paid to stacking errors when add on filter wheels are used. Also, the camera's coupling to the astrograph will require more than a simple "nose

piece" and thumb screw lock to be effective. A circular male dovetail type fitting that forces the camera flange against the focusing device will be required.

4.2 Baffles and scattered light

The internal aperture stop Cassegrain requires the typical baffle tubes on the primary and secondary mirrors to block direct skylight from reaching the focal plane. However these baffles will be short and large in diameter to avoid vignetting imaging rays. Sky light enters the large aperture baffle and eventually scatters its way to the detector, reducing contrast.

Auxiliary baffles inside the pupil (Gunn 2006) have been used to further shield the main baffle tube and the focal plane from scattered light. The Sloan Survey telescope is one such instrument.

5. Conclusions

This article illustrates that a relatively wide field, fast Cassegrain optical system is possible if the aperture stop is placed between the secondary mirror and field corrector optics. The result is a system that is remarkably compact compared to the conventional Schmidt camera of similar characteristics.

6. Acknowledgements

7. References

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