Mirror Magic

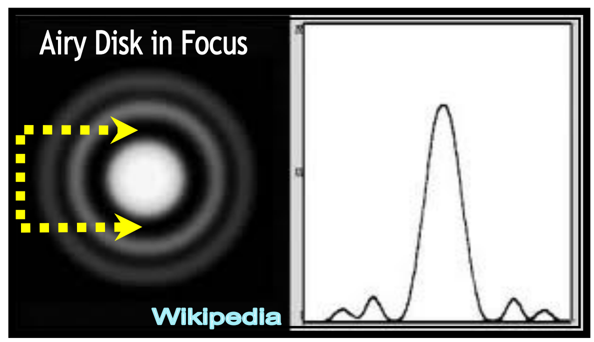
Telescope Mirror Making Basics

Optics, Testing, Mirror Machine, & Figuring

Part I Ver 11.3 By Lonnie Robinson

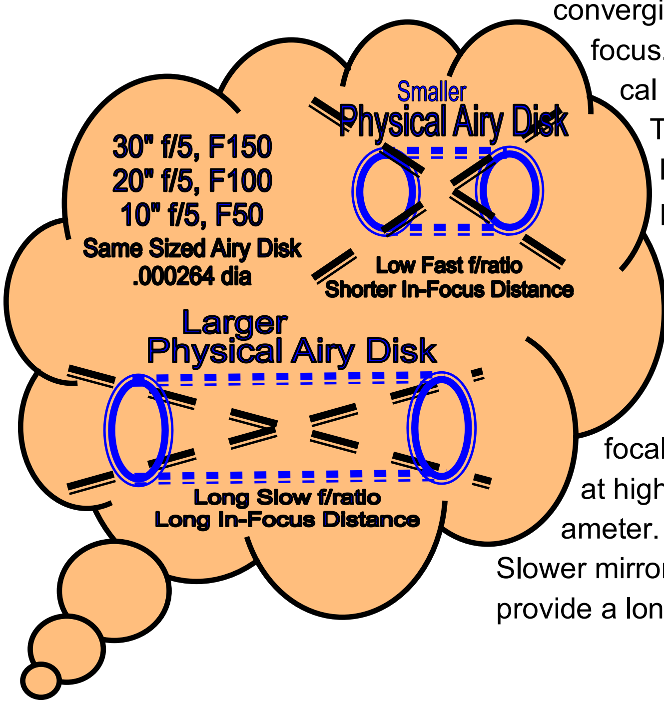
Grinding, polishing, testing, and figuring a parabolic mirror doesn't require sleight of hand, but there is more than just a bit of magic in the process! Magic in the way the Foucault knife edge nulls light casting shadows of hills and valleys on the mirrors surface, seemingly shining right through other hills blocking the way. It’s very magical to test for and plot a solution to perfect the mirrors surface slope measured in billionths of an inch, and then commanding the glass to make it so. Magic is there when you view celestial objects through a large mirror you handcrafted yourself! Magical indeed! Let’s get this adventure started.

Basic Optics for Mirror Making



The Airy Disk named after a British astronomer Sir George Airy, is the central circle of light where a telescope objective comes together in focus (F). There is a series of faint rings around the Airy Disk of decreasing brightness and together they are called the Airy Pattern.

Because of the vibrational nature of light, the rays coming together in at focus diffract and interfere with each other, preventing the them from converging to a single point focus. The result is a small central disk called the Airy Disk with a physical diameter measured from the center of the first minimum dark ring. The size of this disk limits the maximum resolution of all optics. Because it isn’t possible to craft our optics to focus to a single point, we are only required to target the focus within this predetermined central diameter of the central Airy Disk. The result is described as a 1/4 wave **Diffraction Limited Optic,** capable of the maximum resolution possible limited by diffraction, under “excellent” atmospheric conditions.



The Airy disk’s physical size is directly linked to the telescopes focal ratio. Fast mirrors and objectives with smaller f/ ratios reflect light at higher angles resulting in less interference and a smaller Airy disk diameter. They also have a shorter and more sensitive in-focus range. Slower mirrors with longer higher f/ratios have a larger Airy disk diameter, and provide a longer more forgiving in-focus range.

