

A Passion for Astro-Imaging

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Like many folks in the field of optics, my interest in optics began with an interest in astronomy and telescopes. This is a story of how my interest started and how after an amazing career in optics, it has come full circle to become a passion for imaging deep-sky objects in the night sky—and even more optics!

People from all over the world have discovered the satisfaction of taking their own images of the universe and I often communicate with imagers from England, Italy, Russia, China, Oman, Japan, Germany, Israel, the Philippines, Chili, Australia, Iceland, Brazil, Turkey and Norway. At one end of the spectrum is a professional astronomer who, in his spare time, specializes in producing jaw dropping wide-field images of the Milky Way. Another is a theoretical physicist who works in aerospace and who images from his backyard in Seattle. At the other end of the spectrum, there's a guy with no technical background who sells and installs hardwood flooring. He has a backyard observatory with a 24-inch telescope and he is so good at what he does in his spare time that he was among a small group of amateurs who were awarded imaging time on the Hubble space telescope by NASA. Another friend in Australia is among the small group of elite planetary imagers who have developed methods to push image resolution right up against the theoretical limits.

Amateur imagers have discovered super nova, variable nebulas, new planetary nebulas and a lot of other amazing objects. They have done synchronous imaging of the pulsar at the core of the Crab nebula to produce movies of it pulsing, and have committed to decades-long projects to make movies of the nebula expanding over time. The level of technical sophistication among amateur astronomers can sometimes reach a pretty high level.

Many College of Optical Sciences (OSC) graduates, faculty and staff have become expert imagers, contributed to the literature, and participate in amateur astronomy meetings. In fact, I ran into OSC Associate Professor Olivier Guyon at the last North East Advanced Imaging Conference (NEAIC) in 2019 where we were both speakers. Olivier is a professional astronomer who started as an amateur, and we spent some time together enjoying the camaraderie of an amateur meeting where he was recruiting participants to help discover exo-planets.

My Early Days

I first became interested in building a telescope in middle school during the mid-1960s after looking through a wobbly 3-inch reflector that my parents had given me. Back then, the Edmund Scientific catalog was my go-to place to find information about telescopes, eyepieces, and other astro-gear. I read everything I could find about telescopes and eventually joined a local astronomy club in Detroit. The Detroit Astronomical Society met every Friday in a rundown, two-story building at the edge of the Detroit Water Works park—located near downtown off a busy street leading to one of the main GM assembly plants.

Back in the '60s that park was full of drugs, violence and sketchy people—along with a bunch of astronomy club geeks looking at the moon through a long refractor mounted on a huge wooden tripod. The unwritten rule was that no one was ever to go out into the park alone and after a multiple murder happened one night while we were inside, we curtailed our night-time observing sessions. That whole scene was a real eye-opener for a kid from the burbs and I'm sure that if my parents had known more about it at the time, my optics career might have had taken a different path.

The club was run by a very smart guy with a big personality named Mr. Lloyd who would often disappear unexplained for weeks. His daughter eventually let on that he was a field agent for a government intelligence

agency, so he often had to make visits to the middle east. Members would give talks about astronomy, observing, and the best part for me—how to make a telescope.

We had rooms dedicated to grinding and polishing mirrors, and I quickly bought an 8-inch mirror kit—for about \$15. It came with a Pyrex mirror, a glass tool, all of the grades of abrasives for grinding and polishing the mirror and a couple of blocks of pitch for making the polishing lap. I must have spent six months working on that mirror before I was ready to polish the figure. I learned about how to measure the radius of curvature and how to use a knife-edge tester. That mirror eventually ended up in a telescope that I used to take my first astro-photos. It was back in the days of film so I built a little dark room in our basement where I taught myself how to process and print my first images. All of my images were guided by hand so none of them were very good, but I loved the challenge and I had a ball. I eventually built a 12.5-inch Newtonian-Cassegrain telescope and a camera that I used for lunar imaging.

