Kurt J. Foster
Revision v1.0

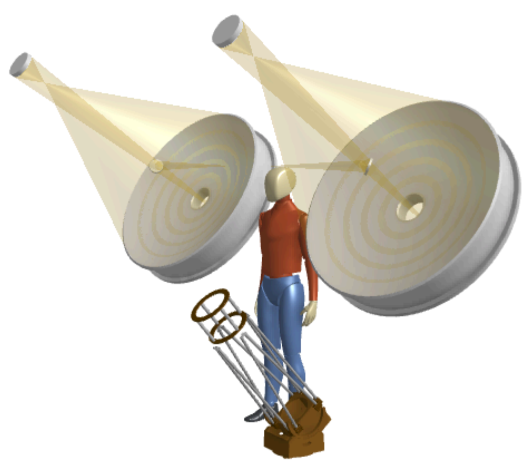
Portable Meter-class Binoculars

It's only the moment you put on your first pair of glasses that you realize how bad your sight was. It's time for a new pair of glasses in amateur astronomy—portable, meter-class binoculars.

Johnny isn't watching the late show tonight ...
The shadows that shiver and shake on the TV screen are shivering and shaking in somebody else's living room tonight. Johnny has discovered something new.
He's traded the fleeting, flickering "thrills" of the 24 inch screen for the timeless excitement and majesty of the night sky. ...
He has, in short, discovered astronomy.
Nothing better could happen than what happened to Johnny. And it happened simply because someone took the trouble to awaken, nourish and satisfy a lifetime of curiosity in Johnny by making him the gift of a fine telescope.
Someone, not so long ago, gave Johnny a Unitron.

When you're committed to something for everyone and not only for your vile self, that makes you a giant.

https://www.coursera.org/learn/first-order-optical-system-design?action=enroll
Things to keep in mind as this project progresses: Do not rush. The biggest mistake is to try and build one system with too many new, untested ideas. If multiple untested methods are put together into one system, the chance of failure increases dramatically. Test early, test often, with hopefully simple experiments.



A mock-up 1.5 meter Gregorian binoscope with associated light paths, relative to 200mm telescope. Person figure is 193cm tall.

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The purpose of this text

To provide the most optimal path toward the engineering, design, and construction of portable meter-class binoculars *and* the engineering, design, and construction of their associated manufacturing equipment.

A big goal of the text is to boil down the entire process into concrete steps, so that anyone who has the space, the tools, and the drive, can accomplish this task. *The Dobsonian Telescope* by Dave Kreige and Richard Berry, first published in 1997, outlined in simple terms how to construct a larger than average telescope, going from sizes of 12.5” to 36” diameter Newtonian reflectors. Both the 12.5” telescope design all the way to the 36” follow a very similar design and construction style. The text allows for someone to choose a wide variety of options to meet their wants and desires. It’s this format that I wish to embody as a rough source for the complete text of a different kind of telescope, *The Portable, Meter-class Binoculars*. You’ll notice my addition of the word, portable, as in Kreige’s book, portable is to be assumed since it is referring to the John Dobson style of telescope. However, with meter-class telescopes, let alone their *binocular* equivalent, are not yet assumed to be portable. That is the ultimate purpose and mission of this text, to enable the portability of this class of telescope.

Following a similar how-to outline as that of Kreige’s book will only last so long, as the complexity of meter-class binoculars are above and beyond the complexities of a single aperture 20” engineered dobsonian telescope design. This size of binoculars are an entirely separate beast that requires its own detailed approach. If the text is to be truly beneficial to the amateur telescope maker, it would allow a wide variety of sizes to be constructed, all hopefully following a similar design and construction procedure. The diameter to diameter ratio of Kreige’s telescopes described in the book is about 1:2.88, for the 12.5” to 36” sizes recommended for that design. The same ratio in comparison to my text would yield 1.25 m to 3.6 m telescopes. Although it may be possible in theory to transport a 3.6 m telescope with its large circular optical members sitting vertically, this class is so big that it’s impossible to transport this diameter while the optics is sitting flat against the floor. As the telescope gets bigger than the allowed design range, the design will sharply turn from bad to worse. Since Kreige’s telescopes go up to 36 inches, the respectable thing to do is to continue the path and start at 1 meter, which is equivalent to 39 inches in diameter, and perhaps the more relaxing approach would be to go up to a 2.5 meter size for the upper end.

- Altium CircuitMaker Free
- ARES Commander (Standalone) $950
- Autodesk AutoCAD LT $490/year
- Autodesk AutoCAD $1,975/year

- Mechanical 3D Modeling
  - PTC Onshape Free
  - SolidWorks
- Computer Aided Milling, Cutting, and Printing
  - The “Kiri:Moto” Onshape App
- FEA and CFD Analysis
  - The “SimScale” Onshape App
- Robotic Simulation
  - MATLAB+Simulink “Simscape Multibody” Onshape App $200
- Controls and Data Acquisition
  - Ignition Maker Edition Free

- Mechanical and Fabrication Tools
  - Woodworking
    - Tablesaw
    - Bandsaw
    - Router
    - Chop Saw
  - Welding Machines
    - Metal Inert Gas
    - Tungsten Inert Gas
    - Oxyacetylene
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      - How to Get Started
      - Casting Techniques
  - Grinding Machines
  - Polishing Machines
  - Test Stands

- Foucault Test Stand
  - Design
  - Build
  - Test
- Star Testing
- Wavefront Test Stand
- Interferometry

- Optical Coating Machines
  - Vapor Deposition

- Designing Large Aperture Optics
  - Introduction
  - Lightweight Optical Structure Design
    - Choosing the Best Optical Material
      - Glass and Glass-ceramic
        - Low Performance
          - Plateglass
          - Untempered
        - Medium Performance
          - Quartz
          - BOROFLOAT® 33
          - Fused Silica
        - High Performance
          - ZERODUR®
          - Ohara E6
          - CLEARCERAM®
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        - Grinding and Polishing
        - Effect of Angle and Gravity
  - Primary Mirror Cell Support Structure
    - Mirror Cell Design
    - Mirror Cell Analysis
  - Other Topics Regarding Optics
    - Adaptive Optics
- Designing the Mechanical Structure
- Design of Electronics and Automation
  - Introduction to Electrical Systems
  - Goal Functions
    - Object Tracking

Preface

This text is meant as a supplement to existing works about designing medium to large telescopes. Although there is a chapter on designing and constructing a beginner small telescope near the front of the book, it is not entirely recommended that you start with this book if you have not read anything about telescope making before. Note that I use the word, '*read*,' as in not 'made'. You can absolutely be a complete beginner when starting this, as I do orient the entirety of the work in a way that nearly anyone could follow and accomplish the tasks to a similar degree, as long as they, and you, have much persistence and also maybe some assistance. To be blunt, it's tailored for practically everyone aside from small children and people who have no idea what telescopes are. In this spirit, I wish to proceed to the central idea of this book.

Many in the community of telescope builders are called Amateur Telescope Makers, even though I beg to differ that any telescope maker is truly an 'amateur,' as many in the ATM community have been trying for decades, if not centuries, on working toward the central thesis of portable, giant, telescopes. However, at this moment in the early 2020s, there may only be less than a dozen groups *in the world* that have fully built and finished a home-ground mirror and a home-built telescope of the size of 40 to 70 inches, essentially 1.0 to 1.8 meters. As of November 2023, Mel Bartels of 'bbastrodesigns.com' lists only six on his website in this category.

Not only that, but with the advent of the Dobsonian telescope, it must now be easy to build, utilize cheap building materials, and be a joy to use. If you asked me this today, I would still agree, 'Is all this too much to ask for?' Yes, it most certainly is, especially where current technology stands. But with that said, it's imperative that when people have access to modern tools, at least some of them try to move the needle of applied technology in any meaningful direction they can. Building bigger telescopes cheaper is certainly moving the needle.

Now the goals of this book might be slightly different from the goals of the community of telescope builders. What has worked for small telescopes is simply not going to work for the big ones. What I aim for is more laborious, more time consuming, and much more difficult to implement, yet I stand behind it with full confidence. The central aim of this text is to provide you with portable, giant, binoscopes.

So why a binoscope you may ask. Of all things, the most important drawback is to wonder how smart it would be to make a telescope even more complicated than it already is. While the idea of a large binocular telescope is not novel, for instance as I am writing these words, the world's largest effective aperture of a reflecting telescope is the aptly named Large Binocular Telescope, or LBT for short, based out of the United States in Arizona. Yet to this day, more than twenty years since first light of the LBT, binoscopes are quite an enigma.

Even though binoculars have been around since the dawn of the telescope back in Galileo's day, they have defied the will to make an exciting entrance into amateur telescope making. While telescope making can be relegated into separate attitudes and ideas surrounding quality of building materials, store-bought or home-made optics, making a truss tube assembly versus cardboard tube… it's always based around a central idea, that of a cheaply or professionally made large Newtonian reflecting telescope. This idea of staying 'cheap' and keeping it 'easy,' has been the de facto reasoning for why so many ignore the prospect of even attempting a binocular telescope.

While building a large binoscope can be extremely rewarding, it is good to be aware of why the community at large doesn't attempt to tackle it. Binoculars versus monoculars of the same optical quality simply do not reason with the cost, difficulty of designing and building, the larger size, and ultimately, the fact that you must create two identical optical systems. But there's certainly something missing from this comparison.

I'd argue that comparing the two is by itself a limited perspective, and dare I mention that we should fundamentally *ignore* all comparisons. At a foundational level, they are completely different scientific instruments. Now this difference certainly fades when discussing the largest telescopes in the world, but in terms of homemade optics, the point still stands. Sure, a single telescope versus a binoscope share the same central idea, reflecting and refracting light to a point for the observer, but they both serve fundamentally separate purposes. The only way to create a true three-dimensional image with a telescope, is through creating an entire telescope for each eye. This separation between the two optical assemblies creates what's called a parallax, and allows the brain to generate an impression of depth, something that is physically impossible with a single optical path.

In the 21st century, creating a truly three-dimensional image for viewing the night-sky at large apertures is the holy-grail of visual astronomers that are amateur telescope builders.

Introduction

"If I have seen further, it is by standing on the shoulders of giants."
An expression written in a 1675 letter, from a thirty-something year old by the name of Isaac Newton.

Astronomers of home-built or store bought views are not unlike the professional ones usually located at the tops of mountains. As a matter of fact, they used to be one in the same. But even in our modern world with nearly 40-meter wide telescopes, they both hold many things in common. They both tend to stay up all night, slowly exploring the night sky with the power of an astronomical instrument commonly called the telescope. The latin of 'telescope' translates as, 'to look at a distance.' But I prefer a different translation—The telescope, for all intents and purposes, is a *time machine*. As far as we know, the speed of light is finite—precisely 299,792,458 meters per second. An object can be so far away from the observer that it can take light thousands of years for it to reach them. It just depends on how they want to travel. For now, the difference between a professional and an amateur astronomer is that the professional is there for a scientific discovery, while the sidewalk astronomer is there for the view.

This separation between that of a paid astronomer and a hobbyist may be common today, but I feel the future holds different plans. As larger amateur telescopes make their way into the public sphere, the separation may become blurred. It is the aim of myself and many others right now, to reverse the idea that the amateur astronomer and the professional are separate. It's time to bridge the gap between professional science and the hobby oriented astronomers. And to build a bridge, we're going to have to get our hands dirty.

Now let me backup for a moment, this is not to say that hobby astronomers don't do science, that's far from it. Pluto for instance, was discovered with a 13 inch wide telescope! There are now thousands of amateur astronomers with larger instruments in terms of pure light gathering power. Many of whom have discovered supernovae occurring in other galaxies, near-earth asteroids, providing endless amounts of data for exosolar planet research in terms of transit data, and variable star activity as well. The issue is the light gathering capacity of the amateur.

With that said, what may be the final frontier of the professionals, is no longer the same frontier for the amateurs. Paid astronomers strive to observe with space based telescopes and land based observatories that now span in the twenty to nearly forty-meter class of optical instruments. With one such proposal even estimating for a 100 meter wide telescope, an absolutely incredible observatory to imagine. Yet on the other hand, with amateurs, the frontier is trying to get the best out of visual astronomy.