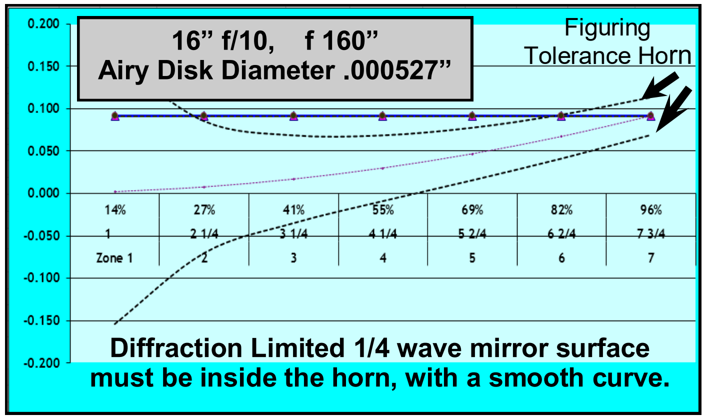
Miles LaCroix Charting

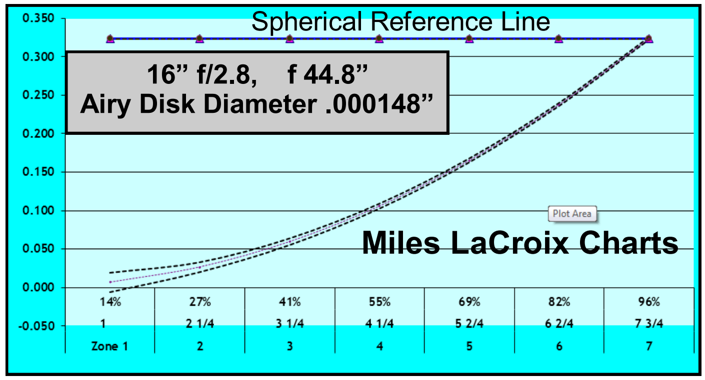
When figuring a mirror, the test results can be plotted in a chart called the Miles LaCroix graph. This graph has a tolerance horn that directly relates to the physical Airy Disk size, displaying the permissible range for the light to focus for a Diffraction Limited optic described as the 1/4 wave Rayleigh Limit.

Each zonal area across an objectives diameter will have a different f/ratio and therefore a different Airy Disk diameter. This diffraction limited tolerance range is displayed in the Miles Lacroix chart as increasing towards the objectives center, indicating a more forgiving figuring tolerance as the f/ratio increases.

If the maximum and minimum figuring tolerances are approached across the mirror's surface, it's important that the final curve is smooth with only gradual changes.

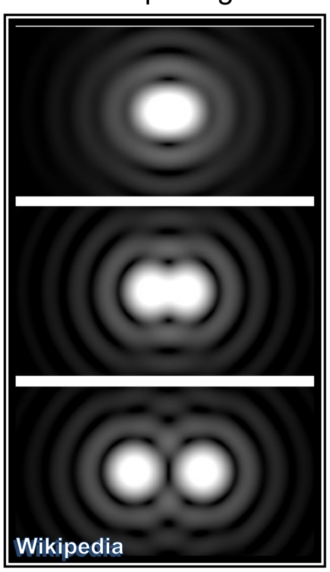
Notice the spherical reference line, it shows how far the parabola departs from a sphere. The faster f/2.8 requires a far tighter figuring tolerance and more glass removal than the f/10. These charts demonstrate why faster, lower, f/ratios require higher precision figuring.

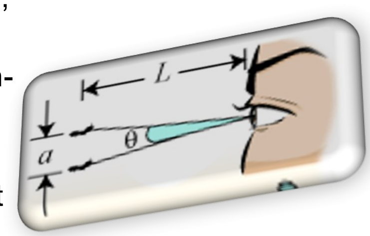




Angular Telescope Resolution

A telescope's Angular Resolution is inversely proportional to the objective size, it defines the image quality and resolution.
The Airy Disk's physical size variation has very little effect on image quality.





Telescope angular resolution describes the smallest object detail that can be resolved, it is an angle against the sky measured in seconds of an arc. An excellent example of angular resolution is viewing approaching car headlights with your eyes. At great distances the two lights are unresolved and will appear merged as one headlight. As they approach there will be a distance where the single light will begin to separate into two headlights. At this point the viewing angle between the headlights can be determined, and this angle will represent the angular resolution your eyes are capable of. The viewing angle of the headlights will continue to increase as they approach. A telescopes angular resolution capability is quantified by the smallest angle that will allow separation between two distant objects like close double stars. The **Rayleigh Limit** and the **Dawe's Limit** are commonly used to describe this point of separation.

When two telescopic stars are closer together than the radius of the physical Airy disk, they can't be split.

Angular Resolution

Objective Diameter	**Resolution** (arc-seconds)
8"	1.4
12.5"	.88
16"	.68
20"	.54
30"	.36

Angular resolution describes the telescopes ability to display objects clearly with high contrast, showing depth and relief, sharpness and detail. Higher resolution will bring out the small fine details of the Moon and planets, adding a more three dimensional effect rather than looking flat and featureless. Saturn's rings and our Moon's craters will show greater detail.