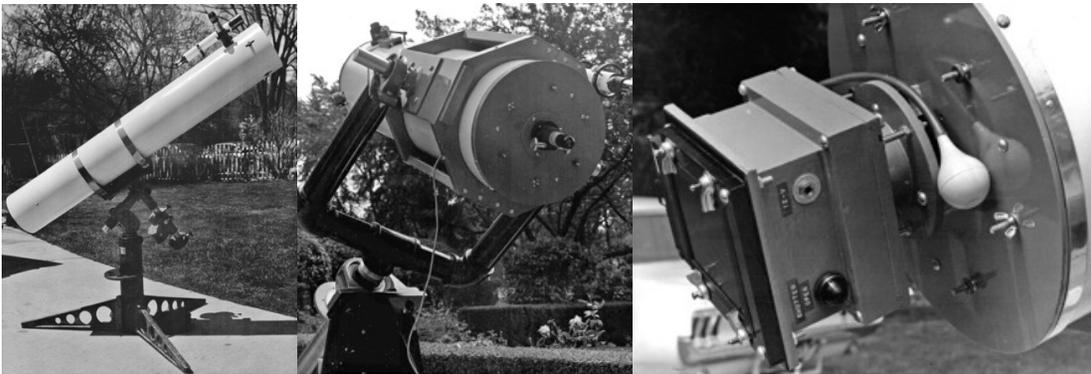


Figure 1. (Left) My first 8-inch Newtonian that I built in the mid-'60s. (Center) The 12.5-inch Newtonian/Cassegrain that I built a couple of years later. (Right) The 4 x 5-inch camera that I made. It was so difficult to use that it never saw much use. Focusing was a significant challenge. (I probably shouldn't admit it but I still have most of this old stuff!)

When it came time for college, it was the reputation of the astronomy department at the University of Arizona (UA) that pulled me away from a scholarship at the University of Michigan. After studying astronomy and physics as an undergraduate and while studying physics as a grad-student at Penn State, I came to the realization that the thing that I loved most about astronomy was the optics so I transferred back to UA to become a grad student at OSC. After getting my degree, I joined WYKO as one of Jim Wyant's partners and mostly forgot about astronomy. At WYKO, I was simply having too much fun designing interferometers, working on atomic force microscopes, and developing new automated optical metrology and processing equipment for the disk drive industry. After a couple of years at OSC as a research professor and after about five years running 4D Technology, I decided to retire. Along the way, I had founded a couple of rapidly growing aviation organizations and running those took a lot of my time so I barely had time for anything else.

My First Digital Image

We eventually moved part-time to central Oregon and at some point, my wife suggested that I bring back some of "those old telescopes sitting in the Tucson garage" for our kids to look through on sparkling summer nights. I quickly realized that it would be far better to simply buy a used, more modern telescope that wouldn't take so much work to get running. Through the classified ads on an astronomy site, I found a guy in Tucson who was selling a Celestron 14-inch Schmidt-Cassegrain Telescope along with a massive rolling pier and a motorized,

tracking equatorial *GoTo* mount, which had the ability to automatically slew to objects in the sky. We made a deal and I took it all back to Oregon. My kids came out to look through the new scope and even though I tried to show them the most interesting objects that I could find, they only lasted about 20 minutes before they had had enough. Once they left, I remembered my early astro-photos so I cobbled up a camera mount for my Canon DSLR, pointed at the Ring Nebula (M57), guessed at the focus, and took a few 30 second exposures. Whoa...that's all it took! I got a lot of color, I could see things that I couldn't see at the eyepiece, and I easily picked up the 15.7th magnitude star at the center of the nebula. That first quick effort produced an image that was easily ten times better than anything I'd ever done with film, and there wasn't any messy processing involved. Those first images weren't very good, but I was hooked.

I immediately wondered how I could improve the image quality and what it would take to get a picture of a galaxy? Up to that point, I had lost track of the technology available to amateur astronomers and I hadn't thought much about capturing images of objects so faint that they were barely visible (if at all) when viewed through an eyepiece. At the time, it also didn't occur to me just how hard it might be to produce a good image. I eventually realized that it generally takes at least a year before you begin to fully appreciate just how hard it is to get an image as good as those you see from the experts. I started with a standard DSLR camera, switched to a modified DSLR to allow more red sensitivity, and eventually moved to a high-end, scientific grade, cooled monochrome CCD camera with color filters. Along the way, I computerized the entire process from finding objects, to tracking, to focusing, to controlling the camera, and eventually to automating the entire data acquisition process so that I could go to sleep after I got it started.

How Hard Could It Be?

