CELESTRON®

# EDGEHD™

## A FLEXIBLE IMAGING PLATFORM AT AN AFFORDABLE PRICE

### Superior flat-field, coma-free imaging

by the Celestron Engineering Team

Ver. 04-2013, For release in April 2013.

# The Celestron EdgeHD A Flexible Imaging Platform at an Affordable Price

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## ABSTRACT:

The Celestron EdgeHD is an advanced, flat-field, aplanatic series of telescopes designed for visual observation and imaging with astronomical CCD cameras and full-frame digital SLR cameras. This paper describes the development goals and design decisions behind EdgeHD technology and their practical realization in 8-, 9.25-, 11-, and 14-inch apertures. We include cross-sections of the EdgeHD series, a table with visual and imaging specifications, and comparative spot diagrams for the EdgeHD and competing "coma-free" Schmidt-Cassegrain designs. We also outline the construction and testing process for EdgeHD telescopes and provide instructions for placing sensors at the optimum back-focus distance for astroimaging.


## 1. INTRODUCTION

The classic Schmidt-Cassegrain telescope (SCT) manufactured by Celestron served an entire generation of observers and astrophotographers. With the advent of wide-field and ultra-wide-field eyepieces, large format CCD cameras, and full frame digital SLR cameras, the inherent drawbacks of the classic SCT called for a new design. The EdgeHD is that new design. The EdgeHD offers clean, diffraction-limited images for high power observation of the planets and the Moon. As an aplanatic, flat-field astrograph, the EdgeHD's optics provide tight, round, edge-to-edge star images over a wide, 42mm diameter flat field of view for stunning color, monochrome, and narrow-band imaging of deep sky objects.

## 2. SETTING GOALS FOR THE EDGEHD TELESCOPE

The story of the EdgeHD began with our setting performance goals, quality goals, and price goals. Like the classic SCT, the new Celestron optic would need to be light and compact. Optically, we set twin goals. First, the new telescope had to be capable of extraordinary wide-field viewing with advanced eyepiece designs. Second, the optic had to produce sharp-to-the-edge astrophotography with both digital SLR cameras and astronomical CCD cameras. Finally, we wanted to leverage Celestron's proven ability to manufacture high-performance telescopes at a consumer-friendly price point. In short, we sought to create a flexible imaging platform at a very affordable price.

Given an unlimited budget, engineering high-performance optics is not difficult. The challenge Celestron accepted was to control the price, complexity, and cost of manufacture without compromising optical performance. We began with a comprehensive review of the classic SCT and possible alternatives.

Our classic SCT has three optical components: a spherical primary mirror, a spherical secondary mirror, and a corrector plate with a polynomial curve. As every amateur telescope maker and professional optician knows, a sphere is the most desirable optical figure. In polishing a lens or mirror, the work piece moves over a lap made of optical pitch that slowly conforms to the glass surface. Geometrically, the only surfaces that can slide freely against one another are spheres. Any spot that is low relative to the common spherical surface receives no wear; any spot that is higher is worn off. Spherical surfaces result almost automatically. A skilled optician in a well-equipped optical shop can reliably produce near-perfect spherical surfaces. Furthermore, by comparing an optical surface against a matchplate—a precision reference surface—departures in both the radius and sphericity can be quickly assessed.

In forty years of manufacturing its classic Schmidt-Cassegrain telescope, Celestron had fully mastered the art of making large numbers of essentially perfect spherical primary and secondary mirrors.

In addition, Celestron's strengths included the production of Schmidt corrector plates. In the early 1970s, Tom Johnson, Celestron's founder, perfected the necessary techniques. Before Johnson, corrector plates like that on the 48-inch Schmidt camera on Palomar Mountain required many long hours of skilled work by master opticians. Johnson's innovative production methods made possible the volume production of a complex and formerly expensive optical component, triggering the SCT revolution of the 1970s.

For more than forty years, the SCT satisfied the needs of visual observers and astrophotographers. Its performance resulted from a blend of smooth spherical surfaces and Johnson's unique method of producing the complex curve on the corrector with the same ease as producing spherical surfaces. As the 21st century began, two emerging technologies —wide-field eyepieces and CCD cameras—demanded high-quality images over a much wider field of view than the classic SCT could provide. Why? The classic SCT is well-corrected optically for aberrations on the optical axis, that is, in the exact center of the field of view. Away from the optical axis, however, its images suffer from two aberrations: coma and field curvature. Coma causes off-axis star images to flare outward; field curvature causes images to become progressively out of focus away from the optical axis. As wide-field eyepieces grew in popularity, and as observers equipped themselves with advanced CCD cameras, the classic SCT proved inadequate. To meet the requirements of observers, we wanted the new Celestron optic to be both free of coma and to have virtually zero field curvature.

## EdgeHD Series

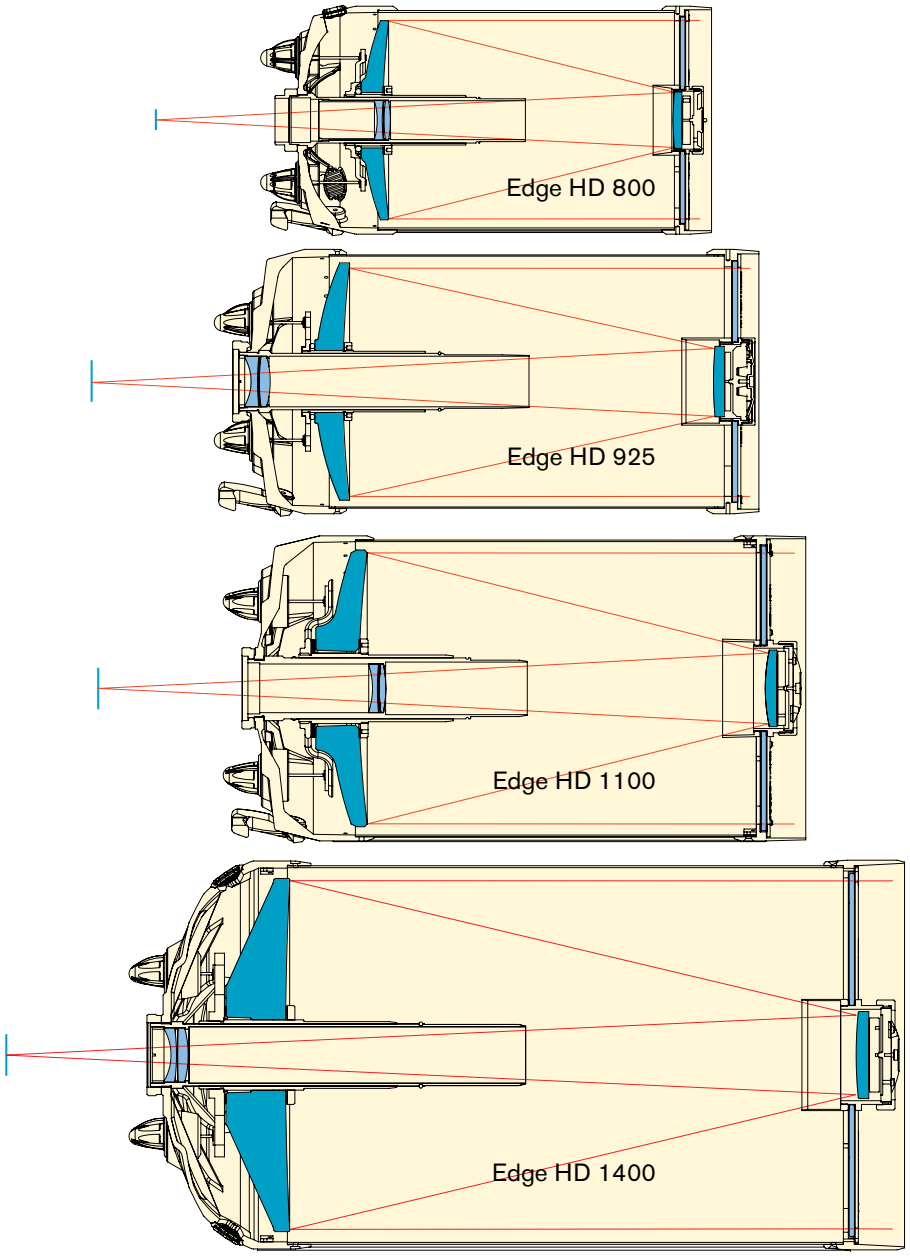


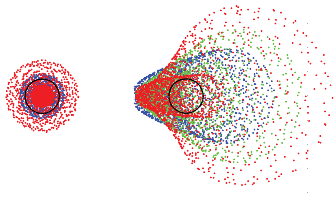

**FIGURE 1.** Celestron's EdgeHD series consists of four aplanatic telescopes with 8-, 9.25-, 11-, 14-inch apertures. The optical design of each instrument has been individually optimized to provide a flat, coma-free focal plane. Each EdgeHD optic produces sharp images to the edge of the view with minimal vignetting.

## OPTICAL ABERRATIONS

For those not familiar with the art of optical design, this brief primer explains what aberrations are and how they appear in a telescopic image.

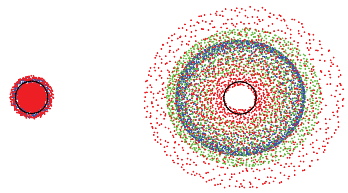
## OFF-AXIS COMA

Coma is an off-axis aberration that occurs when the rays from successive zones are displaced outward relative to the principal (central) ray. A star image with coma appears to have wispy "hair" or little "wings" extending from the image. In a coma-free optical system, rays from all zones are centered on the (central) ray, so stars appear round across the field



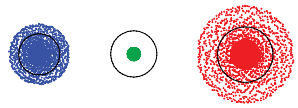
## FIELD CURVATURE

Field curvature occurs when the best off-axis images in an optical system focus ahead or behind the focused on-axis image. The result is that star images in the center of the field of view are sharp, but off-axis images appear more and more out of focus. A telescope with no field curvature has a "flat field," so images are sharp across the whole field of view.



## SPHEROCHROMATISM

In the Schmidt-Cassegrain, spherochromatism is present, but not deleterious in designs with modest apertures and focal ratios. It occurs because the optical "power" of the Schmidt corrector plate varies slightly with wavelength. Only in very large apertures or fast SCTs does spherochromism become a problem.



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## 3. ENGINEERING A NEW ASTROGRAPH

We did not take lightly the task of improving the classic SCT. Its two spherical mirrors and our method of making corrector lenses allowed us to offer a high-quality telescope at a low cost. We investigated the pros and cons of producing a Ritchey-Chrétien (R-C) Cassegrain, but the cost and complexity of producing its hyperbolic mirrors, as well as the long-term disadvantages of an open-tube telescope, dissuaded us. We also designed and produced two prototype Corrected Dall-Kirkham (CDK) telescopes, but the design's ellipsoidal primary mirror led inevitably to a more expensive instrument. While the R-C and CDK are fine optical systems, we wanted to produce equally fine imaging telescopes at a more consumer-friendly price.

As we've already noted, our most important design goal for the new telescope was to eliminate coma and field curvature over a field of view large enough to accommodate a top-of-the-line, full-frame digital SLR camera or larger astronomical CCD camera. This meant setting the field of view at 42 mm in diameter. Of course, any design that would satisfy the full-frame requirement would also work with the less expensive APS-C digital SLR cameras (under $800) and less expensive astronomical CCD cameras (under $2,000). There are several ways to modify the classic SCT to reduce or eliminate coma. Unfortunately, these methods do not address the problem of field curvature. For example, we could replace either the spherical primary or secondary with an aspheric (i.e., non-spherical) mirror. Making the smaller secondary mirror into a hyperboloid was an obvious choice. Although this would have given us a coma-free design, its uncorrected field curvature would leave soft star images at the edges of the field. We were also concerned that by aspherizing the secondary, the resulting coma-free telescopes would potentially have zones that would scatter light and compromise the high-power definition that visual observers expect from an astronomical telescope. Furthermore, the aspheric secondary mirror places demands on alignment and centration that often result in difficulty maintaining collimation.