Increased resolution is similar to using a digital camera with higher pixel counts, and seeing the increase in detail and sharpness. The same goes when comparing the small lenses of pocket cameras to the large aperture Single Lens Reflex cameras. Phased array telescopes are another great example, their angular resolution is calculated from the maximum distance the optics are separated, just like the maximum distance across a single objective. Astronomers always want bigger mirrors to gather more light, and better angular resolution is a huge added benefit.

Interference and Edge Diffraction

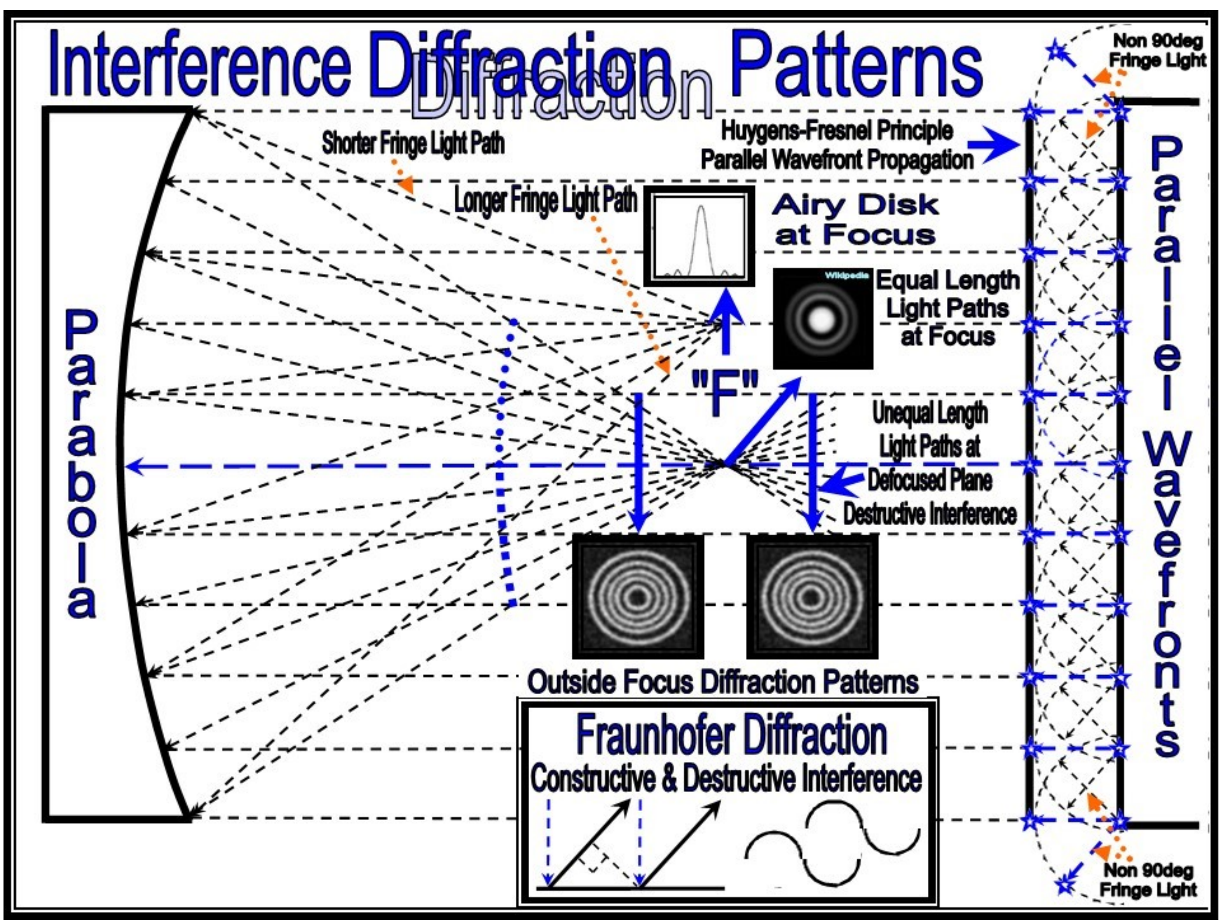
Diffraction and Interference Diffraction are almost identical terms. My preference is to describe light waves scattered after interfering with each other as **"Interference Diffraction"**, and light scattered after hitting an object in the optical path as **"Edge Diffraction"**.