In the end, we're all usually striving towards one thing: Getting the best view through large aperture telescopes. The amateur community loves the Newtonian reflector, and for quite a few reasons. Newtonians are simple, only one curved primary mirror and a flat secondary mirror. This makes the optics easy to align, and easy to house. The large primary mirror is usually placed in a wooden box and rocker that rotates 90 degrees, from the horizon to the zenith straight up. It's very difficult to make a telescope cheaply that's got more visual punch than that of a large Newtonian reflector, especially when built like a Dobsonian style reflector. Fairly easy to build, accessible materials, nothing too fancy, and boom, for $3,650 you get a 25 inch aperture optical instrument that provides breathtaking wide field views and a smooth guiding experience (Bartels 0.64m). And to quote the late Albert Highe, that's what it's all about, fashioning together wood, metal, and glass to turn the cosmos into visual celestial gold, curating endless memorable experiences.

However, there should be no reason to stop here. Yes, we're on good footing, perhaps better than most may realize. But on the path toward achieving the best in amateur astronomy, we must keep charging ahead, otherwise innovation stagnates. In fact, the journey has only just begun. Being able to differentiate with what has worked, and what could work, will mean the difference between completely disrupting amateur telescope making or not. It's everyone's job to question the status quo, to look at a design and think, what did they do right, and perhaps more quietly and humbly ask the inventor, what could have been done to improve it.

For instance, humans are usually born with two eyes, so why are large form factor binocular telescopes so rare? We have a lot of 10 inch, 20 inch, 30 inch, and a few 40 inch class telescopes, but why not *meter* class? If these questions make you shiver, or if this excites you to your bones, or… perhaps you are of the opinion that 'this cannot be done for amateur astronomy!' You are in the right place. Where your comfort zone is expanded, it's where it can truly thrive. Soon, you may be asking similar questions.

This type of technological change is foreign when viewed alone, but look at it from a different perspective, and suddenly it becomes inspiring. Take for instance the different step changes that have occurred in other industries. When looking at other technological disruptions throughout the world that have recently happened, one might zero in on one of the hardest problems currently being solved in rocket science: The holy grail of rocketry. The holy grail of rocketry is that of building reusable rockets that can return to the launch pad automatically and be refueled and launched again, like an airliner. Normally, orbital class rockets used to be throw-away devices, once their job was complete and the satellite was in the correct orbit, they would be designed to force themself back into the thick atmosphere of Earth and burn up in the sky upon reentry.

One day, a company called Space Exploration Technologies was incorporated, and showed up to ultimately become the world leader in reusable rockets. Commonly known today as SpaceX, they achieved world leader status in reusable rockets by having a fundamentally different perspective on it. The team asked why we don't treat rockets like we do aircraft. The engineers likened the situation to what they would do if there was a giant pile of cash that could be caught, and asked how they would catch it. Now achieving their goal would not be easy. Many in the industry thought for certain they would fail. Although success was not a likely outcome in their endeavor, it still shows what happens when you slam up against the status quo. It looks impossible, until it isn't. Today, when SpaceX lands an orbital rocket from space, most people don't even notice. SpaceX has changed the rocket game forever.

The kind of leaps that could be possible within amateur telescope making are obviously nothing of the scale of landing an orbital or interplanetary-class rocket. We deal with small circles of glass, rustic equatorial mounts and jerry-rigged light baffles. The entire hobby is known for being extremely resourceful with a minimal amount of material, time, and skill. John Dobson was an incredible guide in this way of thinking. There's nothing stopping us from combining the advances of modern observatories with the wit and style of the classical cardboard tube and porthole glass Dobsonians of the 1980s. If SpaceX achieved their impossible goals, we can achieve ours. So in the spirit of all the astronomers who have come before, and for those who will come tomorrow, it's time for the holy grail moment in amateur astronomy and amateur telescope making. It's time for portable, meter-class binoculars.

Now if that last statement doesn't sit well with you, or perhaps you were using all sorts of expletives at the words as you read them… you may have thought, "There's no way I will ever own a meter-class telescope, let alone a *portable binocular* of that size." To get to the point, you're absolutely correct. There's no way you think you will own a telescope like that today. But tomorrow, or by the time you have finished this book, I have a feeling you will have changed your mind. That's the beauty of our world today, the impossible isn't always as impossible as it initially seems.

When I started out writing this book, I thought I would be humbled back into the usual corner of small single aperture telescopes and left to such a small magnification that sticking with small aperture hand-guided astronomy would be the best use of my time. Five years later, I am now fully certain that having been in a "that's impossible" category, it's an amazing time to be alive, and I could not have been more wrong. SpaceX didn't land that first Falcon 9 rocket in 2015 by going for it in the first shot. Engineers and Technicians worked up to it. They built a rocket engine that didn't explode, then made sure it gimbaled on the test stand and still worked. They shot a rocket up with it. They then put multiple engines together and worked up until they were all functional and flight worthy. They then tested the landings, many times, failure was common. Now they stick the landing each and every time, without question. This book is no different in its journey. We will start out with simple subjects, and simple telescope ideas, and work our way up, step by step.

As you might imagine, the journey will not be easy. But I guarantee you that you're going to have a blast. Just remember that everyone has to start somewhere, and I've decided it is best to start from the beginning. In May of 2014, I knew zero about telescopes, electronics, optics, glass, you name it. As long as anyone works page by page through this text, I'd say practically anyone can understand this book. They'll be able to see where the conversation is going, learn exactly what to look out for at each step, and work through problems as they happen. At some point, you will actually end up constructing your own set of portable, meter-class binoculars. This book shows how.

However daunting some of this work may seem to the layperson, It's not my intention to be confusing. There's an Einstein saying that goes, "If you can't explain it simply, you don't understand it well enough." Although it's my intention to explain simply, sometimes it is necessary to get into the weeds and fully parse out a specific problem. It's okay if you don't understand everything the first time through. You don't need any more background than average middle school mathematics to understand this book. While there's topics discussing calculus and advanced optical engineering, you too will come to understand these subjects within this book. The way I achieve this is through practical applications and talking through each difficult topic slowly and methodically. That's part of the reason this book is so big. Building a telescope of any size is like building a pyramid, you must start on firm ground and be methodical. We'll use the tools of math, optics, and mechanics just as it should be used, *as a tool alone*, not as the end all be all. That's the power of an applied education, no more boring and endless theoretical applications. When there's a formula, you get a direct physical use of that equation, something you can physically touch. With a little wit and courage, you'll be on your way to becoming a resource others can count on, especially when building large aperture telescopes.

If you've dealt with optics before, or if you're just an all around 'get it done' type of person, it's tempting to jump ahead and go right for the gusto, on building the final project of this book. I won't beat around the bush, the final project is what's on the cover of the book, the meter-sized binoculars. But you have been warned, if you do this you will regret it. That might cut it in other books on building telescopes, and that's not to say it isn't possible that you will succeed, you very well could. But what you might still lack is the knowledge to improve upon the design, to troubleshoot problems, to repair your work of art.

Binoculars of even a few inches (less than 100mm) are mighty impressive instruments. I still get people gawking at my 20x80 Celestron Skymaster binoculars. A large pair of binos that you can wear around your neck might get more use than a jumbo pair like the one we'll embark upon. So why care about building something so big that we won't even use that often? We'll get into these situations later on and there will be a wide variety of different ways to go about solving this problem. Either through a utilization problem, or ease of use issue.

The aim is to provide permanent solutions to previously unavoidable problems. For instance, big telescopes are heavy and small binoculars are far easier to move around, so like with anything in today's world, we use the things that are more ergonomic and quicker to set up. Just grab the small binos and head outside. How would we make a large telescope achieve better ergonomics than that?

The solution to this is two-fold. With the tools at our disposal, we can provide the lightest weight optical system possible, which will maximize portability. The other aspect is that of incorporating an automatic system that can provide incredible views from the comfort of your own bed, through the use of remote astrophotography. The idea is that what limited amateur astronomers before, shouldn't be limiting factors anymore. If you're too tired to spend a night out in the cold, then roll out your telescope from the shed, set it up, then return inside to fire up your remote astrophotography system, and there you are—observing in comfort. And finally, if you did one step further and had the scope already set up, and just pressed a button to roll open the cosmos, you've just made it ergonomically easier to observe with 1.5 meter binoculars than a 1 kilogram, 10x50mm pair.

Foundations of Optical Telescopes, Basic Optics, Light

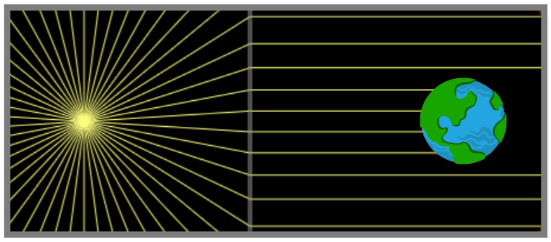
Light is simply electromagnetic radiation. When light propagates through space, it's made up of both electrical and magnetic waves. Physicists call the tiny little packets of this light, photons, an elementary particle that is completely massless.

In order to build telescopes, opticians and amateur telescope makers use ray tracing in order to help them understand from a symbolic view what is happening within the optical system. As light traverses through different types of mediums, either a vacuum like in outer space, or through air, the speed of that light is changed relative to the medium. The ratio that is used to determine different speeds through a medium is called the refractive index, and can be determined with the following formula:

$$Refractive\ index\ = \frac{speed\ of\ light\ in\ a\ vacuum}{speed\ of\ light\ in\ the\ medium}$$

Since the speed of light is constant, as the refractive index increases, the speed in the medium decreases. A simple visualization can be seen here with a single ray of light changing speed upon interacting with a different medium.

In terms of how light rays from distant objects can be manipulated to form images at an eyepiece, consider the drawing from figure 3. In the left side of the figure, a star is at an unknown distance from Earth. Since the star is so far away, once the light rays reach the surface of Earth, the light rays become extremely parallel. This gray divider is representative of the separation between the objects' large distance from each other. Optically speaking, since it is so far away, we'll denote this star to be at an 'infinite' distance to the observer. This is due to the incredibly tiny angular separation between the individual light rays.



Designing Meter-class Binoscopes, Introduction, Optical Background for Meter-class, Available Systems

Currently, as of the early 2020s, there are no such systems available on the market for meter-sized binoculars. The largest available are sub-18 inch diameter reverse Newtonian reflectors and Apochromatic refractors. This is less than half the desired aperture diameter for our purposes. Although you may run across the occasional home-made binocular system that exceeds these dimensions, they are extremely rare and are one-of-a-kind. This lack of availability to the amateur is tough for researching available systems on the market. For the builder of such large binocular systems, this should be kept in mind as they progress through the development process. At the moment, it appears to be a difficult level to excel at.

Moreover, optical systems at the meter level and above are usually regarded as observatory grade systems, and therefore are engineered to that specification. It's highly unusual for amateur astronomers to build meter-class telescopes, and while the amateur astronomer doesn't exactly require the level of capability of observatory grade optics, if the ability is possible it shall be attempted by the designer and builder.

Case in point, take PlaneWave Instruments' Corrected Dall-Kirkham (CDK) 1 meter aperture PW1000 Observatory System, generally regarded as one of the best-in-class observatory grade optical systems. While it's an incredible machine, it's priced well outside the range of amateur astronomers at $575,000. Although steep, it's very reasonable for the technical capabilities. It's unique in its ability to rotate the Nasmyth tertiary to either side of the axis of rotation within ten seconds. It contains light weight fused silica optics, direct drive motors and encoders, and a compact Alt-Az mount to name a few.

The only major downside I have found from this telescope is the rather large central obstruction. The obstruction area comes in steep at 47% of the area of the primary mirror. This translates to a 47cm (18.5 inch) wide disk that is covering the available view. Not small when considering many telescope makers find 18 inch apertures to be quite capable of supplying an impressive view of the cosmos. While optical quality from PlaneWave is some of the best you can achieve at this size, achieving pin-point stars across a 100mm image circle, the visual capability of such a device is relegated to long term exposures, measuring in hours, which is what the observatory is specifically tailored for. If one were to use it for visual astronomy, the contrast of images would not appear as bright as you might expect for this size of mirror.