The inspiration for the EdgeHD optics came from combining the best features of the CDK with the best features of the classic SCT. We placed two small lenses in the beam of light converging toward focus and re-optimized the entire telescope for center-to-edge performance. In the EdgeHD, the primary and secondary mirrors retain smooth spherical surfaces, and the corrector plate remains unchanged. The two small lenses do the big job of correcting aberrations for a small increment in cost to the telescope buyer. Furthermore, because it retains key elements of the classic SCT, the EdgeHD design is compatible with the popular Starizona Hyperstar accessory.

## THE OPTICAL PERFORMANCE OF THE EDGEHD COMPARED TO OTHER SCTS

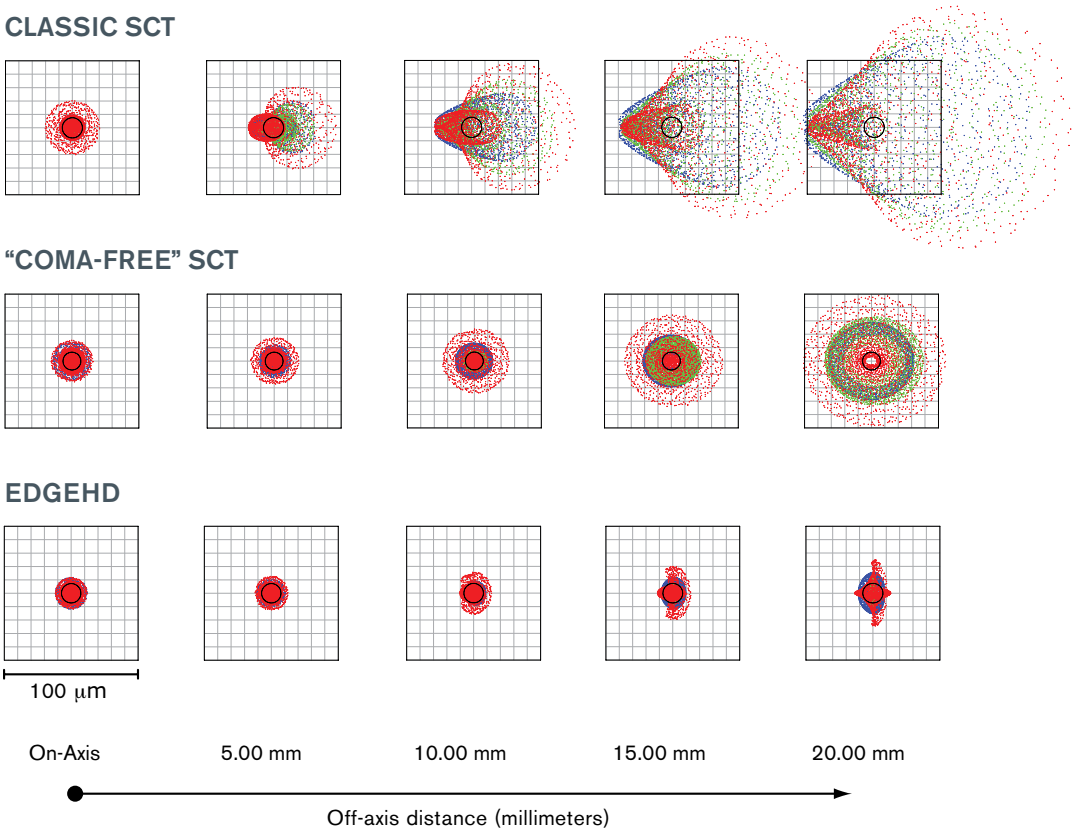



**FIGURE 2.** Matrix spot diagrams compare the center-to-edge optical performance of the classic SCT, "coma-free" SCT, and EdgeHD. The EdgeHD clearly outperforms the other optical systems. The classic SCT shows prominent coma. The "coma-free" SCT is indeed free of coma, but field curvature causes its off-axis images to become diffuse and out of focus. In comparison, the EdgeHD's spot pattern is tight, concentrated, and remains small from on-axis to the edge of the field.

## 4. OPTICAL PERFORMANCE OF THE EDGEHD

Optical design involves complex trade-offs between optical performance, mechanical tolerances, cost, manufacturability, and customer needs. In designing the EdgeHD, we prioritized optical performance first: the instrument would be diffraction-limited on axis, it would be entirely coma-free, and the field would be flat to the very edge. (Indeed, the name EdgeHD derives from our edge-of-field requirements.)

Figure 2 shows ray-traced spot diagrams for the 14-inch aperture classic SCT, coma-free SCT, and EdgeHD. All three are 14-inch aperture telescopes. We used ZEMAX® professional optical ray-trace software to design the EdgeHD and produce these ray-trace data for you.

Each spot pattern combines spots at three wavelengths: red (0.656µm), green (0.546µm), and blue (0.486µm) for five field positions: on-axis, 5mm, 10mm, 15mm, and 20mm off-axis distance. The field of view portrayed has diameter of 40mm—just under the full 42mm image circle of the EdgeHD—and the wavelengths span the range seen by the dark-adapted human eye and the wavelengths most often used in deep-sky astronomical imaging.

In the matrix of spots, examine the left hand column. These are the on-axis spots. The black circle in each one represents the diameter of the Airy disk. If the majority of the rays fall within the circle representing the Airy disk, a star image viewed at high power will be limited almost entirely by diffraction, and is therefore said to be diffraction-limited. By this standard, all three SCT designs are diffraction-limited on the optical axis. In each case, the Schmidt corrector removes spherical aberration for green light. Because the index of refraction of the glass used in the corrector plate varies with wavelength, the Schmidt corrector allows a small amount of spherical aberration to remain in red and blue light. This aberration is called spherochromatism, that is, spherical aberration resulting from the color of the light. While the green rays converge to a near-perfect point, the red and blue spot patterns fill or slightly overfill the Airy disk. Numerically, the radius of the Airy disk is 7.2µm, (14.4µm diameter) while the root-mean-square radius of the spots at all three wavelengths is 5.3µm (10.6µm diameter). Because the human eye is considerably more sensitive to green light than it is to red or blue, images in the eyepiece appear nearly perfect even to a skilled observer.

Spherochromatism depends on the amount of correction, or the refractive strength, of the Schmidt lens. To minimize spherochromatism, high-performance SCTs have traditionally been *f*/10 or slower. When pushed to focal ratios faster than *f*/10 (that is, when pushed to *f*/8, *f*/6, etc.) spherochromatism increases undesirably.

Next, comparing the EdgeHD with the classic SCT and the "coma-free" SCT, you can see that off-axis images in the classic SCT images are strongly affected by coma. As expected, the images in the coma-free design do not show the characteristic comatic flare, but off-axis they do become quite enlarged. This is the result of field curvature.

Figure 3 illustrates how field curvature affects off-axis images. In an imaging telescope, we expect on-axis and off-axis rays to focus on the flat surface of a CCD or digital SLR image sensor. But unfortunately, with field curvature, off-axis rays come to sharp focus on a curved surface. In a "coma-free" SCT, your off-axis star images are in focus ahead of the CCD.

At the edge of a 40mm field, the "coma-free" telescope's stars have swelled to more than 100µm in diameter. Edge-of-field star images appear large, soft, and out of focus.

Meanwhile, at the edge of its 40mm field, the EdgeHD's images have enlarged only slightly, to a root-mean-square radius of 10.5µm (21µm diameter). But because the green rays are concentrated strongly toward the center, and because every ray, including the faint "wings" of red light, lie inside a circle only 50µm in diameter, the images in the EdgeHD have proven to be quite acceptable in the very corners of the image captured by a full-frame digital SLR camera.

Field curvature negatively impacts imaging when you want high-quality images across the entire field of view. Figures 4 and 5 clearly demonstrate the effects of field curvature in 8- and 14-inch telescopes. Note how the spot patterns change with off-axis distance and focus. A negative focus distance means closer to the telescope; a positive distance mean focusing outward. In the EdgeHD, the smallest spots all fall at the same focus position. If you focus on a star at the center of the field, stars across the entire field of view will be in focus.

In comparison, the sharpest star images at the edge of the field in the "coma-free" telescope come to focus in front of the on-axis best focus. If you focus for the center of the image, star images become progressively enlarged at greater distances. The best you can do is focus at a compromise off-axis distance, and accept slightly out-of-focus stars both on-axis and at the edge of the field.

Any optical designer with the requisite skills and optical ray-tracing software can, in theory, replicate and verify these results. The data show that eliminating coma alone is not enough to guarantee good images across the field of view. For high-performance imaging, an imaging telescope must be diffraction-limited on-axis and corrected for both coma and field curvature off-axis. That's what you get with the EdgeHD, at a very affordable price.

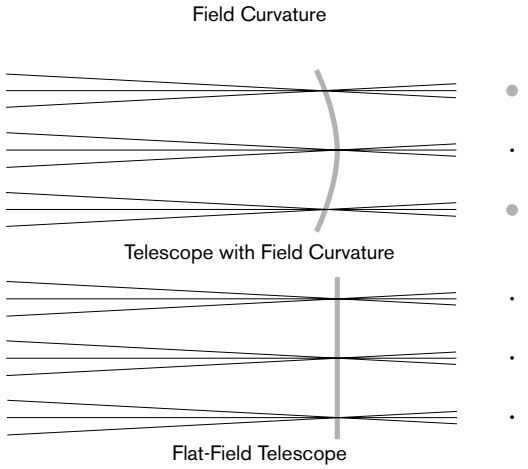



**FIGURE 3.** In an optical system with field curvature, objects are not sharply focused on a flat surface. Instead, off-axis rays focus behind or ahead of the focus point of the on-axis rays at the center of the field. As a result, the off-axis star images are enlarged by being slightly out of focus.

## 5. MECHANICAL DESIGN IMPROVEMENTS

To ensure that the completed EdgeHD telescope delivers the full potential of the optical design, we also redesigned key mechanical components. With classic SCT designs, for example, an observer could bring the optical system to focus at different back focus distances behind the optical tube assembly, changing effective focal length of the telescope. This caused on-axis spherical aberration and increased the off-axis aberration. In the EdgeHD series, the back focus distance is optimized and set for one specific distance. Every EdgeHD comes equipped with a visual back that places the eyepiece at the correct back focus distance, and our Large T-Adapter accessory automatically places digital SLR cameras at the optimum back focus position.

As part of the optical redesign, we placed the primary and secondary mirrors closer than they had been in the classic SCT, and designed new baffle tubes for both mirrors that allow a larger illuminated field of view.

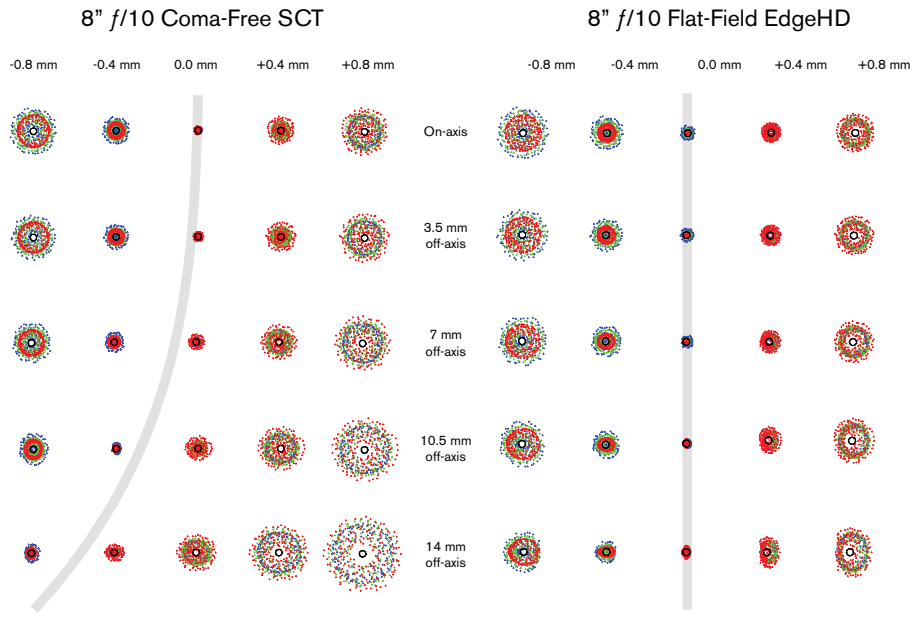
To ensure full compatibility with the remarkable Starizona Hyperstar accessory that enables imaging at *f*/1.9 in the EdgeHD 800 and *f*/2.0 in the EdgeHD 925, 1100, and 1400, all EdgeHDs have a removable secondary mirror.