Interference Diffraction: Light vibrates like sound and radio waves. If the phase relationship of separate light waves is displaced, they react by dimming or canceling each other out. This is called **Destructive Interference,** and is described by the **Fraunhofer Diffraction Theory**. If the light waves are displaced enough to cause a 1/2 wave phase delay, the waves will completely cancel each other out. This darkened area is called a "half-period element".

Light from a star radiates out in all directions in a spherical wavefront pattern, but after traveling the immense distance of even our nearest star, only the forward light supported by **Constrictive Interference** essentially arrives at Earth as a parallel wavefront with all the light waves in phase and reinforcing each other. **Constructive and Destructive interference** is used to described the **Huygens-Fresnel principal** of light wave propagation.

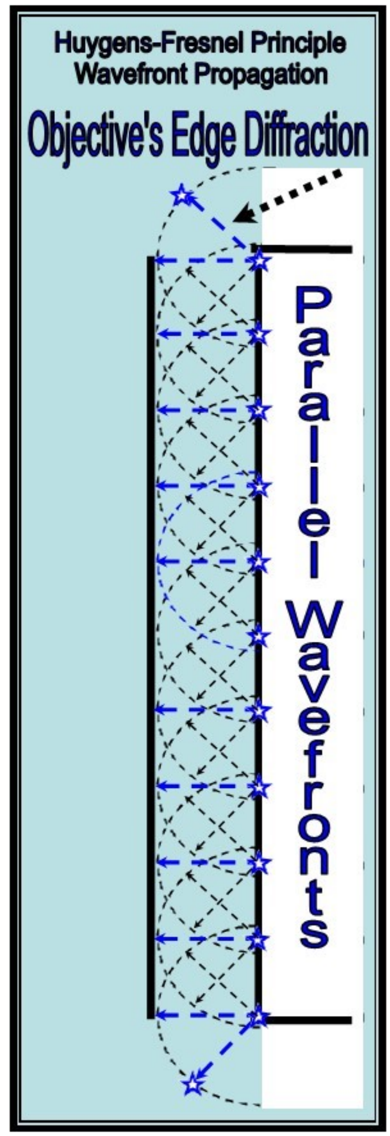
Huygens (1678) proposed star light arrives in wavefronts composed of countless images. Each of these star images radiate out in all directions, but only the forward rays survive destructive interference of their adjoining light points and pass on, in phase, to reinforce the next wave front. The distance between the wave fronts defines the frequency of the light, the wave height defines the light intensity.

Starlight wavefronts reflected from a round parabolic telescope mirror are transformed into a cone shaped wave front, with all the waves traveling equal distances to reach the focal point. These waves are reinforcing

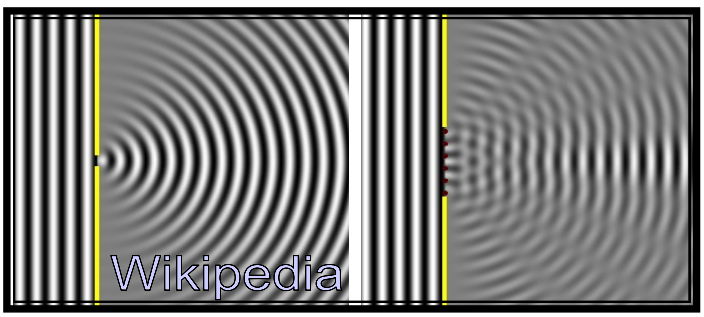


each other by constructive interference, and the focal point is called the Airy Disk. The focused Airy Disk has a "fringe" diffraction pattern. These faint rings are caused by off axis light from neighboring wavefronts, they travel different distances to focus, creating destructive interference and resulting in the faint light and dark rings. The complete pattern of rings is called the Airy Pattern.

If we examine a starlight wavefront reflected from a parabola, moving just inside to outside of focus, the light rays from different zones of the mirror's surface will be spread out from focus on a flat plane. These spread out rays are viewed traveling different distances from the mirrors surface, and the phase difference results in constructive and destructive interference producing the familiar "out of focus" bulls eye diffraction pattern. Viewing this pattern is very similar to putting a bulls-eye mask over the mirror, and viewing the light from select areas of the mirror's surface or zones. If the mirror has surface errors causing light to focus too long or short, it will brighten or dim these rings inside or outside of focus. This star test information can be used to figure or verify your telescope mirror surface profile. John Dobson would say if an outside-of-focus diffraction ring is too bright, that area needs more polishing. These bulls-eye zonal patterns aren't visible in the "focused" Airy disk where all the light comes together in focus.