Getting good images out of a 14-inch scope with an effective focal length of nearly 4 meters can be challenging but I jumped in undaunted. I had spent a career building precision optical equipment so how hard could it be? It didn't take long to find out. One of the first problems is to figure out how to precisely point at an object that you can't actually see. Yes, a good telescope on a permanent pier at a known location with optical encoders tied to an accurate time source should, in principle, be able to point *exactly* where you want it; but it doesn't take long to realize that atmospheric refraction, non-perpendicularity of the optical axis to the declination axis, and mechanical flexure in the optical tube assembly can add up to significant errors that vary with the pointing angle. To accurately center on an invisible object, you've got to learn how to set up the scope so that after an initial slew, it automatically takes a frame of data, plate solves the stars in the field using a digital star catalog, and then makes a correction to precisely center on the correct coordinates. It's not all that hard, but it often takes anywhere from a few hours to as much as a week (depending on the weather) of messing around to get it all working flawlessly. As usual, there are a lot of little things such as coordinate transformations between Epochs, achieving good polar alignment, and properly orienting the image coordinates relative to the mount axis that have to be unraveled. Once that's done a lot of folks use plate solving to map the repeatable pointing errors over the whole sky into a correction table—called a pointing (or sky) model. Depending on the data density, that process can take anywhere from a couple of hours to all night—and you need a clear sky while you build the model or you've got to start all over again! (Don't ask me how I know that.) I've gone through this process many times, but for various reasons, I've never been very impressed by the results so I have given up on it and now just use plate solving for every object. Under most circumstances, basic plate solving only takes about a minute to get the telescope pointed precisely where you want it.

Other basic functions that sound trivial often turn out to be more difficult than you might realize. Take focusing for example. The standard split-image and micro-prism focusing screens on a DSLR are mostly worthless for focusing on a star, so most folks start out by focusing using a magnified image of the star on the rear LCD. Minimize the size of the star and you should be good, right? Unfortunately, it doesn't take long to discover that

simply eyeballing the best focus is a hit-or-miss proposition. Without a way to be completely sure of the correct focus, you can waste a LOT of clear-sky time producing images with soft focus and that's a common beginner mistake.

In 2005, a Russian amateur imager named Pavel Bahtinov solved the problem in a particularly elegant way using a simple diffractive optical element that now bears his name (figure 2). The Bahtinov mask simply goes over the end of the telescope (in the entrance pupil) and produces three diffracted lines in the focal plane. The figures below show what the mask looks like, along with the patterns for a defocused and a focused system. With care, it's possible to set the focus to within about 0.1 waves in the pupil.

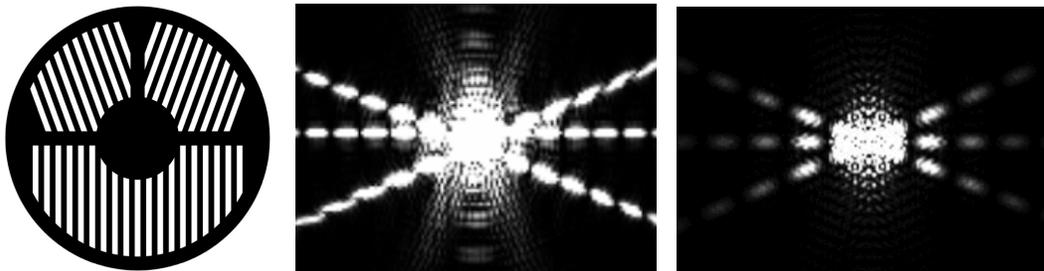


Figure 2. (Left) A Bahtinov Focusing Mask. (Center) A monochromatic diffraction calculation showing 1 wave of defocus. (Right) A diffraction calculation showing perfect focus. With only a little practice, it is pretty easy to achieve a well-centered pattern.

There are of course many other methods to achieve precise focus. The most popular is to simply take multiple exposures of a star through focus using a repeatable motorized focuser to produce a "V-curve" to establish the smallest star image and to set the best focus position. I use astigmatic focusing on my telescope. Astigmatic focusing uses a dichroic beam splitter to direct visible light to the imaging camera while passing near-IR light to a guide camera. The beam splitter produces an astigmatic image so the guide camera uses the star position for guiding and the star shape to determine focus. In this way, you get both focus magnitude and sign—all while guiding. Astigmatic focusing requires careful co-focusing of the two cameras (did I mention how useful the Bahtinov mask can be?). Once aligned and calibrated, astigmatic focusing provides precise initial focus and it allows monitoring focus during each exposure.