Because it covers a wide field of view, the optical elements of the EdgeHD must meet centering and alignment tolerances considerably tighter than those of the classic SCT design. For example, because the corrector plate must remain precisely centered, we secure it with alignment screws tipped with soft Nylon plastic. The screws are set on the optical bench during assembly while we center the corrector plate. Once this adjustment is perfect, the screws are tightened and sealed with Loctite® to secure the corrector in position. This seemingly small mechanical change ensures that the corrector plate and the secondary mirror mounted on the corrector plate stay in permanent optical alignment.

Centering the primary mirror is even more demanding. In the classic SCT, the primary mirror is attached to a sliding "focus" tube. When you focus the telescope, the focus knob moves the primary mirror longitudinally. When you reverse the direction of focus travel, the focus tube that carries the primary can "rock" slightly on the baffle tube, causing the image to shift. In the classic SCT, the shift does not significantly affect on-axis image quality. However, in the EdgeHD, off-axis images could be affected. Because the baffle tube carries the sub-aperture corrector inside and the primary mirror on the outside, we manufacture it to an extremely tight diametric tolerance. The tube that supports the primary was redesigned with a centering alignment flange, which contacts the optical (front) surface of the primary mirror. When the primary mirror is assembled onto the focus tube and secured with RTV adhesive, this small mechanical change guarantees precise optical centration. Following assembly, the focus tube carrying the primary is placed in a test jig. We rotate the mirror and verify that the primary is precisely squared-on to ensure that the image quality expected from the optics is maintained.

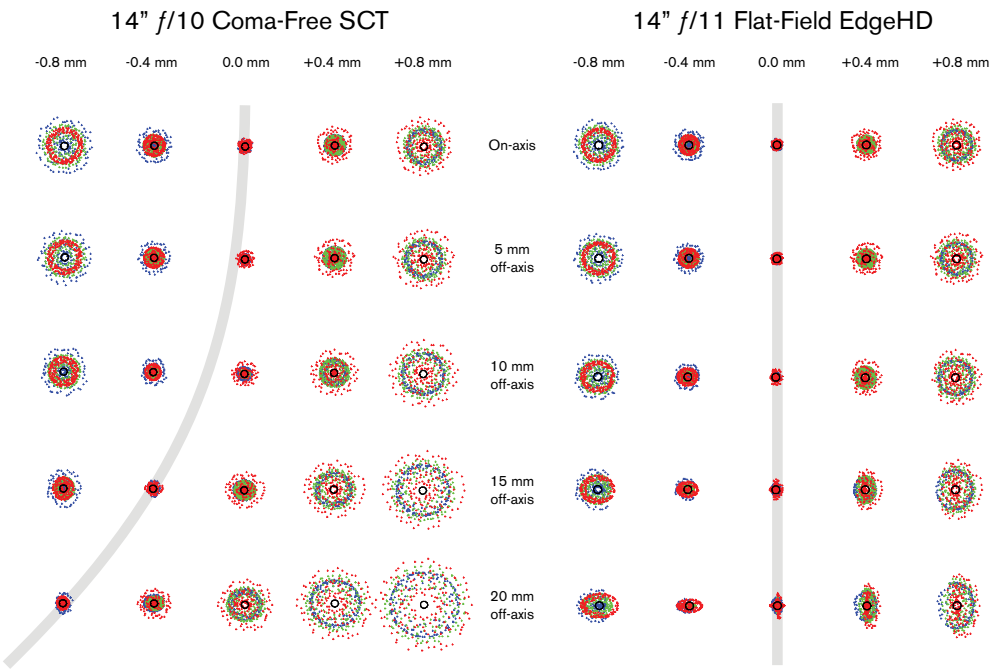
In any optical system with a moveable primary mirror, focus shift—movement of the image when the observer changes focusing direction—has been an annoyance. In Celestron's SCT and EdgeHD telescopes, we tightened the tolerances. During assembly and testing, we measure the focus shift; any unit with more than 30 arcseconds focus shift is rejected and returned to an earlier stage of assembly for rework.

In the classic SCT, astrophotographers sometimes experience an image shift as the telescope tracks across the meridian. The focus mechanism serves as one support point for the mirror. In the EdgeHD, we added two stainless steel rods to the back of the cell that supports the primary mirror. When the two mirror clutches at the back of the optical tube assembly are engaged, aluminum pins press against the stainless steel rods, creating two additional stabilizing support points (see Figure 6).




Spot diagrams plotted for 0.0, 3.5, 7, 10.5, and 14 mm off-axis; showing $\lambda = 0.486$, 0.546, and 0.656 μm.

**FIGURE 4.** Compare star images formed by a 8-inch coma-free SCT with those formed by an EdgeHD. The sharpest star images in the coma-free SCT follow the gray curve, coming to focus approximately 0.6mm in front of the focal plane. In the EdgeHD, small, tight star images are focused at the focal plane across the field of view, meaning that your images will be crisp and sharp to the very edge.




Spot diagrams plotted for 0.0, 5, 10, 15, and 20mm off-axis; showing $\lambda = 0.486$, 0.546, and 0.656μm.

**FIGURE 5**. In a 14-inch coma-free SCT, the smallest off-axis star images lie on the curved focal surface indicated by the gray line. Since CCD or digital SLR camera sensors are flat, so star images at the edge of the field will be enlarged. In the aplanatic EdgeHD design, the smallest off-axis images lie on a flat surface. Stars are small and sharp to the edge of the field.

Telescope tubes must "breathe" not only to enable cooling, but also to prevent the build-up of moisture and possible condensation inside the tube. In the classic SCT, air can enter through the open baffle tube. In the EdgeHD, the sub-aperture lenses effectively close the tube. To promote air exchange, we added ventilation ports with 60μm stainless steel mesh that keeps out dust but allows the free passage of air.

In a telescope designed for imaging, users expect to attach heavy filter wheels, digital SLRs, and astronomical CCD cameras. We designed the rear threads of the EdgeHD 925, 1100, and 1400 telescopes with a heavy-duty 3.290×16 tpi thread, and we set the back focus distance to a generous 5.75 inches from the flat rear surface of the baffle tube locking nut. The rear thread on the EdgeHD 800 remains the standard 2.00×24 tpi, and the back-focus distance is 5.25 inches.

Many suppliers offer precision focusers, rotators, filter wheels, and camera packages that are fully compatible with the heavy-duty rear thread and back focus distance of the EdgeHD.

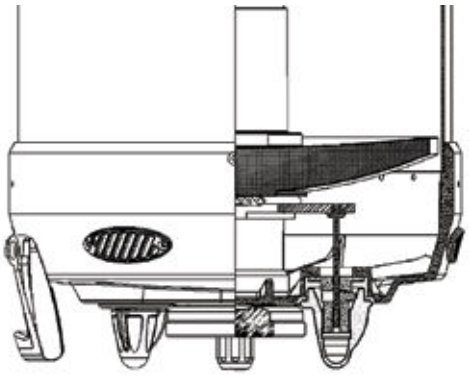


**FIGURE 6.** The mirror clutch mechanism shown in this cross-section prevents the primary mirror from shifting during the long exposures used in imaging.

## 6. MANUFACTURING THE EDGEHD OPTICS

Each EdgeHD has five optical elements: an aspheric Schmidt corrector plate, a spherical primary mirror, a spherical secondary mirror, and two sub-aperture corrector lenses. Each element is manufactured to meet tight tolerances demanded by a high-performance optical design. Celestron applies more than forty years of experience in shaping, polishing, and testing astronomical telescope optics to every one of the components in each EdgeHD telescope. Our tight specifications and repeated, careful testing guarantee that the telescope will not only perform well for high-power planetary viewing, but will also cover a wide-angle field for superb edge-to-edge imaging. Nevertheless, we don't take this on faith; both before and after assembly, we test and tune each set of optics.

Celestron's founder, Tom Johnson, invented the breakthrough process used to make Celestron's corrector plates. Over the years, his original process has been developed and refined. At present, we manufacture corrector plates with the same level of ease, certainty, and repeatability that opticians expect when they are producing spherical surfaces.

Each corrector plate begins life as a sheet of water-white, high-transmission, low-iron, soda-lime float glass. In manufacturing float glass, molten glass is extruded onto a tank of molten tin, where the glass floats on the dense molten metal. The molten tin surface is very nearly flat (its radius of curvature is the radius of planet Earth!), and float glass is equally flat.

We cut corrector blanks from large sheets of the glass, then run them through a double-sided surfacing machine to grind and polish both surfaces to an optical finish. The blanks are inspected and any with defects are discarded.

The Johnson/Celestron method for producing the polynomial aspheric curve is based on precision "master blocks" with the exact inverse of the desired curve. We clean the master block and corrector blank, and then, by applying a vacuum from the center of the block, pull them into intimate optical contact, excluding any lint, dust, or air between them, gently bending the flat corrector blank to match the reverse curve of the block. We then take the combined master block and corrector blank and process the top surface of the corrector to a polished concave spherical surface. With the corrector lens still on the master block, an optician tests the radius and figure of the new surface against a precision reference matchplate (also known as an optical test plate or test glass) using optical interference to read the Newton's rings or interference fringes, as shown in Figure 7. If the surface radius lies within a tolerance of zero to three fringes (about 1.5 wavelengths of light, or 750nm concave), and the surface irregularity is less than half of one fringe (¼–wavelength of light), the corrector is separated from the master block. The thin glass springs back to its original shape, so that the side that was against the master block becomes flat and the polished surface assumes the profile of a Schmidt corrector lens. The corrector is tested again, this time in a double-pass auto collimator. Green laser light at 532nm wavelength (green) enters through an eyepiece, strikes an EdgeHD secondary and primary mirror, passes through the corrector lens under test, reflects from a precision optical flat, goes back through the corrector to reflect again from the mirrors, and finally back to focus. Because the light passes twice through the Schmidt corrector lens, any errors are seen doubled. The double-pass autocollimation test (see Figure 9) ensures that every Schmidt corrector meets the stringent requirements of an EdgeHD optical system.



**FIGURE 7.** Matchplates use interference fringes to check the radius and smoothness of the correction. In this picture, a corrector blank is attached to a master block. The matchplate rests on top; interference fringes appear as green and blue circles. The circular pattern indicates a difference in radius.

Primary mirrors begin as precision-annealed molded castings of low-expansion borosilicate glass with a weight-saving conical back surface and a concave front surface. The molded casting is edged round, its central hole is cored, and the radius of the front surface is roughed in. Celestron grinds the front surface of primary mirrors with a succession of progressively finer diamond abrasive pellet tools using high-speed spindle machines, then transfers them to an abrasive free room where they are polished to a precise spherical surface. Each mirror is checked for both radius and optical spherical figure against a convex precision reference matchplate. When the interference fringes indicate the radius is within ±1 fringe from the nominal radius and the surface irregularity is less than one fourth of one fringe, the mirror receives a final check using the classic mirror-maker's null test familiar to every professional optican. Afterwards, every primary mirror is taken to the QA Interferometry Lab—shown in Figure 10—where the surface irregularity of each mirror is verified, via interferometer, to be within specification.

The smaller secondary mirrors are also made of low-expansion borosilicate glass. Like the primaries, the secondaries are edged and centered, then ground and polished. The secondary is a convex mirror so during manufacture it is tested against a concave precision reference matchplate to check both its radius of curvature and figure. The secondary mirrors are also brought to the QA Interferometry Lab where the radius and irregularity of each mirror is verified through interferometric measurement to assure that each one lies within specification.