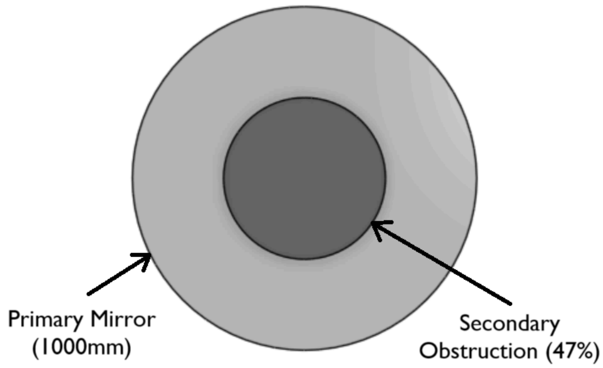


Fig. 1 Central obstruction visualization for the PW1000, a 1 meter observatory telescope.

To account for this specific issue, that is, having the goal of increasing the total contrast for the visual observer, we'll have to decrease the total obstruction area. This can be remedied by either one of two things. First, we could increase the focal length of the primary mirror, enabling the secondary to capture the light cone further out in the optical tube. This would end up decreasing the needed size of the secondary mirror, but it would increase the overall magnification capability, a difficult tradeoff to choose from. However, doing this also increases the total length of the optical tube assembly, making portability even more difficult. A PlaneWave customer of the 1 meter observatory wouldn't need to worry about portability like the amateur telescope maker would. This brings us to the second idea, which seems to have interesting tradeoffs for the portable meter-class telescope builder.

The other idea is simple, and it has everything the visual astronomer would want, and also everything the astrophotographer and portable observatory would want as well; a miniscule visual obstruction at 12.5% of the primary, and a short optical tube length. The difficulty is in the implementation of building it. For instance, it requires a substantially low focal ratio for the primary mirror, at sub f/1.2. The benefits of success, however, are quite extraordinary. Especially if the system is implemented as a binocular system. In short, a binoscope with a 1.5 meter system has 24X the total reflective surface area pointed toward the sky compared to the 1 meter CDK of the PlaneWave Instrument.

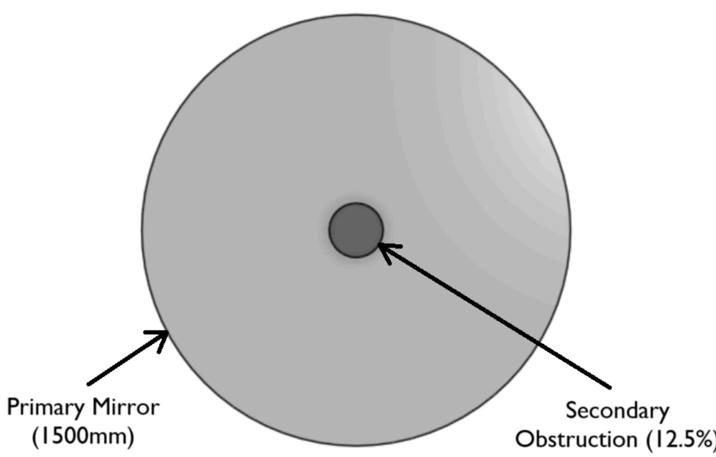


Fig. 2 Central obstruction visualization for a theoretical 1.5 meter portable observatory telescope.

Designing Meter-class Binoscopes, Tools and Software of Optical Systems, Computer Aided Design Tools, A Brief Point on Full-Cloud CAD

As we will learn throughout this book and what will be iterated often is the idea of developing a product. Designing and assembling even the most simple gadget involves aspects of product development, and building sophisticated and sensitive scientific instruments like a large telescope is no different. To be successful in building just one or perhaps millions of the same product, it all starts with slowly building up a digital clone. In order to build our digital clone, we will use an application utilizing full-cloud Computer Aided Design, or CAD for short.

Within the confines of your capabilities, this digital clone should ideally represent the end product as accurately as possible. How accurate you decide to go will depend on a few factors, such as; the quality and performance required of the end product, the number of functions you wish to incorporate, and also the capability of the CAD software you're using. There's no doubt your digital clone will end up being more complicated than you initially think. Adding time and complication to a design adds a different level of anxiety to the product development process. This is why choosing the right CAD tool is key toward building a precise model of your device, and it starts with full-cloud functionality.

Although there are many full-cloud CAD apps out there on the market, it was decided that focus should be on just a single platform: PTC Onshape. Full-cloud CAD means that all changes that are done to a 3D or 2D model determining specific dimensions and surfaces are continuously updated as changes are made. Everything is stored over the internet continuously, so you never have to worry about not saving your work. It's also incredibly easy for multiple people to work on the same project at the same time, and be able to compare the differences between assemblies of parts. There's also the history function, which is similar to the system that Github uses for software engineering. Changes can be saved as a version and then referred back to in the future.

Designing Meter-class Binoscopes, Introduction, System Design Principles, Identifying Needs

Before any design work is to be done, it should be noted what specific needs the underlying telescope should offer. A need is similar to a customer requirements list within the product development cycle. My list is quite cumbersome and lengthy, which is not entirely recommended. It's okay if your system requires more than my list, and it's certainly okay if yours mentions less, the list size is usually proportional to the difficulty of achieving a device that fits all of the needs required. Although success for each item isn't guaranteed.

My list is as follows for the binoscope project:

1. Lightweight and small enough to be transported by a 2018 Honda Fit hatchback.
2. Fully integrated power electronics for remote viewing, tracking, alt-az control etc.
3. More Items

For each item, I can solidify the need into a specific requirement. For the first listed item regarding the weight, I can look up the payload capacity for my vehicle, which is rated at 385 kg or about 850 lbs. Since two occupants conservatively may weigh around 350 lbs together, this leaves about 500 lbs total available, or about 227 kg. This is already looking to be an extremely low figure for a 1.5 meter binoscope.

Designing Meter-class Binoscopes, Tools and Software of Optical Systems, Optical Tools, Optical Blank Forming, A Spin-casting Kiln, Introduction

Once the theory and practice of basic kiln use has been covered, the next logical step in the optical fabrication process is that of building a spin-casting kiln. Spin-casting optics uses centrifugal force to gradually migrate the substrate being melted toward the edges of the mold. This causes less material to be located at the center of rotation for the kiln, thereby eliminating a substantial amount of time for rough grinding. It roughly shapes the front optical surface into a deep concave shape. As we'll learn in this section, by controlling the speed of the spin-casting kiln, we can estimate to a fairly accurate degree how much of a curve we would like to generate.

The first known use of an observatory mirror utilizing spin-casting was casted by the University of Arizona's Steward Observatory Mirror Laboratory in June, 1985. The mirror was used for the Gregorian reflector called the Vatican Advanced Technology Telescope, also known as VATT. It has a diameter of 1.8 meters, a focal ratio of f/1.0 and is made out of a honeycomb construction from borosilicate glass. The mirror in VATT was also the first to utilize the stressed-lap polishing technique, in order to better figure large aspheric mirrors. This polishing technique and its applications toward amateur telescope making is discussed in sections [ENTER CONTENTS HERE]. Another aspect of the VATT that was transformational was that the focal ratio was so deeply curved, that it was three times as compact as previous telescope designs.

Building a spin-casting kiln has its benefits. When utilizing the spin-casting method as a way toward manufacturing optical blanks, it avoids traditional issues that occur in a normal optical forming process and also acts as an effective way to shape aspheric mirrors. The step process when undergoing a spin-cast operation starts off by heating the glass to a molten state, then the kiln would begin to rotate at a constant speed until the glass was in equilibrium while spinning. Then the furnace would begin to cool at a predetermined rate while spinning. As the glass anneals, and fully cools, the furnace would then stop spinning (Zhang and Fu).

Although the exact process is a little more complicated than that, the general idea is the same. We'll get into specific recipe procedures before finally reaching on how to actually design and end up building a functional spin-casting kiln. It involves all the same procedures and main ideas discussed in the previous section on building a normal kiln. However, this build requires us to do a little bit more work into getting the kiln to actually spin.

Designing Meter-class Binoscopes, Designing Large Aperture Optics, Other Topics Regarding Optics, Adaptive Optics

Telescopes have allowed us to travel further, beyond anything our ancestors could have imagined, through essentially building giant eyes for the sky. But there's a major problem. Even if we were to build a theoretical telescope on Earth that operated perfectly and was the size of a mountain, atmospheric disturbance upon the focused image will always be apparent. This is part of the reason we put space telescopes in orbit in order to remove this effect. The result is that what telescopes have allowed us to do, was to travel to distant objects but with blurred vision. Adaptive optics is a technology to mimic the medium of outer space... In essence, canceling distortions of the atmosphere.

The way this is accomplished is through the use of a thin, 2 to 3mm thick deformable mirror, within the light path, usually achieved by deforming the secondary mirror in a classical reflecting telescope. Optical surfaces in this system are deformed hundreds to thousands of times per second by attaching actuator devices to the back surface of the optical face, which then expand and contract based on the amount of current going to the actuators. As of the early 2020s, the rate of deformation of the mirror surface can be over 2000 oscillations per second.

Why Adaptive Optics are Necessary

If not for adaptive optics, telescopes 10 meters wide would have the same spatial resolution of a backyard 8 inch telescope (Max). The depicted chart in figure 1 shows an example difference when an AO system is toggled. On the left, it shows a long exposure of a star from a 1.5-meter telescope with adaptive optics turned off, compared to the right hand image with the adaptive optics turned on. This level of spatial resolution difference is clearly immense.

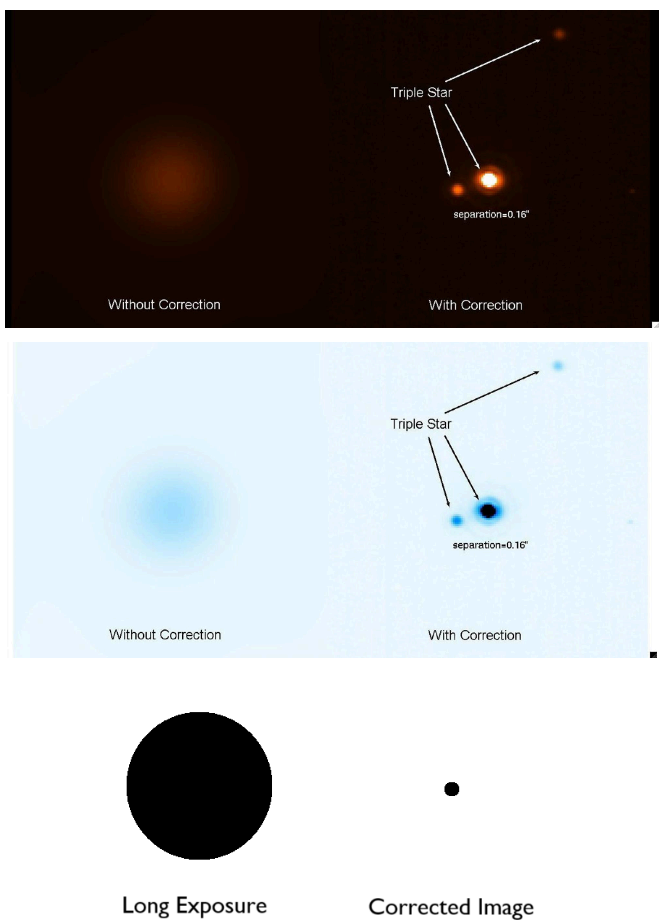


Fig. 1, Left image is a depiction of the size of airy disk for a star with Adaptive Optics turned off for a 1.5m telescope, and right, with AO turned on.

Since resolution disruption is noticeable even with small form optics, utilizing AO systems for meter class telescopes is not only an obvious decision, but also a problem purely limited by the technological challenge. Utilizing a laser to make an artificial star to analyze the atmospheric disturbance requires a laser that operates at more than 45 Watts, and anyone who owns these lasers has to be certified since they can cause damage to low flying pilots operating aircraft. As time marches on, and technological advancements make their way into the amateur telescope making community, it just might be possible to utilize a distant offspring from this technology.