Most telescopes are sensitive to temperature changes so it is vital to frequently check and adjust focus. With astigmatic focusing, my scope automatically monitors and adjusts the focus in real time (every 1-2 seconds) while the shutter is open. Another new method of focusing while guiding uses full-field, spatial autocovariance monitoring but there's more to that story that I can go into here. As you work through focusing issues, you quickly realize that precision motorized focusing is a necessity for astro-imaging.

These are just two examples of some of the basic issues that need to be addressed along the path to producing high quality images. Other issues include managing the thermal stability of the telescope, preventing dew and frost, minimizing stray light, making the equipment mouse-proof (rodents love to chew through the new, environmentally friendly, soy-based cable insulating materials!), achieving perfect optical and mechanical alignment, fixing mysterious electrical noise and software issues, and getting multiple programs to work together. For example, I've learned that on my particular scope, the field imaging performance can be noticeably affected by changes in back working distance of only 100 microns! Getting everything spaced exactly right to achieve perfect image performance all the way out to a 52 mm image circle requires great care, but

that's what it takes to get nice round stars into the corners of a large sensor. Solving problems is both a part of the fun and a part of the frustration so that's where attention to detail and persistence pay off.

It's Raining Photons!

Keep in mind that when imaging faint objects, some of the photons that the camera records may have traveled unimpeded for over a **billion** years before ending their journey by crashing into the silicon in the sensor! You don't need a large aperture professional telescope to record ancient photons, but the sky doesn't exactly flood the camera with signal. It's more like a very light rain of photons. So, an interesting aspect of low light imaging is that it makes the quantum nature of light readily visible in the form of photon shot noise that can be seen in every image. The blotchy appearance apparent in faint regions is (mostly) determined by the Poisson statistics of how individual photons arrive and are recorded by the camera. That's ultimately the reason that we need to gather so much data to produce a good astronomical image. The goal is to drive the ratio of the signal to noise (SNR) to a high level. Signal grows linearly with time, and noise grows as the square root of time so SNR grows as the square root of time. That means that increasing the exposure time by a factor of four improves SNR by a factor of two.

A key problem is that every image contains the signal that we want to measure mixed in with a long list of other unwanted signals, which all contribute additional noise. Unwanted signals include dark current, bias offset, cosmic rays, satellite (and airplane) trails, stray reflections, and sky glow (mostly from back reflected ground lights). A basic characteristic of signals is that they mathematically add so we can directly subtract any unwanted signal that we can measure independently. Signal modulators include optical vignetting, radiometric (\cos^4) fall off, and PRNU (responsivity variations between pixels). Modulators mathematically multiply signals, which means that we can "divide-out" any modulators that we can measure independently (which is a process called "flat fielding"). Noise represents the **uncertainty** in the signal, which includes dark noise, read noise, quantization noise, and photon shot-noise. Noise components have the characteristic that they always add in quadrature so anytime we subtract signals or divide out modulators, we always **add** to the noise in the image.

It's the linear response of modern digital sensors that allows precise calibration, exact alignment, digital filtering, and stacking multiple images to form a linear result with a high SNR. Individual linear images taken with multiple color filters can then be processed and combined to form a color image that can be stretched (made non-linear) to show faint details. Many amateurs dive into understanding the principles of photon transfer to characterize their own sensors and to better understand how to best maximize SNR in their results. It's a pretty deep subject for those with an interest and it's one that often leads to heated discussions on astro-imaging forums.

Long exposures are generally used to ensure that photon noise is the dominant contributor in any given single image, but that approach is being challenged by modern CMOS cameras with extremely low-read noise and very high quantum efficiency. These cameras are being used with very short exposures (0.5 sec – 10 sec) to gather data over long time (2- 30 hours) to produce stunning deep-sky images that reduce some of the adverse effects of long exposures caused by guiding errors and atmospheric turbulence. This approach is called "Lucky Imaging." Since many of the popular cameras have sensors that contain 12-40 mega-pixels, this imaging approach requires **a lot** of storage space and processing time to produce an image. For that reason, it is rarely used in remote observatories where bandwidth limits would mean extra-long download times.