When we designed the EdgeHD optical system, we strongly favored spherical surfaces because a sphere can be tested by optical interference to high accuracy in a matter of minutes. If we had specified a hyperboloidal surface for the secondary mirror, we would have been forced to use slower, less accurate testing methods that might miss zonal errors. Furthermore, coma-free SCT designs with hyperboloidal mirrors still suffer from field curvature—an aberration that we specifically wished to avoid in the EdgeHD design.

Finally, the sub-aperture corrector lenses are made using the same manufacturing techniques used for high-performance refractor objectives. The EdgeHD design specifies optical glass from Schott AG. The 8-, 9.25-, and 11-inch use N-SK2 and K10 glasses, while the 14-inch uses N-SK2 and N-BALF2 glasses. To ensure homogeneity, optical glass is made in relatively small batches, extruded in boules. The raw glass is then diamond-milled to the correct diameter, thickness, and radius. Each lens blank is blocked, ground, and polished, then the radius and figure are compared to matchplates to ensure they meet EdgeHD's tight tolerances.

Our assembly workstations resemble the optical benches used to qualify corrector plates. The primary mirror and corrector plate slip into kinematic support jigs, and we place the secondary mirror in its holder. The sub-aperture corrector lenses meet specifications so reliably that a master set is used in the assembly workstation. Laser light from the focus position passes in reverse through the optics, reflects from a master autocollimation flat, then passes back through the optics. Tested in autocollimation, the optician can see and correct surface errors considerably smaller than a millionth of an inch.

If the combined optics set shows any slight residual under-or over-correction, zones, astigmatism, upturned or downturned edges, holes, or bulges, the optician marks the Foucault test shadow transitions on the secondary mirror, then removes the secondary mirror from the test fixture and translates these markings into a paper pattern. The pattern is pressed against a pitch polishing tool, and the optician applies corrective polishing to the secondary mirror—as we show in Figure 11—until the optical system as a whole displays a perfectly uniform illumination (no unwanted zones or shadows) under the double-pass Foucault test and smooth and straight fringes under the double-pass Ronchi test. The in-focus Airy disk pattern is evaluated for roundness, a single uniform diffraction ring, and freedom from scattered light. In addition, the intra- and extra-focal diffraction pattern must display the same structure and central obscuration on both sides of focus, and it must appear round and uniform.

## EDGEHD'S CLOSE-UP ON THE PELICAN NEBULA

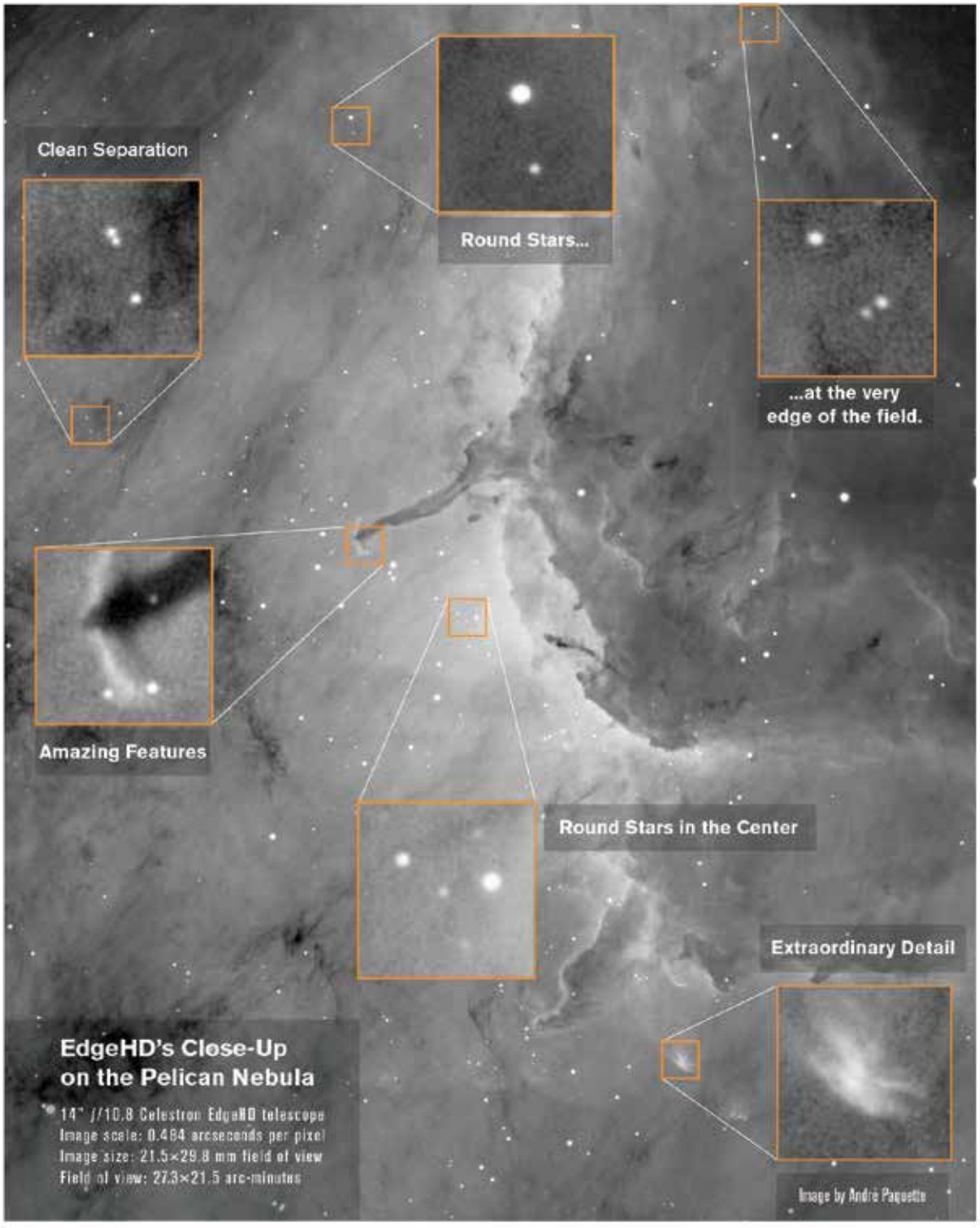



**FIGURE 8**. After all the testing is done, the ultimate test is the night sky. This close-up image of the Pelican Nebula testifies to the EdgeHD's ability to focus clean, neat, round star images from center to edge. The telescope was a 14-inch EdgeHD on a CGE Pro Mount; the CCD camera was an Apogee U16m. The mage above shows a 21.5×29.8mm section cropped from the original 36.8mm square image.

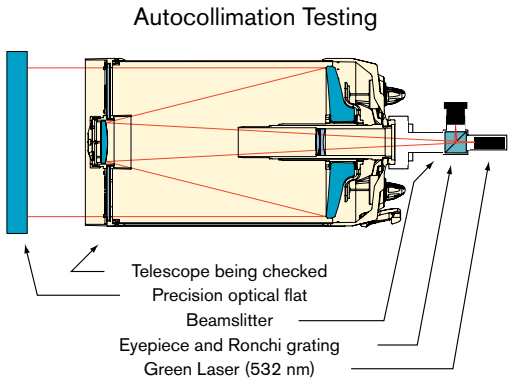



**FIGURE 9.** In autocollimation testing, light goes through an optical system, reflects from a plane mirror, and passes through again. This super-sensitive test method doubles the apparent size of all errors.



**FIGURE 10.** We test all of our primary mirrors on an optical bench by means of laser interferometry. In the picture, stacks of polished primary mirrors await testing.



**FIGURE 11.** To correct any remaining optical errors, the figure of the secondary mirror is fine-tuned against the entire optical system in double-pass autocollimation setup. This delicate match process ensures that every telescope performs to the diffraction limit.

After we remove each set of optics from the autocollimator, we send the components to our in-house coating chamber. Here, the primary and secondary mirrors receive their high-reflectance aluminum coatings, and the corrector lens is anti-reflectance coated. Each set of optics is then installed into an optical tube assembly (OTA).

Completed OTAs undergo the Visual Acceptance Test. In a temperature-stabilized optical test tunnel, green laser light at 532nm wavelength is reflected from a precision paraboloidal mirror to act as an artificial star. With a high-power ocular, a QA Inspector views the artificial star critically.

To pass the Visual Acceptance Test, an optical tube assembly must meetthe following requirements:

- The in-focus Airy disk must be round, free of scattered light around the disk, and display only one bright ring.
- Inside and outside focus, the diffraction patterns must be round, uniform, and appear similar on both sides of focus.
- Observed with a 150 line-pairs-per-inch Ronchi grating, the bands must be straight, uniformly spaced, and high in contrast.

Because its optics have been tested and tuned in error-revealing double-pass mode, and because each assembled OTA has been tested again and qualified visually, the telescope's images should be flawless when observing and imaging the night sky.

## 7. FINAL ACCEPTANCE TESTING AND CERTIFICATION

Before it can leave Celestron's facilities, every EdgeHD must pass its Final Acceptance Test, or FAT. We conduct the FAT on an optical test bench in a specially-constructed temperature-controlled room (Figure 12). Rather than use laser light for this test, we use white light so that the FAT reproduces the same conditions an observer would experience while viewing or photographing the night sky. To avoid placing any heat sources in the optical path, the light for our artificial star is carried to the focus of a precision parabolic mirror through a fiber-optic cable. After striking the parabolic mirror, the parallel rays of light travel down the optical bench to the EdgeHD under test, through the telescope, to a full-frame format digital SLR camera placed at its focus.

Using a set of kinematic test cradles, there is no need to change the test configuration between different EdgeHD telescopes. We simply place the telescope in its test cradle on the bench, and it's ready for testing. The Final Acceptance Test verifies an EdgeHD's ability to form sharp star images in the center and on the edges of a full-frame (24×36mm format, with a 42mm diagonal measurement) digital SLR camera. The QA Inspector attaches the camera to the telescope, focuses carefully, and takes an on-axis image. The telescope is then pointed so the artificial star image falls in the corner of the frame, and without refocusing, the inspector takes another image. The process is repeated for each corner of the camera frame, and another picture is taken at the center of the frame.

To pass the test, the telescope must form a sharp image at the center of the field, at each corner of the camera frame, and again at the center. The images are examined critically. To pass, every one of the test images must be tight, round, and in perfect focus. Any EdgeHD that does not pass the FAT is automatically returned to the assembly room to recheck the collimation and centering of its corrector plate. No EdgeHD can leave the factory until it has passed its FAT.

Throughout the telescope-building process, we maintain a quality-assurance paper trail for each instrument. All test images are numbered and cross referenced. Should a telescope be returned to Celestron for service, we can consult our records to see how well it performed before it left our facility. Once a telescope has passed the FAT, we apply Loctite® to the set screws to permanently hold the alignment of the corrector plate. The instrument is then inspected carefully for cosmetic defects. It is cleaned and packaged for shipment to our dealers and customers.



**FIGURE 12.** In the Final Acceptance Test, the EdgeHD optics must demonstrate the ability to form sharp images at the center and in the corners of a full-frame digital SLR camera, with a sensor that measures 42mm corner-to-corner.

## 8. VISUAL OBSERVING WITH THE EDGEHD

Because both the Celestron EdgeHD and our classic SCTs are diffraction-limited on-axis, their performance is essentially the same for high-magnification planetary or lunar viewing, splitting close double stars, or any other visual observing task that requires first-rate on-axis image quality. However, the EdgeHD outshines the classic SCT when it comes to observing deep-sky objects with the new generation of high-performance wide-field eyepieces.

The classic SCT exhibits off-axis coma and field curvature which are absent from the EdgeHD design. Modern wide-field eyepieces, such as the 23mm Luminos, have an apparent field of view of 82 degrees, so they show you a larger swatch of the sky. Gone are the light-robbing radial flares of coma and annoying, out-of-focus peripheral images so sadly familiar to observers. With the EdgeHD, stars are crisp and sharp to the edge.