Technological Challenges for the Amateur Astronomer

With the largest telescopes ever built coming online in the 2020s and 2030s, they are now such an immense optical system that the difference AO makes in its resolution power will make or break the project. Having this in mind is crucial to understanding the limitations currently imposed upon the amateur. Looking into how these large scale observatories built their AO systems to function in both visible and IR spectrums will also be important in understanding the technological challenges that lie ahead.

Utilizing Adaptive Optics for home built telescopes requires a multi pronged approach toward producing a workable prototype. You must first analyze the spectrum of light you wish to observe. Since visible light is where the majority of amateur astronomers are operating, we should focus our attention there, at 380 to 750 nanometers.

Appendix, Optical Design Best Practices

https://www.youtube.com/watch?v=0iRqVAYf27A&list=PLtt6-ZgUFmMLgUOuMk4_TPS_ku8UFCp71

Rules of Thumb, Before You Start

- Before you start, let marketing specifications dictate where effort should be emphasized. If producing just one thing, the cost will be high and performance will be high. If producing 1000 of one thing like a telescope, balance cost plus quality considerations relatively equally.
- Quantify limits
    - What are the size constraints
    - How much space is necessary
    - What weight is a limiting factor
- Consider Environmental Factors
    - Will it be damaged by weather
    - Solar radiation
    - Design for reliability with environment in mind
    - Quick changes in temperature can damage optics
- Design with mounts and stages
    - Integrating the locations of components
- Thoroughly understand the first order parameters
    - Familiarize with first order equations
    - Optimization tools will not make up for poor first order parameters
- Field of View (FOV) is Where you usually start your design process
    - Once you have FOV, you can then set your AFOV
- Design the system to be close to first order. Minimize angles to make the system more paraxial and closer to first order.

- From Snell's law, the greater the angles the rays form with a surface the greater the deviation from the paraxial approximation. This will help minimize aberrations.
- As you design, keep in mind that the system needs to be:
    - Buildable
    - Testable
    - Alignable
- You can design a nice looking system that is highly impractical.
- Thinner optical components cause greater effects of tolerances on the system, it will be more fragile. Don't design robust systems with thin components.
- If Curvature is Too Weak
    - If the radius of curvature is too weak (very flat) the alignment of the lens will be very difficult.
    - It's better to make the surface flat and compensate somewhere else in your system.
- Don't have sharp edges for the optics
    - Sharp edges are fragile and prone to damage.
    - Sharp edges may occur even for thick lenses if the diameter is not large enough to accommodate the radius of curvature near the edge.
- Design with symmetry
    - If the two surfaces of a lens are nearly symmetrical with slight variation it is better to require symmetry.
    - If the difference in the sides is not easily distinguishable by eye, the assembler will not know which direction to insert the lens in the system, it will make the alignment process much more expensive.
    - If the radius of curvature is similar to both sides of the optic, set the radius of both sides as the same, and then compensate somewhere else in your system.
- Design with symmetry around the aperture stop
    - This helps reduce aberrations
- Watch out for overly sensitive components
    - If small adjustments to the component produce large changes in optical performance, system alignment will be extremely difficult.
    - Watch for components that produce sharp bends in the ray tracing, these components will likely be sensitive to small changes.
    - Spread out your aberrations.
        - Two optical systems can have the same performance and set of aberrations but in one the aberrations are distributed between the lenses and in the other one lens is primarily responsible.
        - The system with the concentrated aberrations will be harder to align and produce less consistent performance.

Considerations, Tolerancing, and Assumptions

- Geometric Considerations are important in design
    - Optical software does not prevent or warn their users from creating impossible designs. To ensure a manufacturable system, it is important to consider several details throughout the design process.
    - Overestimate Lens diameter by ~1mm early in the fabrication process.
        - Reason: Removing material from an oversized lens is easier than adding material to an undersized one.
    - Keep ET > ~0.7mm and do not make edges too sharp.
        - Reason: Too thin and sharp of edges can result in breakage and/or damage.
    - Maintain a Karow/Z-factor > 0.56

- Reason: Karow/Z-factor: measurement of a lens's ability to self-center between two bell chucks. Too small and the lens may need to be manually centered.
- Keep Concentricity > 2mm
  - Reason: Lenses with nearly concentric radii are difficult to center since a large amount of material must be removed to correct for surface-to-surface relative decentering.
- Make center thickness (CT) intentionally thick when designing.
  - Reason: Processes such as adjusting surface quality after main lens production will naturally lessen the CT.
- Avoid hemispherical (R <= 0.7D) and near flat (sag <= 100 micrometers) surfaces
  - Reason: Difficult to manufacture.

- Tolerancing Process:
  1. Define qualitative properties for merit requirements
  2. Estimate tolerances of components
  3. Define assembly and estimate assembly tolerances
  4. Calculate sensitivities and estimate performance
  5. Adjust tolerances while considering balance with cost, quality, and schedule
  6. Iterate the process with other engineers, fabricators, and management, return to #1
  - Refer to table in this document from Edmund Optics to see tolerancing table:

Spherical Lens Manufacturing Specifications			
	Commercial	Precision	High Precision
Diameter	4 – 200mm	4 – 200mm	4 – 200mm
Diameter Tolerance	+0/-0.100mm	+0/-0.025mm	+0/-0.010mm
Thickness	±0.100mm	±0.050mm	±0.010mm
Sag Height	±0.050mm	±0.025mm	±0.010mm
Clear Aperture	80%	90%	90%
Radius	±0.3%	±0.1%	Fix to Test Plate
Power (P - V)	3.0λ	1.5λ	λ/2
Irregularity (P - V)	1.0λ	λ/4	λ/40
Centering (Beam Deviation)	3 arcmin	1 arcmin	0.5 arcmin
Bevel (Face width @45 degrees)	<1.0mm	<0.5mm	<0.25mm
Surface Quality	80-50	40-20	10-5

  - Tolerancing Methods and Assumptions: Monte Carlo
    - Monte Carlo generates random combinations of optical elements by selecting indiscriminate parameter values within each tolerance range, simulating a single production of one product.
    - Important that the peak probability aligns with the desired specification, and that the tail does not include too many outcomes that are unacceptable.
    - Outcomes of Monte Carlo Method
      - Simulations of unique optical systems which may be produced in real life.
      - Ability to analyze how individual fabrication and assembly of a single unit will perform given components which have measurements lying in different places of the tolerance range.
      - Allows engineers to dictate whether tolerances must be tightened or may be loosened to still ensure proper functionality.

- Other Tolerancing Tips
    - Round to 3 decimal places unless necessary
        - More decimals means higher cost
    - 1:8 thickness to diameter ratio for hand-held optics
    - Maximize self-centering components
        - Active alignment is time consuming and costly
    - Diameter Tolerance
        - Diameter tolerance of a circular optical component is the acceptable range of values for the diameter.
        - If the diameter of an optical lens deviates from its nominal value it is possible that the mechanical axis can be displaced from the optical axis in a mounted assembly.
    - Centering
        - Centering, also known by centration or decenter, of a lens is specified in terms of beam deviation δ:

$$\delta = \frac{\Delta}{f}$$

        - Once beam deviation is known, wedge angle W can be calculated using the refractive index of the lens material:

$$W = \frac{\delta}{(n-1)}$$

    - Stack-Ups of Assembled Systems
        - Manufacturers assemble lenses into assemblies and must be able to ensure that groups of lenses still perform within specification.
        - Physical assemblies have some degree of deviation from ideal design specifications such as tilt and decenter effects.
        - Optical assemblies require additional attention to individual element wedge and tilt as well as system-level stack-ups as elements and spacers push against each other but are subject to limitations of inner diameter of the barrel.
        - Stack-up models should attempt to accumulate tilt and decenter effects while keeping elements anchored to the optical axis for additional accuracy.

Describing Surface Irregularities

- Keep Going through videos, link at the top of this area.

Appendix, First Optical System Tutorial With OpTaliX-LT

Reference Manual Version 11.80 www.optenso.com/download/optalix_reference.pdf
This tutorial is roughly based on this Youtube video: https://www.youtube.com/watch?v=IXGKtRIBwnM

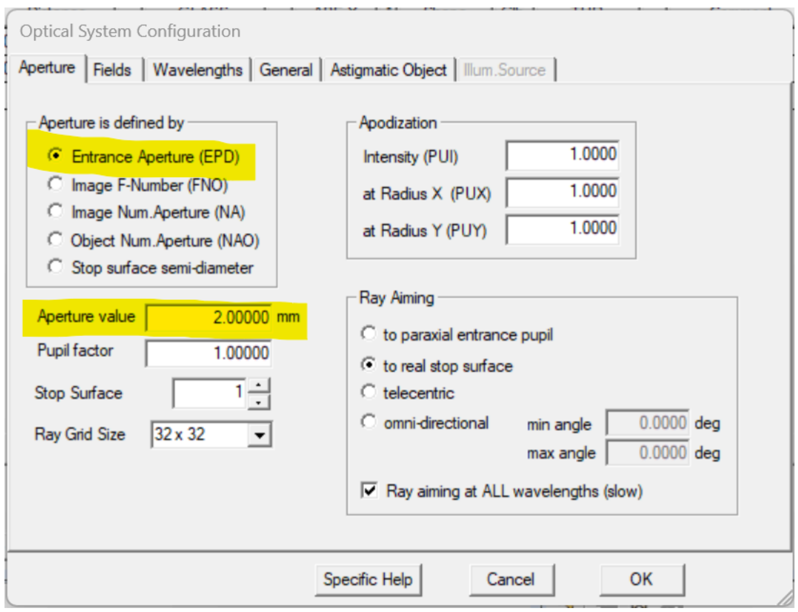
Your First Optical System With OpTaliX-LT

We'll design your first lens in Optenso OpTaliX-LT. It will show you how to design a singlet lens for collimated (parallel rays) visible light. Here are the design parameters. Aperture stop is not included because it will be a separate freely movable surface.

Specification	Constraint
Material	N-BK7
f/#	2.5
Focal Length	50 mm
Angular Field of View	±5 Degrees

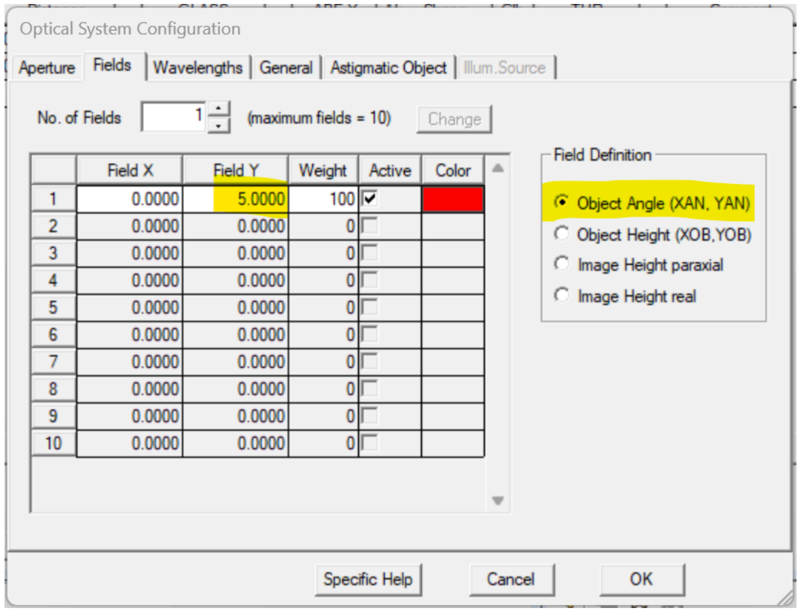
1. Clear the current optical system in the software
    a. Save your current work, if you have any, with “Ctrl+S”, before proceeding.
    b. Go to the “File” dropdown and click “New”, press “Yes”. Another way to do this same operation is through the command line input when typing “len” in the command line box, not including the quotation marks, press enter, then press “yes” to proceed.