Processing the Data

Once you have the data, you have to process it, which is another very satisfying aspect of the hobby. Image processing is as much of an art as it is a science, and to learn it well requires a lot of reading, getting advice from

fellow imagers, attending technical seminars, and taking courses on processing techniques. At the end of the day, there's an aspect of judgment about how to best present an image with respect to color, framing, balancing detail against noise, and creating illusions of depth as an artistic presentation of scientific data. Imagers at the very pinnacle of skill produce images with amazing detail and impact—and they make it look easy. It doesn't take long to learn that this type of imaging is as far from "point and shoot" as it gets, and it's not at all unheard of to spend months or even years gathering the data needed to produce just one image. It's no wonder that the international group of serious imagers who work at the highest levels is relatively small! Most of my imaging projects are completed within a couple of months, though I've done a few in a week and a couple that took about three years.

The software required to process deep-sky data goes far beyond the capability of most general-purpose photo processing software such as PhotoShop™. Over the last 16 years, a world-class software package called PixInsight produced by a group of programmers in Spain has taken the world of deep-sky imaging by storm (<https://www.pixinsight.com>). It provides all the necessary tools to calibrate, align, filter and stack images along with an ever-growing suite of sophisticated image processing tools. At its core, PixInsight makes heavy use of wavelet transforms to allow filtering and processing data at different image scales. PixInsight is now used by most professional observatories throughout the world. Still, the tools in Photoshop and other image processing programs are often complementary to the tools in PixInsight, and most folks use multiple programs to complete an image. On its own, image processing can be surprisingly addictive and there are a number of folks who never take their own data. Some of these folks work with other imagers and many download data from the Hubble archive to process their own versions of Hubble images. Many of these images have made it into the popular press.

Everyone is a Specialist!

One thing to point out is that astro-imagers break down into three distinct groups—each with their own technology and specialized expertise. The first group is made up of the folks who specialize in imaging the sun. This specialty involves narrowband-stacked tunable filters to allow photographing solar prominences and turbulent activity on the solar surface at various atomic-lines. Hydrogen-alpha is by far the most popular. Most of these folks are using refractors up to about 150 mm aperture on equatorial mounts. Practitioners get to operate during normal hours during the daytime, and they produce images with jaw-dropping detail and amazing movies of solar activity.

The second group of imagers concentrate on solar system objects ranging from the moon to the planets, comets, and Earth-bound satellites. In order to maximize resolution under atmospheric turbulence, these folks generally use sensitive, high-speed cameras to take thousands (or more often tens of thousands) of images in one session. They then use special software to sort out the best portions of each frame to create a sharp composite image. In spite of atmospheric turbulence, the results can bump right up against the diffraction limit for the aperture used. Both Fourier and wavelet filtering can help to enhance image detail. This is a field where raw aperture and active optical systems may not have a significant advantage over the telescopes that amateurs can operate, and a few amateur images have been among the best-ever produced by Earth-based telescopes. Some of these folks produce stunning movies of the planets as they rotate. Jupiter and Mars are the prime targets for movie makers. The holy grail for lunar imaging is to achieve sub-kilometer resolution, and it's not uncommon to see that goal reached. A few planetary experts have used their skills to produce pretty high-resolution images of orbiting spacecraft—like the ISS. Damian Peach and Christopher Go are among the world's top planetary imagers and you can see their respective images here: <http://www.damianpeach.com>; <http://astro.christone.net>.

I belong to the last group of imagers who work on imaging faint, deep-sky objects (DSO) such as galaxies, planetary nebula, emission nebula, dark nebula, and wide field mosaics of large objects such as the Milky Way. Deep-sky imaging relies on gathering a lot of data in order to maximize SNR of very faint objects. Most DSO imagers operate telescopes with an aperture in the range of 100 mm – 355 mm but some folks run observatories with scopes up to around 1.7 m. Some of the most seriously-addicted folks have well over \$1M invested in their observatories and a few imagers run multiple high-end scopes all over the world! In recent years, large aperture (300 mm – 500 mm,) wide field, high speed, catadioptric telescopes in the range of F/1.9 – F/4 have become very popular because of their ability to produce very deep, wide-field images with relatively modest exposures. In fact, Dick Buchroeder (an OSC alum) helped Starizona (a local Tucson astronomy shop) develop a popular wide-field adapter for Celestron Schmidt-Cassegrain telescopes to create a modern-day wide-field, high-speed replacement for the original Schmidt camera capable of producing amazing astronomical images. Many imagers use sophisticated scientific grade CCD and CMOS large-format, low-read noise, monochrome cameras that can cool the sensor to ~55C below ambient to reduce dark noise. Most of the more sophisticated scopes are located in dark-sky locations at hosted observatories, where owners run them either remotely or where they run totally automatically.