The back of the EdgeHD 800 features an industry standard 2.00×24 tpi threaded flange. A large retaining ring firmly attaches the 1¼-inch visual back, and this accepts a 1¼-inch Star Diagonal that will accept any standard 1¼-inch eyepiece.

The EdgeHD 925, 1100, and 1400 feature a heavy-duty flange with a 3.290×16 tpi threaded flange. This oversize flange allows you to attach heavy CCD cameras and digital SLR cameras. For visual observing, use the adapter plate supplied with each telescope to attach the Visual Back. The 2-inch Diagonal (also supplied with these telescopes) accepts eyepieces with 1¼-inch and 2-inch barrels.

To your discerning eye—as an observer with experience—on a night with steady air and good seeing, a properly cooled EdgeHD performs exceptionally well on stars. You will see a round, clean Airy disk, a single well-defined diffraction ring, and symmetrical images inside and outside of focus. Every EdgeHD should resolve double stars to the Dawes limit, reveal subtle shadings in the belts of Jupiter, and reveal the Cassini Division in Saturn's rings. On deep-sky objects viewed with a high-quality eyepiece, star images appear sharp and well defined to the edge of the field of view. The EdgeHD reveals faint nebular details as fine as the sky quality at the observing site will allow.

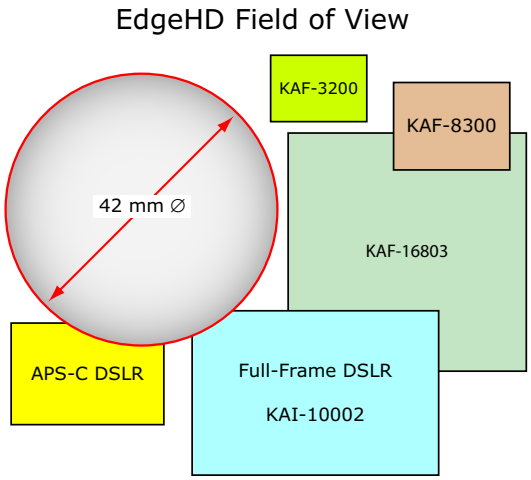



**FIGURE 13.** EdgeHD telescopes are designed to provide good images across a flat 42mm diameter field of view. Compare this with the size of a variety of image sensor formats. The popular APS-C digital SLR format fits easily. The full-frame DSLR format is fully covered. EdgeHD even covers the 36.8mm square KAF-16803 format remarkably well.

## Imaging with Celestron EdgeHD Telescopes

| EdgeHD | Aperture<br>Focal Ratio<br>Focal Length | Secondary Ø<br>Obstruction1 | Back Focus<br>Distance<br>Adapter<br>Thread Size | Image Circle<br>Linear Ø<br>Angular Ø | Airy Disk<br>Angular Ø<br>Linear Ø<br>Rayleigh[2] | Image Scale<br>arcsec/pixel<br>(6.4 µm<br>pixel) |
|---|---|---|---|---|---|---|
| **EdgeHD 800** | 203.2mm<br>ƒ/10.456<br>2125mm | 68.6mm<br>34% | 133.35mm<br>2.00"-24 tpi | 42mm Ø<br>68.0 arcmin | 1.36" Ø<br>14.0µm Ø<br>0.68" | 0.62"/pix |
| **EdgeHD 925** | 235mm<br>ƒ/9.878<br>2321mm | 85.1mm<br>36% | 146.05mm<br>3.29"-16 tpi | 42mm Ø<br>62.2 arcmin | 1.18" Ø<br>13.2µm Ø<br>0.59" | 0.57"/pix |
| **EdgeHD 1100** | 279.4mm<br>ƒ/9.978<br>2788mm | 92.3mm<br>33% | 146.05mm<br>3.29"-16 tpi | 42mm Ø<br>51.8 arcmin | 0.99" Ø<br>13.3µm Ø<br>0.50" | 0.47"/pix |
| **EdgeHD 1400** | 355.6mm<br>ƒ/10.846<br>3857mm | 114.3mm<br>32% | 146.05mm<br>3.29"-16 tpi | 42mm Ø<br>37.4 arcmin | 0.78" Ø<br>14.4µm Ø<br>0.39" | 0.34"/pix |

[1.] The Ø symbol means diameter. Central obscuration is given as a percentage of the aperture.

[2.] The Rayleigh Limit for resolving doubles with equally bright components. The " symbol means arcseconds.

## 9. IMAGING WITH THE EDGEHD

The Celestron EdgeHD was designed and optimized for imaging with astronomical CCD cameras, digital SLR cameras, video astronomy sensors, electronic eyepieces, and webcams. We designed the EdgeHD 800 to deliver the best images 5.25 inches (133.35mm) behind the surface of the telescope's rear cell 2.00×24 tpi threaded baffle tube lock nut. The EdgeHD 925, 1100, and 1400 form their best images 5.75 inches (146.05mm) behind the telescope's rear cell 3.290×16 tpi threaded baffle tube lock nut. For best results, the image sensor should be located within ±0.5mm of this back-focus distance.

It is easy to place a digital SLR (DSLR) camera at the proper distance using the Small T-Adapter (item #93644) for the EdgeHD 800, or the Large T-Adapter (item #93646) for the EdgeHD 925, 1100, and 1400. The small adapter is 78.35mm long while the large adapter adds 91.05mm, in both cases placing the best focus 55mm behind the T-Adapter. Because 55mm is the industry standard T-mount to sensor distance, add a T-Ring adapter (T-Ring for Canon EOS, item #93419; T-Ring for Nikon, item #93402) and attach your camera to it. That's all there is to placing your digital SLR camera at the correct back-focus location. (By the way, if you've never heard of the T-mount system, you need to know about it. The T-mount is a set of industry standard sizes and distances for camera lenses. A standard T-mount thread (M42×0.75) is available for most astronomical CCD cameras. The standard T-mount flange-to-sensor distance is 55mm.)

The T-mount system also makes spacing an astronomical CCD camera easy. Consult your CCD camera's documentation to find the flange-to-sensor distance for your CCD camera. Attaching the Celestron T-Adapter to your EdgeHD gives you the standard 55mm spacing. If your CCD's front flange-to-sensor distance is 35mm, you need an additional 20mm distance. A 20mm T-mount Extension Tube, available from many astronomy retailers, will help you achieve the correct back focus distance. If you require a more complex optical train for your CCD camera, consult a trusted astronomy retailer.

For imaging, we recommend using T-system components because threaded connections place your CCD camera or digital SLR at the correct back focus distance for optimum performance. Not only are they strong, but they also hold your camera perfectly square to the light path.

To mount a high-performance video camera, add the T-Adapter plus a T-to-C adapter. (Like the T-mount system, the C-mount system is an industry standard. It uses 1×32 tpi threads with a back-focus distance of17.5mm.)

For consumer video systems such as electronic eyepieces, planetary cameras, and webcams that attach to the telescope using a standard 1.25-inch eyepiece barrel, simply use the same components that you use for visual observing. Just remove the eyepiece from the telescope and replace it with the camera.

Many imaging programs allow you to shoot short exposures through the telescope. On a solid, polar-aligned equatorial mounting, you may be able to expose for 30 seconds or more. With such exposure times, you can capture wonderful images of the Moon, planets, eclipses, bright star clusters, and objects like the Orion Nebula.

However, for long exposures on deep-sky objects, you will need to guide the telescope. The days of guiding by eye are over; electronic auto-guiders are the new standard. A functional and relatively inexpensive autoguiding setup consists of a small refractor mounted piggyback on your EdgeHD telescope. You will need a dovetail bar attached to the EdgeHD tube. Celestron offers an 80mm guide telescope package (item #52309) to be used with the NexGuide Autoguider (item #93713). For sub-exposures exceeding 10 minutes or so, piggybacked guide telescopes potentially suffer from differential flexure; for such imaging, consider the Off-Axis Guider (item #93648).

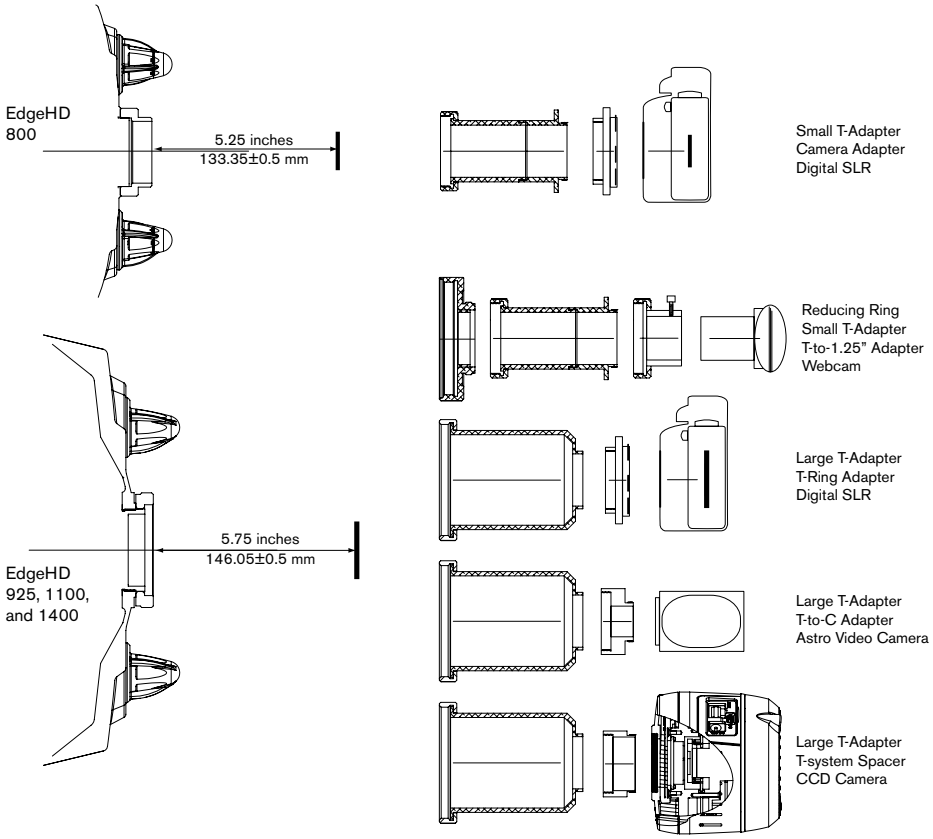



**FIGURE 14.** It is easy to position your digital SLR camera, an astronomical CCD camera, a high-performance video camera, or an inexpensive webcam at the focus plane of your EdgeHD telescope. For the sharpest wide-field imaging, your goal is to place the sensor 5.25 inches behind the rear flange of the EdgeHD 800, or 5.75 inches behind the rear flange of the EdgeHD 925, 1100, and1400.

For those who wish to make images with a faster focal ratio than EdgeHD 1100's *f*/10 or the EdgeHD 1400's *f*/11, we designed a five-element 0.7× reducer lens for each of these EdgeHD telescopes. (For more information, see Appendix B.) The Reducer Lens 0.7× for the EdgeHD 1100 is item #94241; for the 14-inch, item #94240. (The newly-released EdgeHD 800 Focal Reducer is item #94242.)

The reducer lens attaches directly to the 3.290×16 tpi threaded baffle tube lock nut on the back of the telescope. Since the back focus distance for the 1100 and 1400 reducer lens is 5.75 inches (146.05mm), you can use the same T-Adapter and camera T-Ring you would use for imaging at the *f*/10 or *f*/11 focus. The linear field of view is still 42mm diameter, but the angular field is 43% larger, and exposure times drop by a factor of two.

For super-fast, super-wide imaging, the EdgeHD telescope series supports Starizona's Hyperstar lens. Mounted on the corrector plate in place of the secondary mirror, the Hyperstar provides an *f*/1.9 focal ratio on the EdgeHD 1400, and *f*/2.0 or *f*/2.1 on the 800, 925, and 1100. Covering a 27mm diameter field of view, the Hyperstar is a perfect match for APS-C format digital SLR cameras. Because of the short focal length and fast focal ratio, sub-exposures are just a minutes. With a solid, polar-aligned equatorial mount, guiding seldom necessary.