2. Define the system aperture of our new lens.
    a. Go to the “Edit” dropdown and select “Configuration”.
    b. In the new Configuration window, make sure you are under the “Aperture” tab, then inside the “Aperture is defined by” area, select Entrance Aperture (EPD).
    c. Under the “Aperture value” input box, enter 20 mm.
    d. Your window should look like this, options of interest are highlighted:

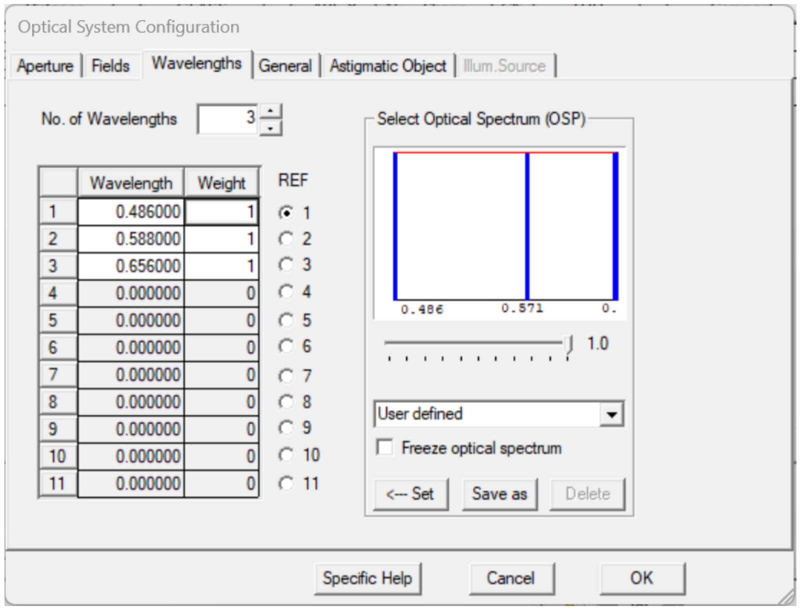


3. Define the field for our configuration.
    a. Select the “Fields” tab within the same configuration window.
    b. On the right side of this window, make sure the “Field Definition” is set to “Object Angle”.
    c. Since our Angular Field of View from figure 1 is +/- 5 degrees, we will set under the first row input and the “Field Y” column the value of “5”.

d. Your window should look like this, options of interest are highlighted:

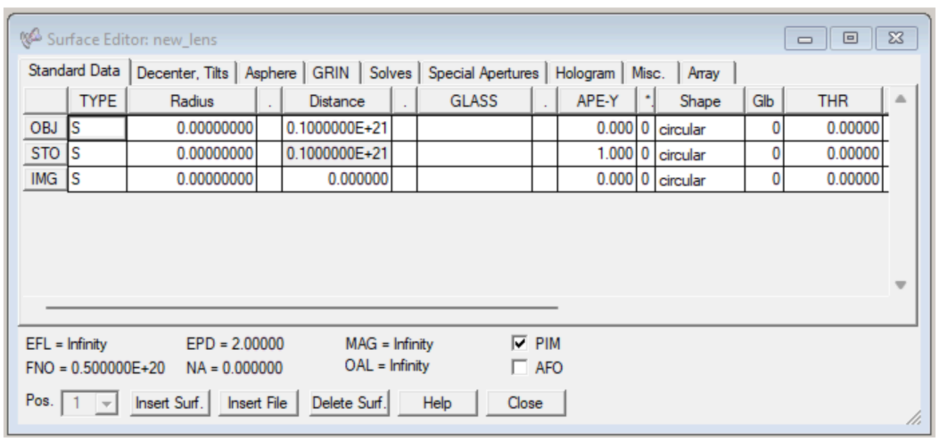


4. We will now set the wavelength of light for our optical system.
    a. Since visible light will be used for our system, and visible light contains a range of values from approximately 380 to 700 nanometers (0.38 to 0.7 microns), we'll enter three different values for the wavelengths.
    b. Under the same Optical System Configuration window as the previous steps, select the “Wavelengths” tab at the top of the window.
    c. The first thing we change is the “No. of Wavelengths" option which is normally set to a value of “1”. We will change this to the value of “3”. The optical spectrum graph to the right will update as you make changes within this tab.
    d. We'll then enter the three wavelengths into the three rows that are available to us. The units for the numbers we enter are in microns (1 micron = 1000 nanometers).
        i. The first will be set to wavelength “0.486”.
        ii. The second will have “0.588”.
        iii. The third will have “0.656”.
    e. Now update the weight value to “1” for each wavelength row. Your window should now look like this:

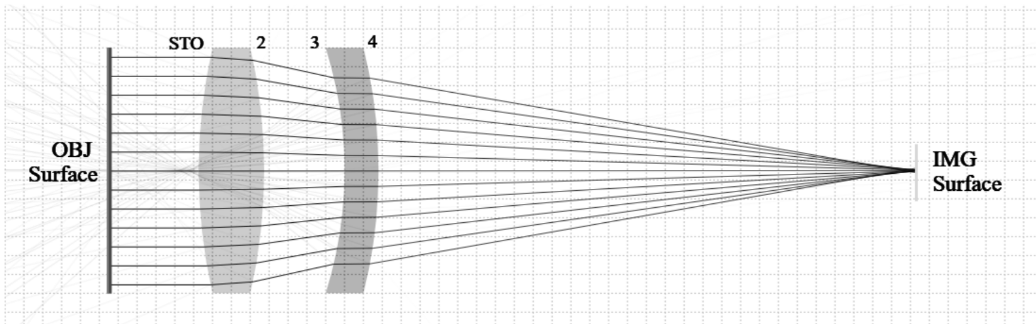


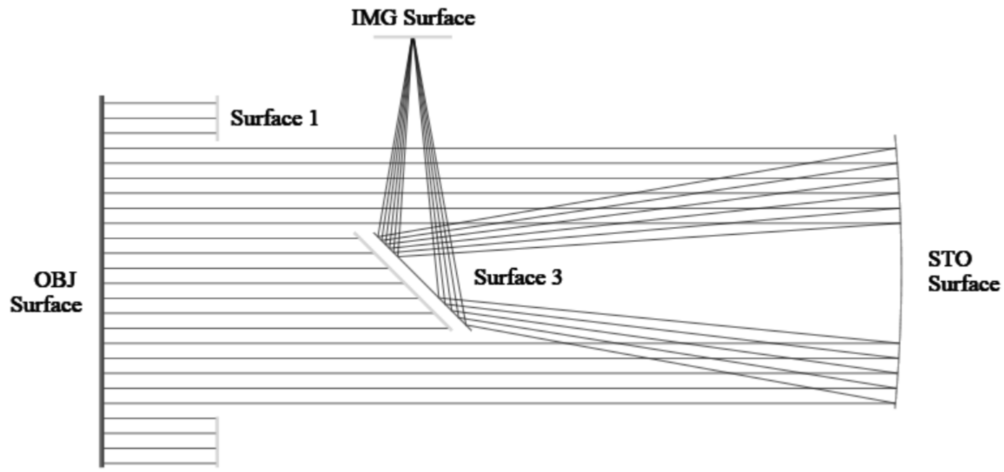
f. Press “OK” to close this window.

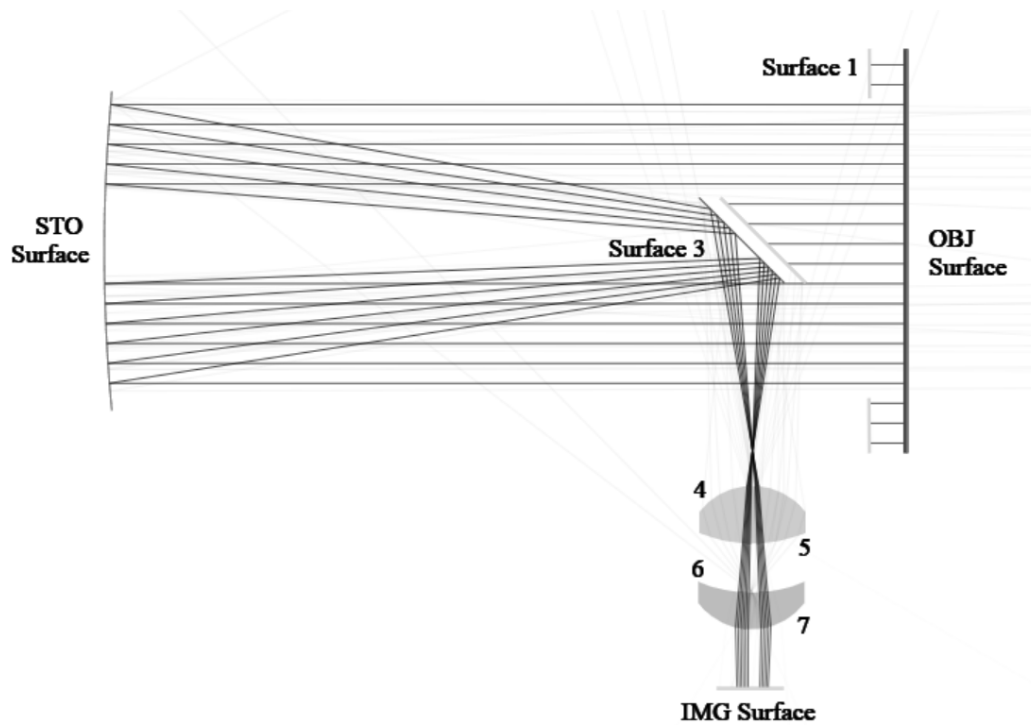
5. Next, we’ll enter information into the lens data Surface Editor.
   a. If you don’t see the Surface Editor window, go to the “Edit” dropdown and select “Surface Editor”. This window is a spreadsheet where you can enter relevant lens design parameters. By default there are only three surfaces, the OBJ (Object), STO (Aperture Stop), and IMG (Image). Any optical system will have at least these three.



   b. As we move down the rows, we move along the optical axis, starting with the Object and ending with the Image. Each row’s type by default is a “**S**pherical surface,” denoted by the letter “**S**”. Other letters and their meaning can be found in section 8.6 in the *Optalix Reference Manual*. Each row contains information regarding that surface. For our example, we will add two additional surfaces. However, before we do that, let’s quickly see where exactly these surfaces reside in an optical system.


STO
2
3
4
OBJ Surface
IMG Surface


IMG Surface
Surface 1
Surface 3
OBJ Surface
STO Surface


Surface 1
STO Surface
Surface 3
OBJ Surface
4
5
6
7
IMG Surface

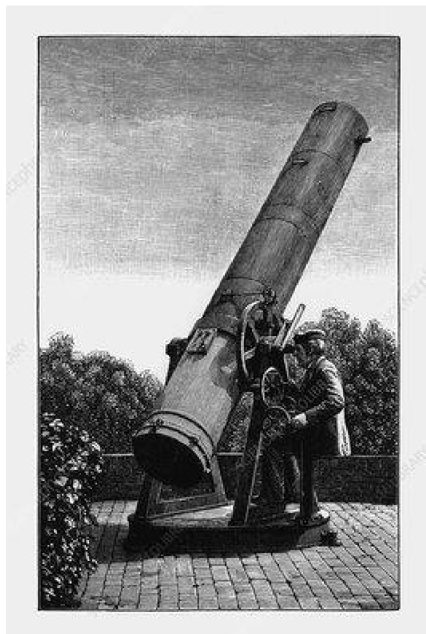
c. To add the two surfaces, click anywhere on one of the boxes within the IMG (Image) row, then click the “Insert Surf.” button twice. This will provide two surfaces above the image with labels “2” and “3”.
d. The labels in the spreadsheet are in units of millimeters. The rows that have “0.1000000E+21” mean that the distance is essentially at infinity. We would usually regard an object in the night sky to be at infinity distance, since the object’s rays of light, when they reach Earth, are extremely parallel. To be specific, it translates to the number 100,000,000,000,000,000,000 mm, which is equal to 10.57 light years in length, not exactly infinite, but certainly adequate for our intents and purposes.
e.