A lot of this stuff can get pretty expensive, but don't go away with the idea that it takes barrels of money to get good results. Award winning images can be taken with very simple, relatively inexpensive equipment. Armed with the right kind of DSLR, a decent mount, high quality optics, and a little skill, many amateurs produce breathtaking images of the Milky Way and other large-scale objects. New, relatively inexpensive, high quality, cooled CMOS astro-cameras out of China are bringing high-end imaging capabilities to the masses, which is fueling new growth in the hobby.

My Equipment

I've since traded that first C14 for a totally customized C14 Edge HD system that I designed in collaboration with the folks at Celestron. It incorporates the standard Edge HD Schmidt-Cassegrain optics, which includes a field-flattener to produce a flat, well-corrected field with pinpoint stars out to a 52 mm imaging circle. I've aligned and tested the optical system with a 4D Technology PhaseCam, and the system is diffraction-limited over the full clear-aperture with an on-axis Strehl ratio of 0.92. I redesigned the factory-supplied focusing system for zero backlash and image shift so that it can be used with my "real-time" astigmatic auto-focusing system. This system uses a dichroic beam splitter to provide closed-loop star tracking in the NIR (750 nm – 1000 nm) along with a diffraction-limited auto-focus system that runs continuously—even with the shutter open during long exposures. Under good atmospheric conditions, the autofocus system maintains focus to within about 1/10 wave (in NIR.)

Thermal issues turn out to be a pretty big deal with these systems. I've done a thermal analysis of the C14 to show that it has a thermal sensitivity of about +/-0.25C (this is the temperature needed to shift focus outside the depth of focus). On nights when the air temperature drops rapidly, it is entirely possible for the telescope to go out of focus during a single exposure without real-time control. Small fans run constantly to prevent thermal gradients in the tube. These gradients are generated by differential radiative cooling of the telescope tube sitting under the cold night sky. I use a reflective thermal insulating material called *Reflectix* to minimize these effects. My scope also incorporates a homemade, automated Arduino controlled anti-dew system. It constantly monitors temperature and humidity and when dew is possible, it applies just enough heat to keep the temperature of the front of the corrector plate above the local dew point, as determined from a heat-exchange model that I developed.

The scope sits on a massive Astro-Physics 1600 German equatorial mount equipped with precision optical encoders to improve tracking and to allow finding objects very quickly (shown in figure 3). It has a pointing accuracy of about 0.5 arc-seconds and it can easily track with an accuracy of less than 0.2 arc-seconds rms under good conditions. Under the very best seeing conditions, I've achieved star images with a FWHM (full-width at half-max) as small as 1.0 arc-seconds using 20-minute exposures, although a FWHM of 1.5 arc-seconds is a more typical "good" value. The system is always seeing-limited.

The FLI-ML16803 scientific grade camera that I use has a 36 mm x 36 mm 16 Mpx monochrome CCD sensor with 9-micron pixels that can be cooled to -50C below ambient to reduce dark current. The camera has pre-flash capability to allow for calibration of residual bulk-imaging (RBI) that results from trapped charge leakage from the bulk silicon at low temperatures. Colors are obtained by imaging through precision thin-film color filters—typically luminous (L) and RGB filters along with 3 narrowband filters centered on specific bright spectral lines for hydrogen alpha, triple ionized oxygen and doubly ionized sulfur. I typically use 1200 second sub-exposures to make sure that read noise ($\sim 9e^-$) is well below other noise levels. A typical image might be processed from a combination of well over 100, 1200 second sub-images taken over many sessions. When you add up all of the additional calibration images that go into creating a single 6 MB image, there might be 3-5 GB of image data involved.



Figure 3. My custom Edge 14 HD at the Deep-Sky West Observatory in northern New Mexico. The image on the left shows the Astro-Physics 1600 German equatorial mount. The telescope itself is wrapped in *Reflectix* to minimize differential radiative cooling. The image on the right shows the camera, focusing, and guiding instruments. The main CCD imaging camera is out of view behind the large filter wheel holder seen behind the red CMOS guide camera. Small fans behind the primary mirror gently circulate air to prevent laminar thermal air currents inside the telescope tube.