Of course, the focal length of any EdgeHD telescope can be extended using a Barlow lens such as the Celestron 2x X-Cel LX (item #93529) or 3x X-Cel LX (item #93428). Using a Barlow, imagers can reach the desirable f/22 to f/32 range for ultra-high-resolution lunar and planetary imaging.

In summary, the Celestron EdgeHD telescopes provide a flexible platform for imaging. You can work at the normal *f*/10 or *f*/11 Cassegrain focus for seeing-limited deep-sky images or add the reducer lens for wider fields and shorter exposure times. With a Hyperstar, you can grab wide-field, deep-sky images in mere minutes. And finally, you can extend the focus to capture fine lunar and planetary images with a quality Barlow lens. When you buy an EdgeHD telescope, you're getting an imaging platform that covers all the bases, from fast, wide-field imaging to high-resolution imaging of the moon and planets.

## 10. CONCLUSION

The classic Schmidt-Cassegrain telescope introduced tens of thousands of observers and imagers to astronomy and nurtured their appreciation for the wonder of the night sky. Today, observers and imagers want a more capable telescope, a telescope that provides sharp close-ups as well as high-quality images all the way across a wide, flat field of view. But, consumers want this advanced optical technology at an affordable price.

Celestron has designed the EdgeHD to meet customers' needs. The EdgeHD is not only coma-free, but it also provides a flat field so that stars are sharp to the very edge of the field of view. In this brief technical white paper, we have shown you the inner workings of our new design. We also demonstrated the care we exert as we build and test each EdgeHD telescope. We trust that we have proven that an EdgeHD is the right telescope for you.

**You may find the following resources to be useful in learning about optical design, fabrication, and testing:**

## 11. REFERENCES


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Wikipedia. Search references to T-mount. See: http://en.wikipedia.org/wiki/T-mount and associated camera system links.

Wilson, R. N., Reflecting Telescope Optics I and II. Springer-Verlag, Berlin, 1996.

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# Appendix A:

## Technical Profiles of EdgeHD Telescopes

When evaluating astronomical telescopes, astroimagers must bear in mind the many factors that influence image quality. The major factors at play are:

- The image formed by the telescope
- The sampling by pixels of the image sensor
- The diffraction pattern of the telescope
- The "seeing" quality during exposure
- The guiding accuracy during exposure

To aid astroimagers, this Appendix presents a spot matrix plot for each of the telescopes in the EdgeHD series. To determine the size of the images that you observe in your exposures, these must be compounded with the other factors that affect your images.

In the spot matrix plots we have provided, each large gray box is 64µm on a side, and consists of a ten small boxes 6.4µm representing a pixel in a "typical" modern CCD camera. The black circle represents the diameter of the Airy disk to the first dark ring. It is immediately clear that for each of the EdgeHDs, two 6.4µm pixels roughly match the diameter of the Airy disk. This means that under ideal conditions, a CCD camera with pixels of this size will capture most of the detail present in the telescopic image. Referring to Figure A1, the left column shows the Airy disk for a telescope with a central obstruction of 34%. Because the light in the Airy disk is concentrated into a smaller area in the center, capturing all of the image detail in a planetary or lunar image requires using a 2x or 3x Barlow lens to further enlarge the Airy disk.

Unfortunately, ideal conditions are fleeting. During a typical CCD exposure, atmospheric turbulence enlarges the image of all stars, and furthermore, it causes the images to wander. On the steadiest nights, the "seeing" effect may be as small as 1 arcsecond. In Figure A1, the "superb seeing" column shows blurs with a FWHM (full-width half-maximum) of 1 arcsecond. The next column shows excellent seeing (1.5"), and the right column shows 2" seeing blurs, typical of many nights at most observing sites. It is important to note that as the focal length of the telescope increases, the diameter of the seeing blur increases in proportion. With a small telescope, seeing plays a smaller role. With the large apertures and long focal lengths of the EdgeHD series, nights of good seeing become particularly valuable.

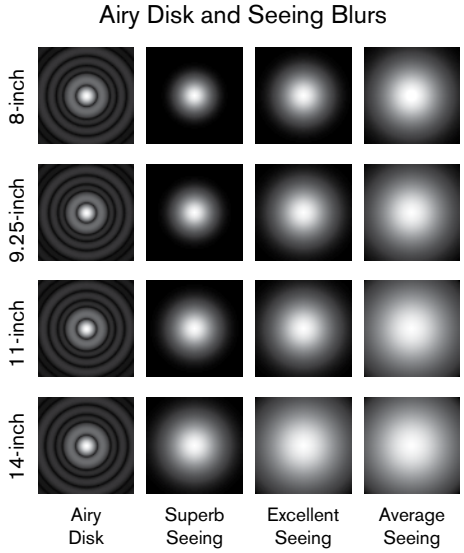
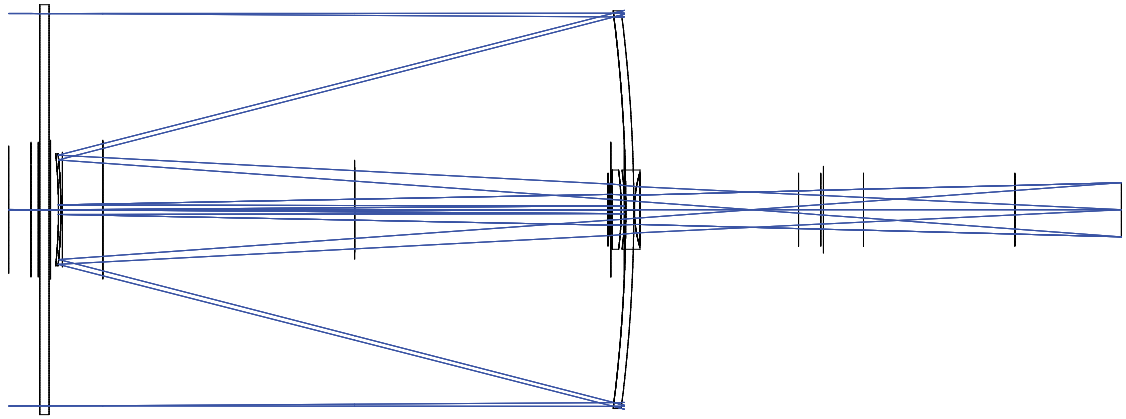
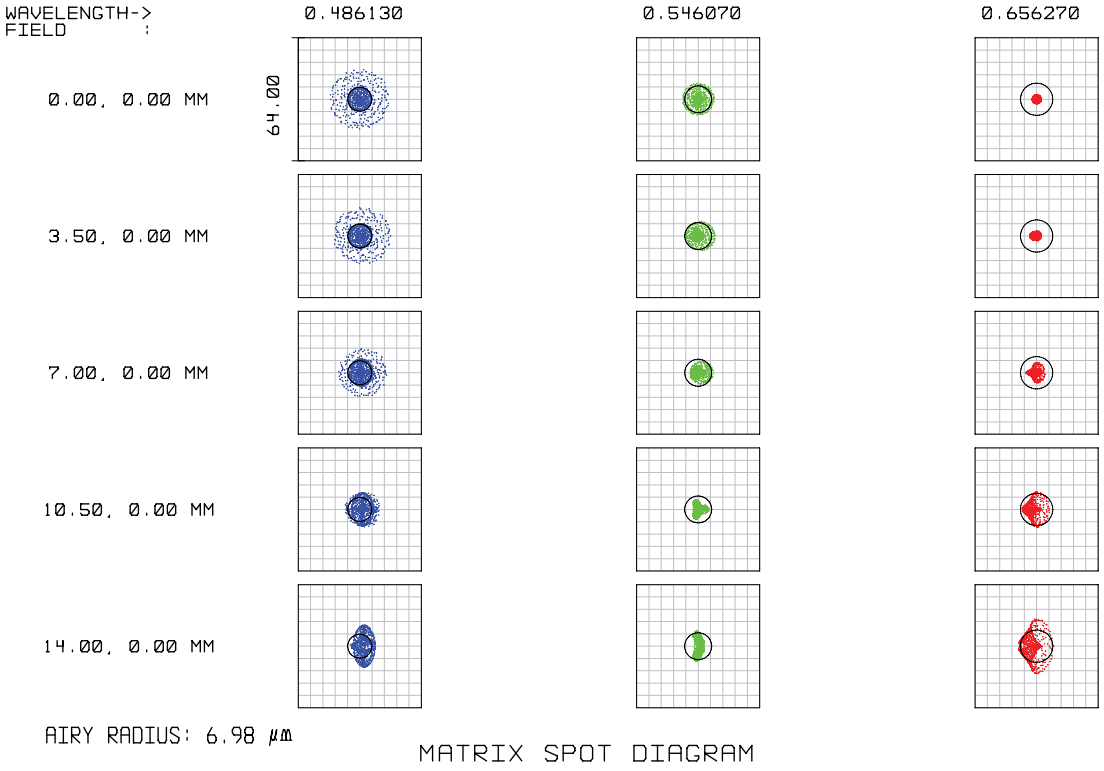



**FIGURE A1.** Shown at the same scale as the matrix spot diagrams are the Airy disk and the point-spread-function of seeing disks for average (2.0"), excellent (1.5"), and superb (1.0") seeing.

## Celestron EdgeHD 800



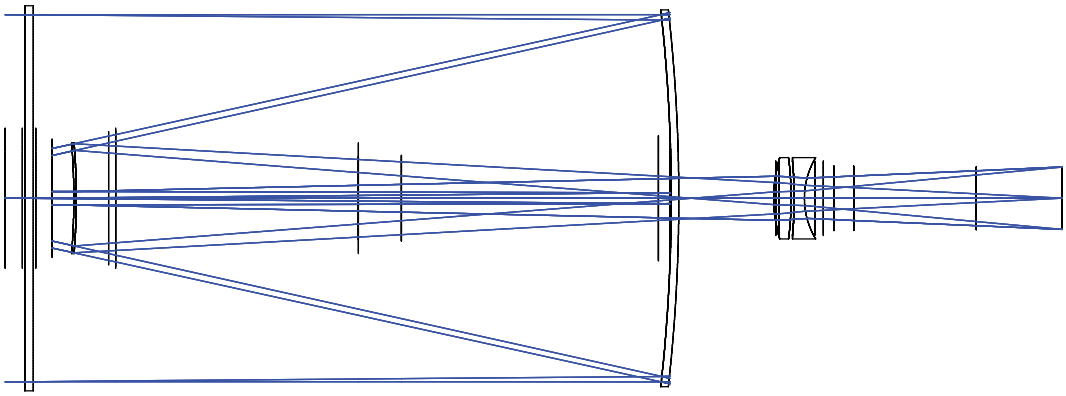


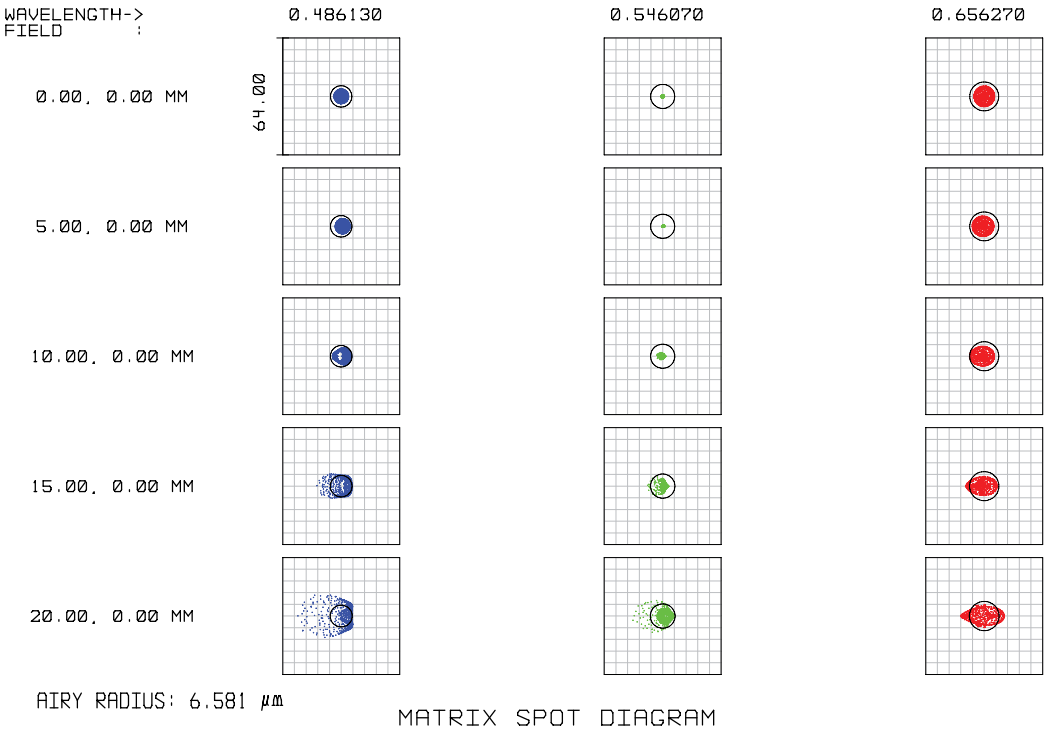

On-axis, the spots show that the 8-inch EdgeHD is diffraction-limited in both green (for visual observing) and red (for imaging). And because blue rays are strongly concentrated inside the Airy disk, the 8-inch EdgeHD is diffraction-limited in blue light. Off-axis, its images remain diffraction-limited over a field larger than the full Moon.