The Gregorian Telescope

- The Gregorian telescope has its history as far back as 1663, with James Gregory having just published his *Optica Promota* (The Advance of Optics), where he outlines the design of a parabolic mirror system now known today as the Gregorian reflecting telescope. First physically realized ten years later by Robert Hooke.
- A Gregorian telescope simply consists of two concave circular mirrors. The largest mirror, the primary, is placed at the end of the optical light path similar to a Newtonian reflector. The shape of the primary mirror is made so as to form the shape of a concave paraboloid. The secondary mirror is smaller than the primary, and is located so as to collect light after the primary mirror. The secondary’s surface is to be ground into the shape of a concave ellipsoid. Then the light is reflected back toward the primary mirror, down through a hole bore through the center of the primary mirror so that the focused light can escape the light tube and enter a focus point at the eyepiece or photon collector.
- Achieving this formation of mirrors, focused out the backside of the optical tube, allows the user to view an up-right image, an aspect that is not possible with a normal two-mirror Newtonian reflector. This setup also makes it useful for terrestrial observations and easies the stress on pointing to different objects in the sky.
- Examples include the Giant Magellan Telescope and the Large Binocular Telescope.
- My interest in the Gregorian
  - My interest in the Gregorian goes back to the mid 2010s, when I sketched up a life-size ray-trace drawing regarding a possible new combination of mirrors I called the Gregewtonasmyth, pronounced Greg-Ew-Ton-Naz-Mith. Which incorporates Gregory’s design, Newton’s, and finally James Nasmyth’s classic design. After retiring, Nasmyth built a home-made 20” reflector telescope and incorporated what’s called a “Nasmyth focus,” wherein there is a tertiary diagonal mirror that points the light cone perpendicular to the main light path, usually parallel with the axis of rotation of the entire optical tube assembly. This allows an individual to never have to move their body when viewing different objects. It also allows for heavier instruments to be mounted to the telescope frame.
  - When I finished my sketch, I sent it to Gordon Waite of Waite Research, and he felt the design could certainly work, however, because the size of the primary was around 15 cm in diameter, the secondary would be uncannily small, about 2.5 cm across. This secondary would then be focused on a tertiary mirror that was even smaller. All of this

was interesting in theory, but making it practical and buildable was another thing, the adjustment on collimation of this alone would prove to be difficult, so in this case, it would be advantageous to make a larger primary mirror!

- The reason for this small obsession of mine was simple; I'm a lazy observer, I want both feet on the ground, I want both eyes open, and rather than standing I would much prefer to sit in a chair. Standing isn't your body sitting still, it's constantly trying to balance itself from falling over and although you don't notice it day to day, trying to keep your head still when standing and observing at night can be slightly dizzying. And not only that, If we really spend hundreds of hours and perhaps thousands of hours building the most impressive optical instrument we can, why go through all that trouble just to have to climb a 10 foot ladder *in the middle of the night* to just have a look through the thing?



- Another mode of thinking that led me to this design is the ease of building comparatively to a cassegrain style binoscope. This is due to the added difficulty of perfecting the secondary mirror surface. Although a Newtonian binoscope would be far easier, incorporating a Gregorian style reflector is the only way to get an upright image similar to that of a refractor binocular, and combined with the magnification capability of a long focal length telescope.
-

The Main Goal

- Acquire through the purchase of an existing system and/or through the design and construction of a custom system in order to achieve the following:
    - The best visual observation telescope in the world
        - Not all optical systems are created equal, needs to achieve the best of all worlds
        - Least possible secondary obstruction
        - Pin-point stars, no diffraction lines
            - Use either curved secondary holder vines or a novel/rare approach like attaching a vine to the baffle
        - Maximizing angular resolution for a visual experience
            - Highest quality image that isn't blurry. Is high magnification going to impede visual quality, probably. Is this impossible or perhaps barely possible to have super high quality visual images with high magnification, high focal length increases overall magnification.
        - Able to use both eyes while observing.
        - Probably need to build a calculator for determining how important each aspect is and optimize towards a central idea.

Other Goals & Main Ideas

- Gregorian Binoscope that contains the following specifications:
    - 1.42 meter wide aperture for each primary mirror, creating an estimated effective aperture of about 2.0 meters wide, this figure is calculated with the idea that there is zero obstruction. This exact 2.0 m figure is difficult to estimate until testing is achieved.
    - Primary mirror and secondary mirror are centered with the optical axis
    - Both primary and secondary mirrors are concave, allowing an upright image to be displayed at the focus point
    - Each secondary concave mirror will focus light toward a 45 deg. tertiary flat mirror positioned between the secondary and primary
    - Primary mirror will have a hole cut in the center to allow access to the tertiary
    - The tertiary flat will then focus light toward the eyepiece configuration, which contains a fourth mirror, another 45 degree flat
- Quick ray diagram sketch (Fig. 1) utilizing RaySim, showing a theoretical ~100X400, 100 magnification, 400mm aperture size, binocular setup incorporating a Gregorian style reflector setup.
    - Black bar across top is the incoming light rays
    - Sketch is not meant to be an accurate depiction of correctly sized and positioned optics, for example, the location of the eyepieces would not allow for any room for a person's head to fit in that space.
    - IPD (Interpupillary distance), the length between both of someone's pupil's is listed as a visual reference for the majority of viewers requirements

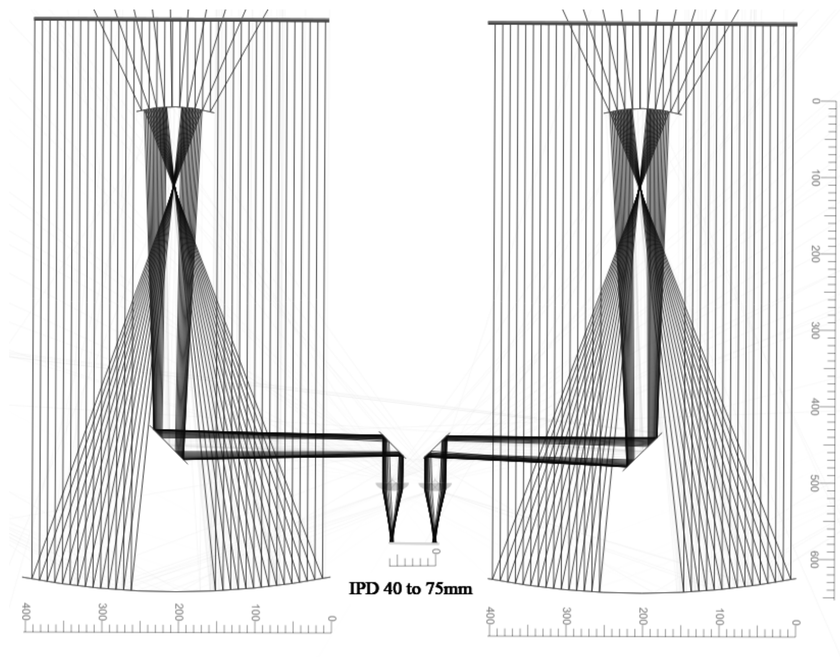
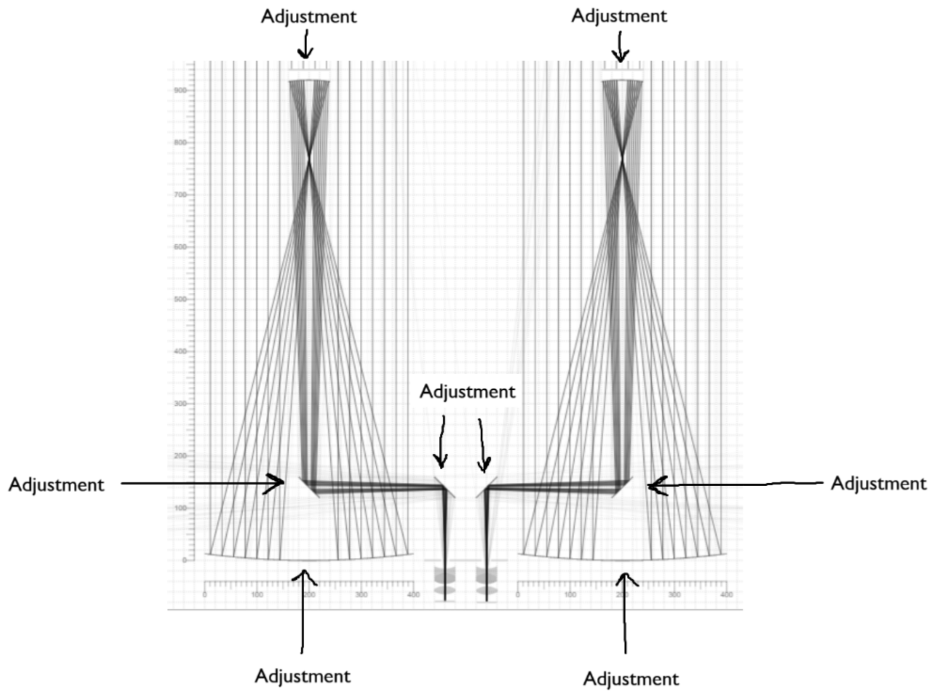
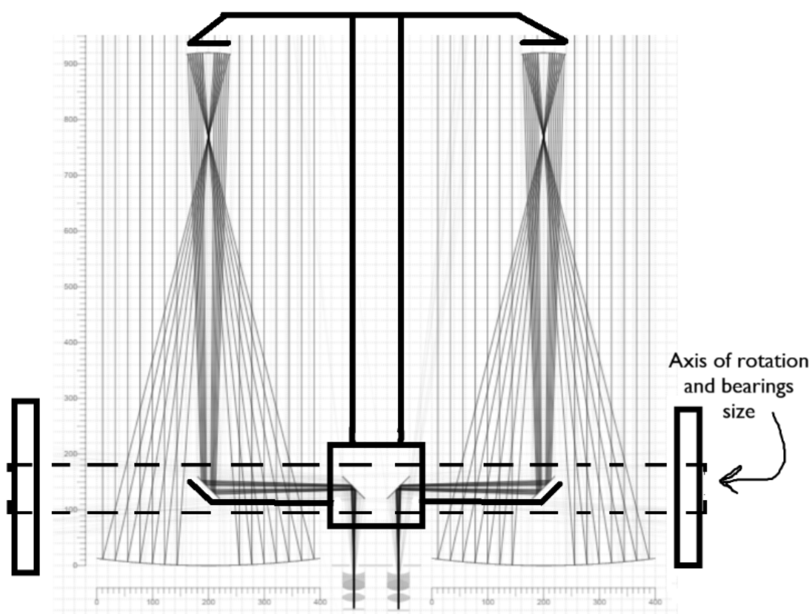


Fig 1. Ray trace sketch for 16” Gregorian binoscope reflector





^^ Lower spider vanes need redesign ^^
This style will block outgoing rays from the primary.

- The benefits of this design
    - Unlike the convex secondary of the cassegrain telescope, the secondary mirror in the Gregorian is foucault testable, so the optics isn't as difficult to fabricate as a cassegrain for amateur telescope makers.
    - Views will be extraordinary and not common within any of amateur astronomy

        - Both astronomical and terrestrial observations will be unmatched in terms of magnification for the overall packaged size
        - Views will be upright and oriented as if someone had eyes the size of the binoculars. As long as the optics are designed and manufactured correctly, it allows for a very comfortable viewing experience.
        - You will see dimmer stars, just go out at night and compare one eye with two eyes. It's a summation factor of about 1.4 at night (Otte).
        - Humans use two eyes all the time, so it feels uncomfortable to return to a single eyepiece monoscope after using a binoscope, and takes time to adjust. Easy to adjust to a binoscope after using a monoscope, but not the other way around. Sticking to just one optical path should be an antiquated problem.
        - According to Mel Bartels, during a test in 2003 comparing a 22 inch binoscope with a 28 inch monoscope, "The brain much prefers the comfort of binocular viewing: the sense of presence, the silkiness of faint, distended objects, the ability to concentrate and the removal of background noise by the brain were all noted as improvements due to the binocular view."
    - Total focal ratio of the whole system is smaller than a single aperture of just one of the scopes alone. For example, if you are building a 30 inch Newtonian binoscope, and each primary mirror has a focal ratio of f/2.7, the combined focal ratio will be f/1.9 together (Bartels 0.76m). Gregorians have already infamously high focal ratios, meaning objects will be much larger, but less clear, so lowering this already high focal ratio is a good benefit to consider with a Gregorian binoscope.
    - See the summation factor paper written by Otte: http://arieotte-binoscopes.nl/Binocular%20Summation%20Factor%20revised%202019.pdf
- The drawbacks of this design
    - Extremely difficult to build and operate, must always obtain optical alignment when pointed to anywhere in the sky or ground
    - Collimating the optical system is more tedious and error prone when building and using the scope than compared to a regular Newtonian reflector (Otte 2). A specialized setup will be required for varying sizes. Large meter-class binocular telescopes will probably require electronic collimation, unless some other means is devised.
    - Binocular optical systems are far more expensive per aperture size
        - Weigh the comparison between this design and a large equivalent light collector single aperture telescope with binoviewers
            - Pros: Cheaper and easier to build a single aperture telescope
            - Cons: A binoview splits one image into two, while a regular binocular telescope is giving each eye its own telescope. Binoviewer *cannot* produce a 3D effect, it is fundamentally not 3D.
    - More difficult to manufacture than a single aperture telescope of comparable performance
        - While this is a reasonable point, for instance, it may be theoretically easier to build a 2 meter telescope rather than a binocular 1.42 meter pair, this comparison becomes exceedingly difficult as the size gets bigger because the technical difficulties exponentially rise as the aperture gets even slightly bigger.
    - A completely different kind of engineering problem, compared to the newtonian reflector: one newtonian reflector telescope has two mirrors, whereas this gregorian binoscope will most likely contain a total of at least 8 mirrors.
- Other Accessories that could be included