My scope currently sits in a commercially-operated remote observatory located about 30 miles outside of Santa Fe, NM at an altitude of 7,400-feet where the skies are very dark and the sky quality is pretty good (figure 4). I've configured it so that I can operate it remotely from anywhere in the world through an internet connection. Once I start it, it will run automatically all night before shutting itself down at dawn. I love being out under the stars but as I've gotten older, I've almost completely lost my ability to stay up all night, so being able to get a good night's sleep while imaging is the best thing ever! I'm coming up on three years of running the scope this way and I've found that it has its own rewards—along with its own occasional special frustrations. When something breaks, I've got to make a 2,300-mile round trip service visit! Yes, there are folks at the observatory who can help with minor problems, but the more serious issues require a visit and it's a long trip out to the middle of

nowhere! It took a while to get there, but my scope is coming up on a full year without a service visit—and it's been running every clear night.



Figure 4. A view of one of the Deep-Sky West observatories in New Mexico with the roof open. All of these telescopes are remotely operated and it is quite a show as they all come to life as it gets dark each night. In this image, most of them are parked in a position to point at remotely controlled, illuminated flat panels, which are used for image calibration. (Something went wrong with that one scope in the foreground that's pointed straight up!)

What's Next?

What's next for most amateurs with "the bug" is a new, bigger/better scope, and I'm no exception. A year ago, I ordered a 0.5 m, F/6.8 CDK (corrected Dall Kirkham) professional-grade telescope to replace the 14-inch scope. Unfortunately, the sky in New Mexico isn't stable enough to support the larger aperture so a big part of the decision to go larger was wrapped up in the question of where to put it? After meeting with some folks who run a hosting observatory just to the south of the GMT site in Chile, I had the answer! The new site boasts well over 300 clear nights with median seeing conditions roughly four times better than in New Mexico—AND it's in the southern hemisphere where there's a whole new sky to explore. The annual site rental costs are comparable to New Mexico, but of course, shipping the equipment down there combined with import costs is not inexpensive. The other "little" down side is the roughly 16,000-mile round-trip required to service the equipment if something goes wrong. Fortunately, the observatory has a professional staff on site to help with problems. I am hoping that my experience in New Mexico will help me to be better prepared to run a scope in another hemisphere, but we'll see.

Before accepting the telescope from the manufacturer, I tested it using a 4D PhaseCam interferometer to demonstrate diffraction-limited optical performance (shown in figure 5). I'm now in the process of configuring and commissioning the new scope in Oregon where I've built a temporary roll-out base to test it under the skies. I'm also making modifications to use the same camera and guiding package that I currently use on the 14-inch scope, although under the very best seeing conditions, the camera may be a bit under-sampled so I may eventually have to switch to a camera with somewhat smaller pixels. The field of view will actually be slightly

bigger than the 14-inch and the signal from the 20-inch should be about 2.5 times larger than with the 14-inch scope (for extended objects). The mount uses all direct-drive motors without gears so the slew rates are quite high (~50 deg/sec) and it runs without backlash or periodic errors. Stand back when this thing is running—it will knock you silly if it hits you in the head! Each axis has optical encoders with tracking accuracy better than 0.05-inch. I am attempting to have it all running in Oregon within a month, so standby for some initial results.



Figure 5. (Left) My new 20-inch Planewave CDK telescope in my shop in Oregon on a homemade roll-out base for initial testing. The base wedge is set for the latitude of the observatory in Chile so there's an additional compensator wedge to allow polar alignment in Oregon. The whole assembly weighs about 700 lbs. (Right) The telescope being tested at the factory in double pass against a 45-inch precision Zerodur flat with a PhaseCam 6100 Dynamic interferometer.

I hope that this quick story of my interest in astro-imaging has piqued some interest in the hobby. It combines all sorts of interesting technical challenges in the areas of optics, mechanics, sensors, thermodynamics and control systems—among other things—so it's especially well-suited to anyone with a technical background who enjoys problem solving. To get started, you don't need much more than a DSLR, a little mount, and the ability to get outside at night every once in a while. Just be forewarned that it can be very addictive. You can see more of my images on my Astrobin page here: https://www.astrobin.com/users/jhayes_tucson/. And the story of my new 20-inch scope (including photos) can be found at <https://www.astrobin.com/dklko5b/E/?nc=user>. **Clear skies!**