For an imager using an APS-C digital SLR camera, relative illumination falls to 84% at the extreme corners of the image. Although for bright subjects this minor falloff would pass unnoticed, for imaging faint objects we recommend making and applying flat-field images for the best results. For CCD imaging, we always recommend making flat field images.

Portability and affordability are the hallmarks of the EdgeHD 800. Although the 8-inch covers a 42mm image circle, we optimized its optics for the central 28mm area, the size of an APS-C chip in many popular digital SLR cameras.

## .Celestron EdgeHD 925



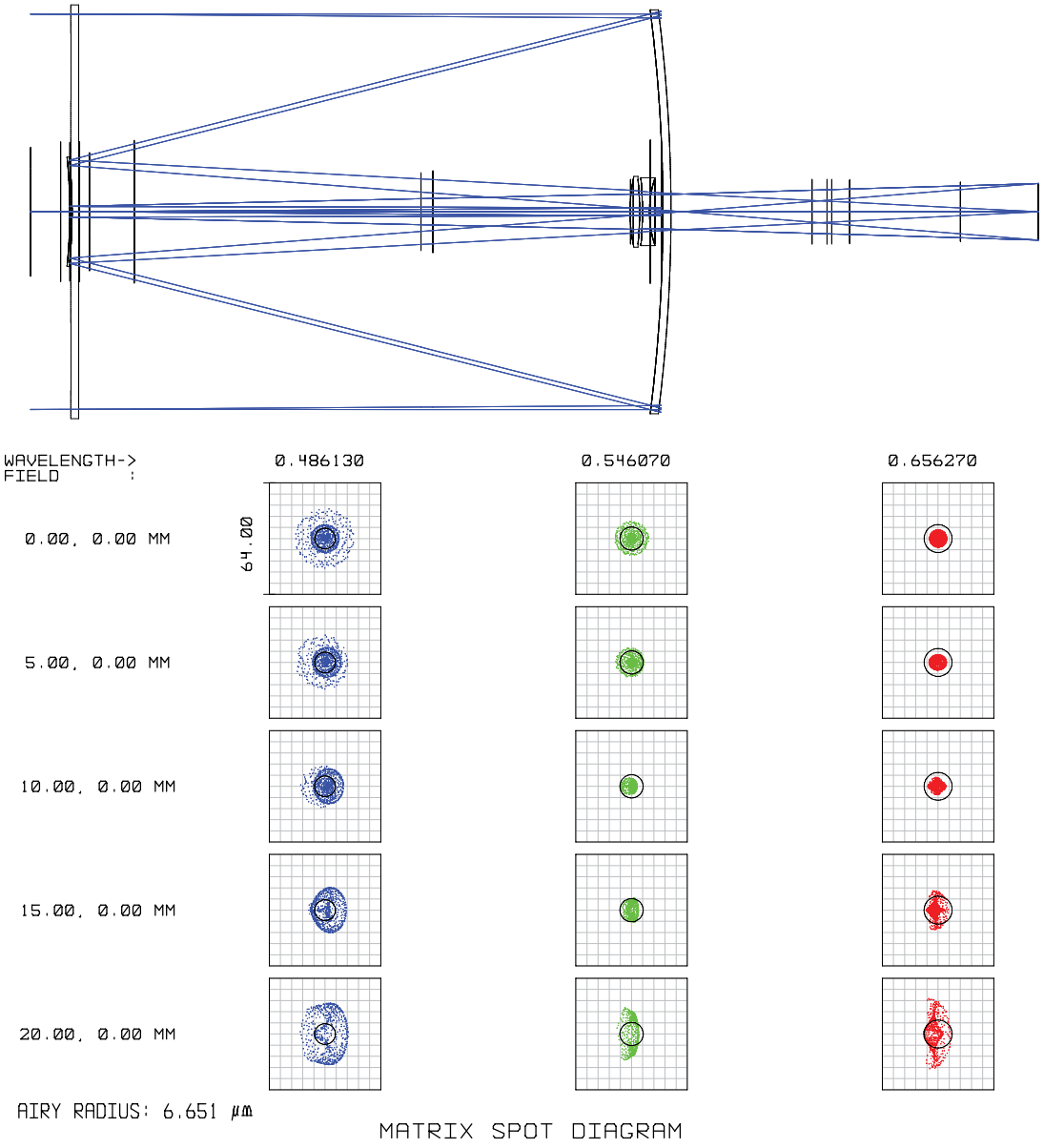



The spot matrix shows that on-axis images are diffraction limited at all three wavelengths, and remain diffraction-limited over the central 15mm. While blue and red are slightly enlarged, in green light images are fully diffraction-limited over a 38mm image circle. The size of the off-axis blue and red spots remain nicely balanced.

On a night of average seeing, stars will display a FWHM of 23µm, comparable in size to the spot pattern at the very edge of a 42mm field. Relative illumination in the EdgeHD 925 is excellent. The central 12mm is completely free of vignetting, while field edges receive 90% relative illumination. For most imaging applications, flat fielding would be optional.

For full-field imaging on a tight budget, the EdgeHD 925 is an excellent choice. It offers nearperfect on-axis performance and outstanding images over a full 42mm image circle.

## Celestron EdgeHD 1100



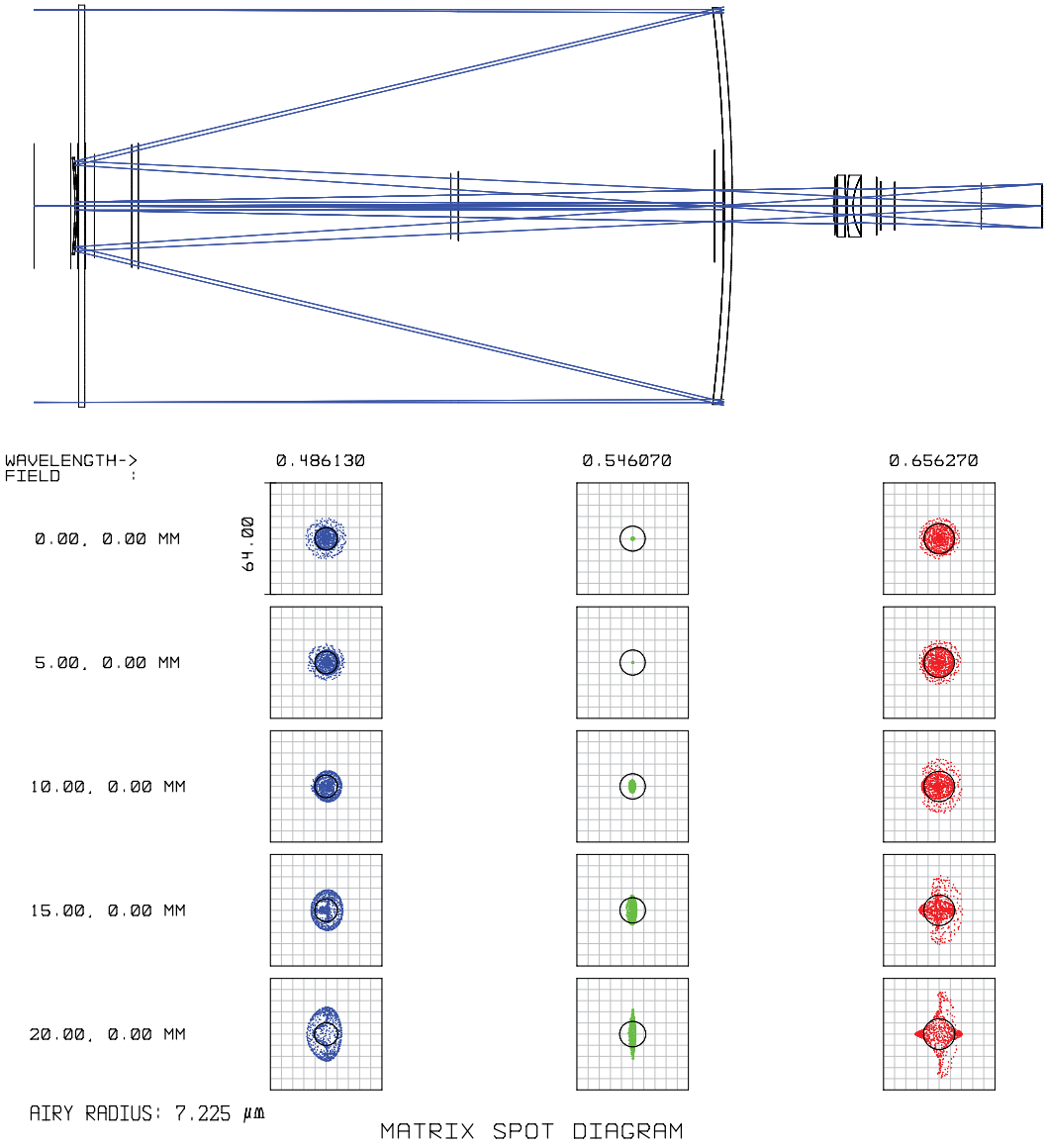

The 11-inch EdgeHD is optimized to produce its sharpest images in green and red; at these wavelengths it is diffraction-limited over roughly two-thirds of the full 42mm image circle. The relative illumination remains 100% across the central 16mm, then falls slowly to 83% at the very edge of a 42mm image circle.

For pictorial images with an APS-C digital SLR camera, flats are unnecessary. For monochrome imaging with an astronomical CCD camera, we always recommend making flat-field images.

On nights when the seeing achieves 1.5 arcseconds FWHM, star images shrink to 18µm at the focal plane. On such nights, the EdgeHD 1100 delivers fine images over a 30mm image circle, and well-defined stars over the full 42mm field.

The EdgeHD 1100 is a serious telescope. Its long focal length and large image scale give it the ability to capture stunning wide-field images of deep-sky objects with a large-format CCD camera.

## Celestron EdgeHD 1400




In the matrix spot diagrams, note the tight cluster of rays in green light, and the well balanced spherochromatism in the blue and red. These spots are far better than spots from a fine apochromatic refractor of the same aperture.

In green light, the EdgeHD 1400 is diffraction-limited over a 28mm image circle, although atmospheric seeing enables it to display its full resolution only on the finest nights. Relative illumination is 100% across the central 16mm, and falls slowly to 83% in the extreme corners of a full-frame 35mm image sensor. We have seen excellent results when the 14-inch EdgeHD is used with a KAF-16803 CCD camera over a 50mm circle.