  - High quality solar filters that fit at the end of the optical tube assembly for both mirrors to allow the viewing of the Sun.
  - When not tracking an object, but tracking the rotation of the sky, there will be a physical joystick that allows for the jogging of the view. The reason the scope still operates in tracking mode continuously is because the goal is to give the feeling of exploring across a fixed sky. This is especially important under high magnification, as objects will quickly move in and out of the field of view if the scope was not tracking the sky.
  - This same joystick will also allow the movement of an electrically activated variable magnifying barlow lens, for both eyes, so as to allow for a dynamic zoom effect. The field of view will autofocus as the zoom occurs. This idea may have to be optimized for a custom made eyepiece pair. Wouldn't want any trouble merging the images due to manufacturing differences of two seemingly similar eyepieces, but actually not, due to being built at different times.
  - The ability to dynamically alter between a purely visual binocular scope and a purely astrophotography telescope. There will be multiple modes of operation; the first is when both telescopes are used for both eyes, just like a regular binocular scope. The second mode is a hybrid style, so that viewing through one of the eyepieces with one eye is possible, but also able to capture a long exposure image with a small CCD camera on the scope. The third mode of operation is the ability to take long exposure images with both optical tube assemblies.
  - Interchangeable filters for viewing under different wavelengths.
  - Tracking motors will be capable of moving the binoscope fast enough to keep track of the ISS - https://www.astronomy.com/space-exploration/satellite-tracking-for-amateurs/

Reflector Basics

Text

Gregorian Reflector

Text

Binocular Basics

- The optical axis *must* be parallel, to at least one arcminute, which is approximately 1.7% of a degree (Walker)
- My goal should be to align the optical axis to at least one arc***second***, or better, which is 0.028% of a degree.

Feasibility

- Is the ray trace feasible

References

Bartels 0.76m, Mel. *Design of a 30 inch [0.76m] binoscope by Mel Bartels*, "bbastrodesigns.com/30/30%20inch%20binoscope.html", web accessed, October 10, 2023.

Bartels 0.64m, Mel. *A 25 inch [0.64m] F2.6 Telescope by Mel Bartels*, "https://www.bbastrodesigns.com/25/25%20inch%20F2.6%20Telescope.html", web accessed, October 18, 2023. Archive.org historical reference, "https://web.archive.org/web/20230518043301/https://bbastrodesigns.com/25/25%20inch%20F2.6%20Telescope.html", recorded May 18, 2023.

Max, Claire. *Introduction to Adaptive Optics and its History*, NSF Center for Adaptive Optics University of California at Santa Cruz and DOE Lawrence Livermore National Laboratory American Astronomical Society 197th Meeting, web accessed, October 23, 2023. "https://www.cfao.ucolick.org/EO/Resources/History_AO_Max.pdf"

Otte, Arie. The Binocular Summation Factor and its relevance for Deepsky Observing Part 1, Scientific Background (2019), "http://arieotte-binoscopes.nl/Binocular%20Summation%20Factor%20revised%202019.pdf" web accessed, October 10, 2023.

Otte 2, Arie. *Merging of the Images*, "http://arieotte-binoscopes.nl/Merging%20of%20the%20Images.htm" web accessed, October 10, 2023

Walker, Bruce H. *Optical Engineering Fundamentals, Second Edition*, SPIE Press, Bellingham, WA (2008), web accessed, October 10, 2023.

Zhang and Fu, Xinming Zhang and Weijie Fu. *Numerical simulation assisted curve compensation in spin casting of optical mirror blank*, Optik, Volume 207, 2020, 164406, ISSN 0030-4026, https://doi.org/10.1016/j.ijleo.2020.164406. (https://www.sciencedirect.com/science/article/pii/S0030402620302400)

Webpage Links

Academic Articles:

- https://www.researchgate.net/publication/242604656_Ultra-lightweight_Deployable_1m-Class_Optical_Telescope_for_SSA_Applications
- https://apps.dtic.mil/sti/pdfs/ADA531777.pdf
- https://link.springer.com/article/10.1007/s10443-021-09994-9
- https://www.spiedigitallibrary.org/Search?term=Optical%20Engineering%20Lightweight%20mirror&webSyncID=0cda4b93-0568-d140-2374-dd6262b5de08&sessionGUID=927d64dc-e280-9425-d063-ad95edeaee51&_ga=2.257539339.1499246225.1697470485-1439110881.1696888540&access=Open_Access
- Lightweight, large mirrors: http://www.altazinitiative.org/Word%20Documents/Alt-Az%20Aerospace%20Telescopes_1b.pdf

- Large Binocular Telescope Diagram: https://web.archive.org/web/20100702213715/http://medusa.as.arizona.edu/lbto/images/Focal.jpg
- Mirror Blank Spin-Casting: https://www.sciencedirect.com/science/article/abs/pii/S0030402620302400#:~:text=In%20the%20process%20of%20spin,until%20reaching%20a%20equilibrium%20state.
- Adaptive optics and its history: https://www.cfao.ucolick.org/EO/Resources/History_AO_Max.pdf
- More Adaptive optics information: http://www.eso.org/sci/facilities/develop/ao/what_ao.html
- Giant Magellan Telescope Adaptive Optics for Visible range: https://arxiv.org/abs/1407.5098
- Optics layout for portable adaptive optics: https://arxiv.org/pdf/1806.08050.pdf
- A small observatory application with working Adaptive optics: https://hartsci.com/
- Basic class in telescope: http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/telescopes/phy217_tel_principles.html#figure1
- AI Algorithm Unblurs the Cosmos: https://www.sciencedaily.com/releases/2023/03/230331120633.htm#:~:text=Now%20researchers%20at%20Northwestern%20University,images%20from%20ground%2Dbased%20telescopes.
  Academic paper: https://arxiv.org/pdf/2211.01567.pdf
- 100 meter telescope: https://www.eso.org/sci/facilities/eelt/owl/OWL_design.html
-

Quick Software Links:

- https://www.ansys.com/products/optics-vr/ansys-zemax-opticstudio
- Free, but dated Optical Design and Analysis software: https://www.atmos-software.it/Atmos8_9.html
- Optical Design Software, updated August 2023, for $74.00 USD (OpTaliX-LT from https://www.optenso.com/index.html)
- https://arachnoid.com/OpticalRayTracer/
- Interesting 3D CAD software for optics engineering: https://www.quadoa.com
-

Quick Documentation Links:

- http://atm.udjat.nl/telescopes/gregorian/gregorian.html
- https://www.handprint.com/ASTRO/ae2.html
- https://www.cloudynights.com/topic/331973-classical-cassegrain-vs-gregorian/
- http://www.dreamscopes.com/pages/articles.htm
- This company may release a cheaper product for amateur astronomers in 2024, stay tuned to the website for updates: https://www.compositemirrors.com/
- https://go.4dtechnology.com/l/996321/2023-07-27/2fhrb/996321/1690474906GKw1D7J7/PhaseCam_6010_Visible_Data_Sheet.pdf
- http://www.dreamscopes.com/images%26graphics/2016/LFW_May2016Issue_160190-1565e-396mmCA_LightweightMirrorArticle.pdf
- Big resource for basic optics: https://www.telescope-optics.net
- Material chart for clearceram: https://www.oharacorp.com/wp-content/uploads/2022/11/material-chart.pdf
- How optical glass is manufactured: https://www.thomasnet.com/articles/custom-manufacturing-fabricating/how-is-optical-glass-manufactured-process-steps-and-breakdown/
- Meter-class gregorian design outlined: http://www.ceravolo.com/gregorian.html

- Large Binocular Telescope 3D design drawings by European Industrial Engineering in Mestre, Italy: http://oldweb.lbto.org/eie01.htm
- Large Binocular Telescope Observatory Quick Facts: https://www.lbto.org/quick-facts/
-

Specific Tutorial Links:

- Large Grinding Machine for Mirrors up to ***1.1***m, not 1.5m: https://www.bbastrodesigns.com//grindingMachine/GrindingMachine.html
- Ignition Maker Edition: https://www.youtube.com/watch?v=gDgUyYvwXQY
- Optalix Tutorial: https://optenso.com/download/optalix_tutorial.pdf
- How to Design Optical Systems: https://wp.optics.arizona.edu/jsasian/wp-content/uploads/sites/33/2018/11/RJ-2018-Opti-517-Designing-Optical-Systems.pdf
- Basic 400 mm Gregorian Binocular Telescope design: https://phydemo.app/ray-optics/simulator/#XQAAAALaCwAAAAAAAABFKcrGU8hqLFnplfssnTFrXtfVEiB24SmQ11hBHLnxmyapBp_cRg2rdIQs4cQZDY5GKRoRGMnC7GkNQnTvkCPwpSMISaL-OzcRBF-A18dm0AzBkYN819RCi1_Xw--2OhoC0JqbNzBBEEDMngn8zTuNtvIKKkPw3Jl0cXmK01zZrkKHsG5S7Ffvri8DK3wiq9uRsDuiih6KuFkqfWDDRVclsdi9GTZHo7zaO9IXjn42qFVn_iYzAzsUTMXfPpPvUwVLpw5hm2Ulb6prTwyMFydNKqlauc79EMU6WYWuwO2TDMmDDQbt5VXxXyK66m5mUBEYCRBaygybno8rQiAx_aX1CEN6QiWvdnRjOta3cmUQf-TzG8T426LqEuoglFkwQtkeCG2JDa14nPfO6_xrWrg9v0uAc_VRycdKmlowPW1R4hgwyFR_BsJe5JW3P3OtmBrE6AKexNgc6TXIZpRiqASOYjxKANFHUjOZo4G0w3p1ElOy5iMSdQQk_u-VqxYtinIsYqk3wWrn67iQC8_s52WQISIJSts0LjCnNE8RqqN3qkfg7KPt30dCJMaviPzLuJTgFy5X_42SsChlx9K2Xbi8wJ4DWRaG3DXGAGNddnEoSJLJN8JWZqk6qJxMtqEIV9KEM5G0-uHuGK0LaH_N45WxnXVxlF8zjJcrOYNWAw1RY5giC48uhTebCZfLZR0zel_1z_TTqKhflQjl_TGA6i5qNOM39HA-8SwtfZEx80OBNLWVvl-b9nrpWnUepM_I6ScCMZbhhPWoCTKnVMXKyZ29hEh6XMY-pikkinqD8AXRxfOkj5CG4nIy4p5z8THUhwDaDzRNGB34wI6LKymtnqieEMAHT3THEV7KGfMNo7PdwbnRhUeznSIL27BI5uFPevCnPl8ekPIztMGBWLAjnGHDiSeF5wPBqZthTs28Vb0pdvJseet-Nl9A4hmJbSOi3VfRfulcdZMHrKbeg-HUsZb1WG_6ke5q_BlamuAFdYOvqVh-ck9J6b-Rs10D_tDX4u6CDL6phcJh5buxDzehB6oX8UE0ZTIOmpiNE4PawydhMs1FdlsEG9UXbGLSw1iVmvt0G6Vb5IWup6Xa7Q5GjaCFQp2CsYjdvf_S-xThQmKDHSF-pV_WHl-qHNwiazdlXfxq0_qg6DUSX1s3E98jx05-OHJi_RosDtaZHtvJUk__r9ztPg
-