The EdgeHD 1400 is a massive telescope, well suited to a backyard observatory or well-planned away-from-home expeditions. Its long focal length and large image scale offer skilled imagers the opportunity to make images not possible with smaller, less capable telescopes.

# Appendix B:

## TECHNICAL PROFILE OF THE EDGEHD 0.7× FOCAL REDUCER LENS

Perhaps the most useful accessory you can get for an EdgeHD telescope is a focal reducer. Although the long focal length is a great advantage in capturing detailed images of nebulae, galaxies, and especially of planetary nebulae, it also means the field of view is sometimes smaller than desirable. The relatively slow focal ratio also means rather long exposure times. We designed our 0.7× Focal Reducer to provide a field of view 1.4× larger in angular diameter, giving you twice the sky area coverage and halving the exposure time required to reach a given signal-to-noise ratio. If your passion is imaging large deep-sky objects, imaging in Hα, SII, and OIII narrowband, capturing the faint reflection nebulae often found around Barnard's dark objects, or just cutting your exposure (and guiding) times down, the focal reducer is a "must-have" item.

Back in the days of film astrophotography, focal reducers came to be poorly regarded. Although they would shorten the focal length, they also produced fuzzy star images, had bad field curvature, and suffered from severe vignetting. But the days of film and ersatz focal reducers are over. The modern EdgeHD focal reducer is the product of optical engineering and precision manufacturing on a par with the design and production of wide- and ultra-wide-field eyepieces.

We designed three EdgeHD 0.7x focal reducers, each specifically tailored to the EdgeHD 1400, 1100, and 800, respectively. The 1400 and 1100 reducers contain five precision optical elements, while the 800 contains four elements. To attain a level of performance worthy of the EdgeHD, the designs employ low-dispersion lanthanum rare-earth glass to control both chromatic and geometric aberrations. All optical surfaces are multi-layer anti-reflection coated to maximize light transmission, provide high-contrast images, and minimize image ghosting.

The matrix spot diagram shows that star images on-axis are diffraction-limited in green light, while rays at all wavelengths concentrated near the Airy disk. Even at the outer edge of the 42mm image circle, green and blue rays are clustered tightly, while red shows only a weak flare.

Both physically and mechanically, the 0.7× Reducer Lens is more than comparable to a top-of-the-line wide-field eyepiece. The CNC-machined housing easily supports the full weight of your CCD camera or digital SLR camera without sag or movement. And for safe storage, each unit is provided with threaded metal covers for both the front and the back.

The EdgeHD 0.7× Focal Reducer

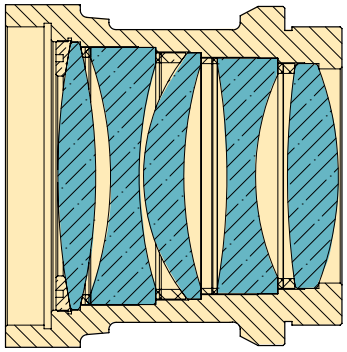
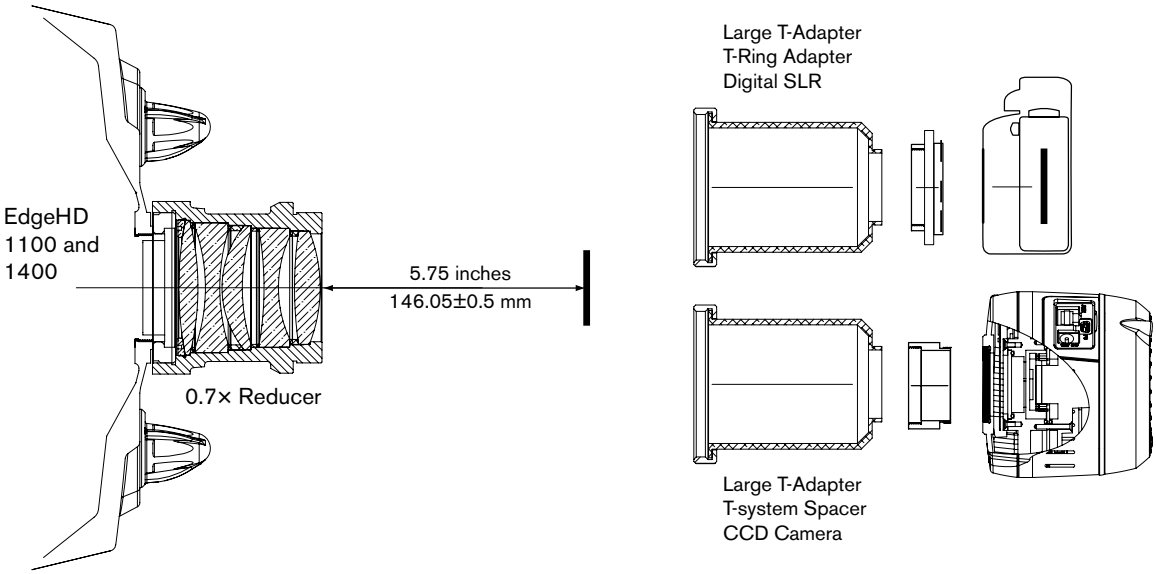
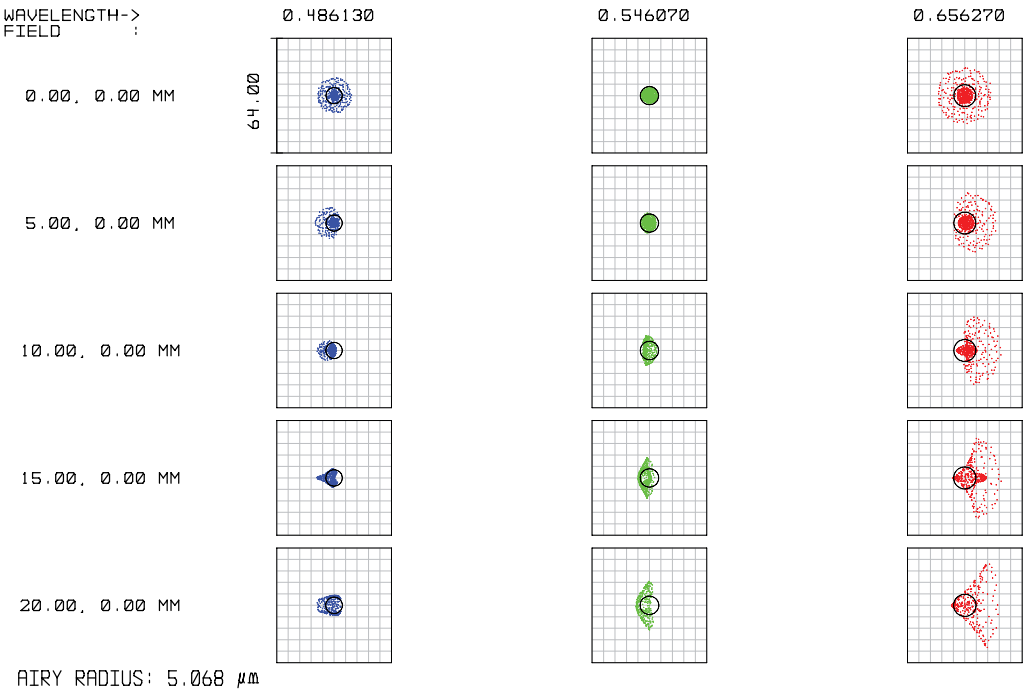


**FIGURE B1.** The EdgeHD 0.7x Focal Reducer shortens the focal ratio of the of the EdgeHD 1400, 1100 and 800 while maintaining sharp images across the full field. This enables CCD imagers to reach the same signal-to-noise ratio on extended objects in half the exposure time, and brings even the faintest deep-sky objects within the range of your high-end digital SLR camera.

## Celestron EdgeHD 0.7× Reducer

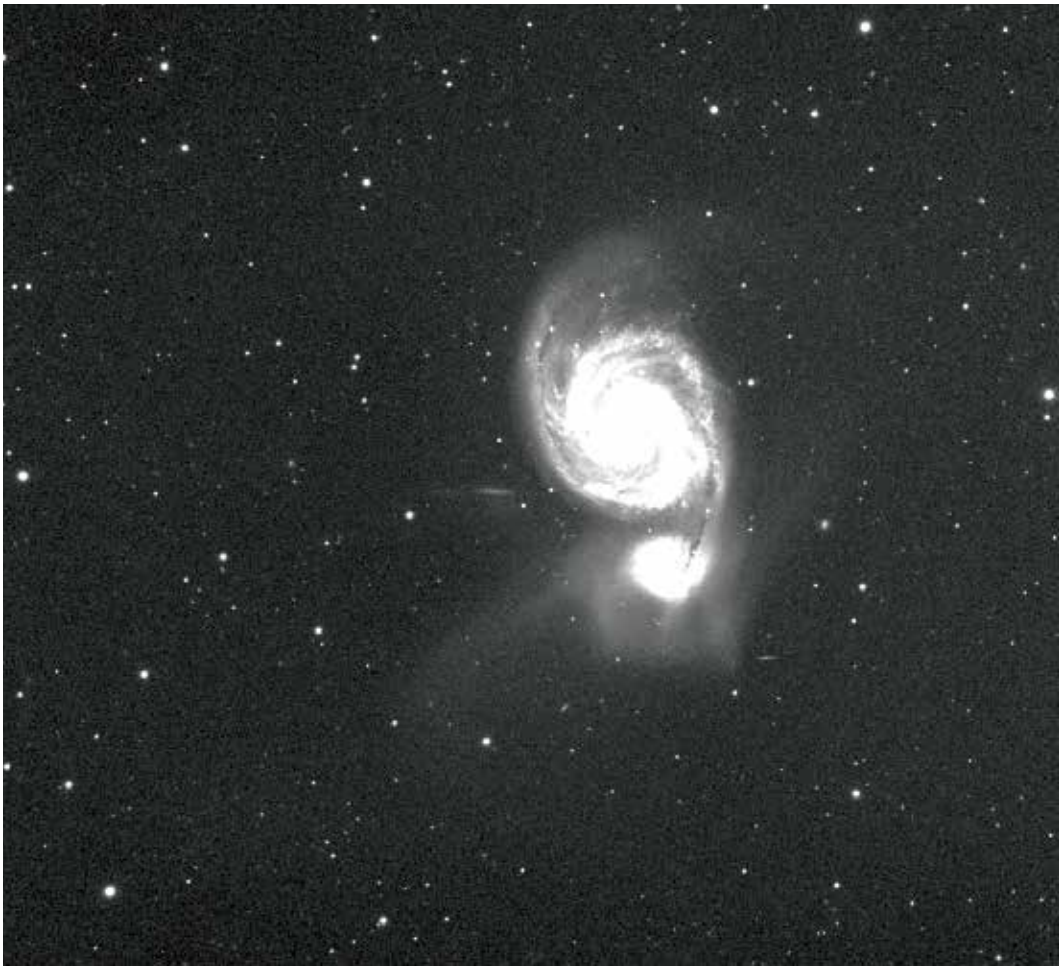



The matrix spot diagrams show that the bulk of rays cluster tightly in or near the Airy disk, with a diffuse scatter most strongly seen in the red light. Plotted at the same scale as those for the EdgeHD, the spots demonstrate that the focal reducer's star images are even smaller than those of the telescopes.

For observers who wish to pursue faint nebulae in RGB or in narrowband, the 0.7× Focal Reducer is a valuable accessory that halves the necessary exposure time with no sacrifice in resolution or image quality.

## Image by André Paquette



Imagine the thrill of seeing the first images from your Celestron EdgeHD! A quick glance at the whole image shows that you have captured your target's faint outer extensions. Across the field, from one side to the other, star images are sharp, crisp, and round. As you process your image, fine details in the target object reveal themselves. Star clouds, delicate dust lanes, subtle HII regions—it's all there, credit to your skill and the design of your EdgeHD telescope. The image shown here is a single monochrome 10-minute exposure taken with an Apogee U16 camera (KAF-16803 CCD chip) and a Celestron EdgeHD 1400 telescope on a CGE Pro mount.



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