Books, Textbooks Purchase Links:

- Fundamentals of Optics by Jenkins and White, 2001, full 766 page PDF link: https://handoutset.com/wp-content/uploads/2022/07/Fundamentals-of-optics-Francis-Jenkins-Harvey-White.pdf
- Large list of 98 optical science and engineering books: https://www.amazon.com/dp/B08TMSZNYF?binding=paperback&ref=dbs_m_mng_rwt_sft_tpbk_tkin&qid=1698092218&sr=1-99
- Book on Optomechanics, published 2023, for only $60: https://www.amazon.com/dp/B08TMSZNYF?binding=paperback&ref=dbs_m_mng_rwt_sft_tpbk_tkin&qid=1698092218&sr=1-99
- Optics manufacturing book, published 2019, for only $70: https://www.amazon.com/gp/product/0367877732?ref_=dbs_m_mng_rwt_calw_tpbk_9&storeType=ebooks&qid=1698091978&sr=1-58
- Optical Engineering Textbook, published 2023 for $93: https://www.amazon.com/Modern-Optical-Engineering-4E-PB/dp/1265902658/ref=sr_1_20?crid=

20ASUDT4GWE97&keywords=optical+engineering&qid=1698089566&s=books&sprefix=optical+engineering%2Cstripbooks%2C124&sr=1-20
- Optics by Hecht: https://emineter.files.wordpress.com/2020/04/hecht-optics-5ed.pdf
- Maxbright II Binoviewer: https://www.baader-planetarium.com/en
- Handbook of Optical Design: http://optdesign.narod.ru/book/Handbook_of_Optical_Design.pdf
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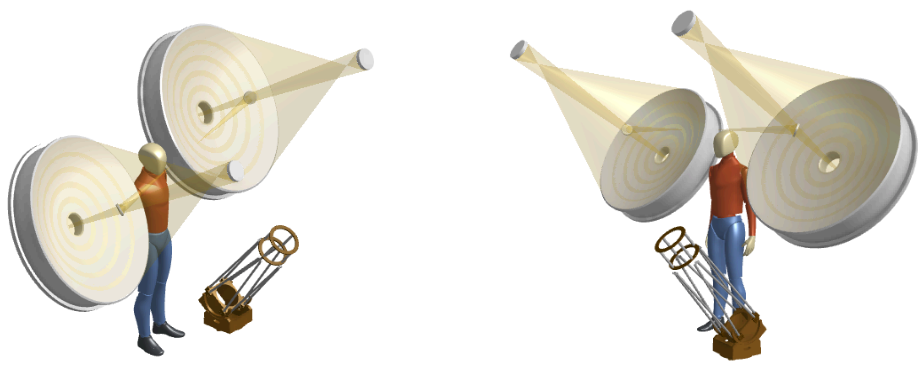
Journal Entries

10/16/2023 - Starting academic review today for checking on recent advancements within light weight mirror design. Adding resources to review at a later time when that subject comes up.

10/17/2023 - Worked on outline for the book. Although the outline is incredibly short at the moment, it helps me parse together the totality of the subject matter, which is to say, rather dense. Also came up with two different ideas that may or may not be feasible. The first one is an optical design which somehow seems more gnarly than that of the Gregorian binoscope. The second idea is taking long exposure images at night using a polaroid, where the polaroid is attached to the telescope focuser. Image of the sky was achieved for a 5 minute exposure using the Polaroid 600 SLR 680 Folding Instant Film Camera.

10/18/2023 - Adjusted the outline for the book to be better organized. Changed it so that it is gradually working up to more and more complex optical systems. Reason for “book” organization is to help my brain better organize how I could best approach the subject of large Gregorian binocular telescopes.

10/21/2023 - Created some CAD mockups for a pair of 1.5 meter binoculars in Onshape.



10/22/2023 - The ‘dream scope.’ The idea is as follows: A dual 1.5 meter binocular wherein the focus point resides behind the optical tube assembly, utilizing a Gregorian (primary and secondary are concave) light path with a total focal ratio of approximately f/4 to f/6, such a low focal ratio for this optical system requires an extremely fast primary mirror, and a slowish (f/12 to f/16) secondary mirror. Has this been achieved? Yes, by the LBT observatory and others in Arizona. Outlined details are mentioned in the goals sections above.

11/1/2023 - If the LBT observatory in Arizona was scaled down to a 1.5 meter design, how would it look? The primary is 8.417 meters, so this translates to a ratio of 1.5 divided by 8.417 = 0.178210764. This means the secondary (undersized) is equal to 0.16235 meters, which is about 6.4” diameter.

11/7/2023 - I must increase the chances of success with this project by gaining a firm understanding of what my specific goals are. I will attempt to outline them here in detail.

- Large aperture size that is unlike common designs. 1.5 meters sensor.
- A giant telescope that is tailored to the natural view of the universe.
- An experience that is centered around the user and is most comfortable to the human eye.
    - Binocular assembly. Provides full brightness and comfort to each eye.
    - Wide field of view. 110 degrees viewing capability for each eye.
    - Be seated at the eyepieces at all viewing angles.

Idea List

1. Binocular telescope that allows multiple modes:
    a. Each optical path can be combined into a single large binocular format
    b. Single eyepiece each (for use with viewing giant wide angle eyepieces) where each eyepiece is separated enough so that two people can use the scope at the same time.
    c. Allow a binoviewer to be attached to said individual optical path, so that both users can enjoy partial stereoscopic viewing of the exact same object and viewing quality.
    d. Be able to attach a CCD camera to either optical path (1 optical path or 2 different optical paths to combine later) or to combine the binoview into a 3D camera light path for 3D astrophotography.
2. Image stabilizer that mimics an Adaptive Optics result

3. A Binocular Viewer that mimics the experience of a VR field of view. VR systems fundamentally take two slightly different fields of views of the same image.
    a. Field of view of the human eye is 135 degrees. VR headsets are around 110 to 120.
4. Vibration while panning under high magnification will be apparent. In order to prevent this from causing discomfort for the viewer, since the goal is to give a spacewalk panning experience, use a floating lens element (research implementation by Nikon and Cannon) that is “moved orthogonally to the optical axis of the lens using electromagnets. Vibration is detected using two piezoelectric angular velocity sensors, called gyroscopic sensors, one to detect horizontal movement and the other to detect vertical movement. This image stabilizer corrects only for pitch and yaw axis rotations, and cannot correct for rotation around the optical axis. Have it activated automatically.”
5. The Gregorian Nasmyth-focus Binoscope, is it possible to keep the eye piece at the same focal point for a binoscope system, we’ll have to figure that out.
6. Would it be possible to utilize the double binoscope optical pathways in order to essentially average out the atmospheric distortion. This could be achieved by a few different ways. The first is that as an image from one optical sensor goes into the detector, it takes a single pixel of that light and compares it to the location of the same pixel for the other optical path. It then takes the average of the two pixel colors.
7. People have different pupil sizes, would it be possible to have an adjustment on the eyepiece that allowed for different pupil diameters, say adjustment between 4mm to 7mm.
8. Engineer eyepieces specifically for the binoscope, that have adjustable magnifications and other adjustments. This way you reduce the likelihood of purchasing two different eyepieces that do not exactly match thereby being unable to merge the two images.

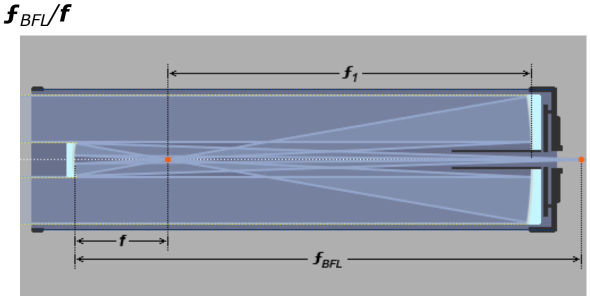
Appendix

Large Telescope Builders

- Obsession Telescopes
- Lockwood Custom Optics
- Optiques Fullum
- Webster Telescopes

Calculating Focal Ratio of Gregorian

The effective focal length $\boldsymbol{f}$ *is derived as the primary mirror focal length* $\boldsymbol{f}_1$ *multiplied by the secondary magnification, calculated as* $\boldsymbol{f}_{BFL}/\boldsymbol{f}$



An Early Investigation into Portable, Meter-class Binoculars

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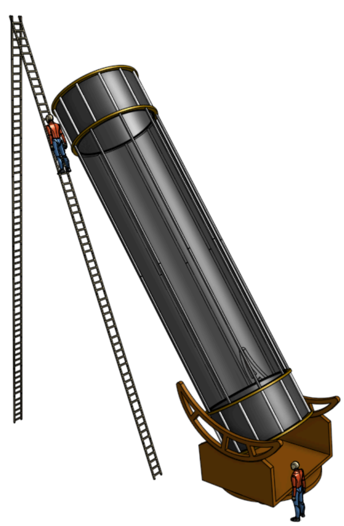
ABSTRACT

Portable, meter-class binoculars will revolutionize the way people view the universe

INTRODUCTION

The prospect of achieving greater light gathering capability for portable astronomy has never been closer. Yet at the same time, as world-class organizations around the globe design and build enormously complex space and land observatory systems, portable optical systems still have major limitations in terms of aperture size and relative enjoyment of use for the device. Not only that, there are substantial flaws in the underlying designs of smaller aperture telescopes. Although incredibly elegant, lightweight, and large light-bucket capacity, the big and portable Dobsonian telescopes seem to have reached a crescendo effect that started in the mid 1990s up until today. Consider for a moment just how little the overall design has changed for the premium Dobsonian telescopes and the manufacturers that have built them. Yes, we are seeing more lightweight versions of similar apertures, yet the premise is still the same, how will we gain even more light gathering power without risking life and limb for yourself or others? Will this be the future of the next generation of large amateur telescopes?



As a fellow telescope builder, it is clear to see what went wrong. John Dobson revolutionized the portable telescope by incorporating an easy-to-make design. He only cared about getting everyone on Earth to see what the sky looked like, not getting the best view possible. He built his instruments out of plywood and cardboard, optics out of thrown away porthole glass in a shipyard. He didn't source the most premium birch plywood, or choose the highest performing focuser. He did what was *required* to get a great view of the sky, to show other people who had not looked before.

In essence, what the modern truss-pole Dobsonian telescopes have done, to state plainly, is simply overengineered upon John Dobson's design, and forgot what John Dobson's goal was all along… cheap, portable, sidewalk telescopes. Take for example if you were to purchase a single commercial truss-tube telescope for $15,000, how many home built 8" telescopes could that money build? If it simply cost a generous $500 to construct one, let alone purchasing material on mass to incorporate savings, you would still have 30 telescopes for essentially the price of *one*. In my experience, this comparison can be quite shocking when finding out that the views through an even more expensive telescope are approximately the same as the views through the 8" on an average night. To call the $15,000 telescope a 'dobsonian' is to do John Dobson a disservice. They are engineered, truss-tube, portable, Newtonian reflectors plain and simple.

The idea of the large Newtonian reflectors have gotten to the point that they either require a large central obstruction from the secondary due to the sagitta of the primary being so steep, or they require a 10 to 15 foot ladder just to look through the thing. I could only guess how you would feel letting others crawl up a tall ladder in the middle of the night just to look through your telescope. Ladders are designed for short term use during the daytime, not for looking through an expensive scientific instrument in the middle of the night when it's below freezing.

We must all ask ourselves, as scientists, technicians, engineers, builders and makers, 'why has the hobby and industry copied a design style without the same initial goals?' It's the equivalent of project scope-creep for the hobby of telescope building as a whole. We need outside the box thinking, new ideas that have yet to be tried. 'Could it be possible to build a telescope larger than the biggest premium truss telescopes, have it in fact still be portable, have it be in a binocular configuration, have it match and surpass the performance of the premium Dobsonians, and provide for seating and standing *on the ground* for viewing the sky at all angles?' I do believe it is possible, and it's what I intend to outline in this paper.

I. THE GOAL

A big part of why I got into telescope making was not only for the adventure, but for the relative price of a finished telescope compared to commercial telescopes.

Kurt J. Foster
Revision v1.0