Edge Diffraction occurs any time light encounters a sharp edge or obstacle like the circular edges of a objective mount, a mirrors edge, or hardware such as secondary mirrors and spiders. The outermost angled light rays are permitted to radiate out in their circular pattern without the destructive interference of it's neighbor. This results in a flaring or brightening around an object or edge. We see edge diffraction with Foucault and Ronchi tests as these unrestricted rays illuminate the zonal mask edges, knife edge, or Ronchi screen lines. The outer ring of the out of focus diffraction pattern is always a bit brighter than the inner rings, this is caused by diffraction from the circular edge of the mirror, objective, or the optical tube's edge.



Edge diffraction from a small objective affects the image quality more than a large one. Like waves in water going through a very small opening in a wall, most of the waves are diffracted or redirected. Larger openings allow a larger portion of the flat parallel wavefront to continue straight on through the opening.

It's the distance between the round edges of an objective (diameter) that dictates how much edge diffraction will effect the overall Airy pattern and the out of focus diffraction pattern.

Secondary mirrors block incoming light from the mirrors center and displaces some of the Airy Disks light out into the Airy Pattern. The result is a loss of image brightness, resolution, and contrast. Try to keep the secondary obstruction less than 19% linier, any less is barley noticeable visually. Refractors have a big advantage in this area, there is no central obstruction, but they suffer more edge diffraction effects from their smaller objectives.

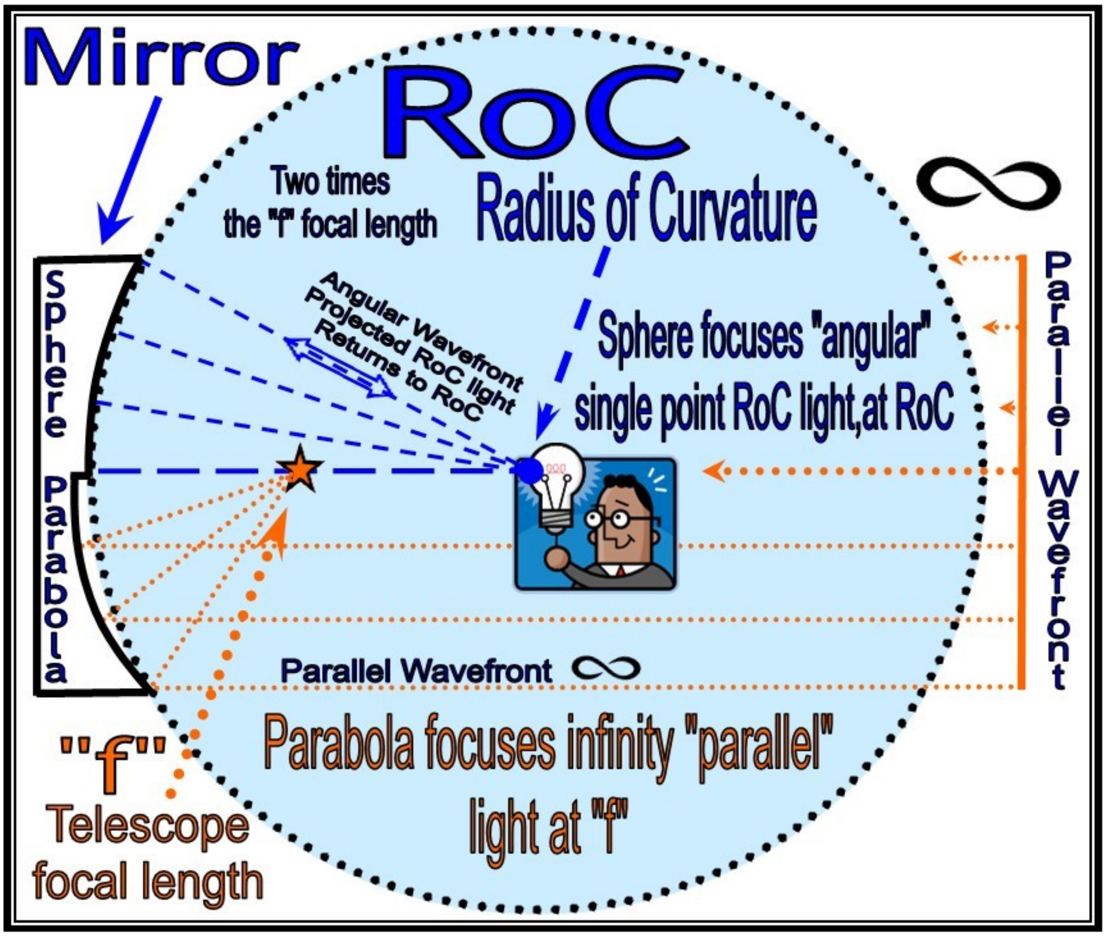
What is this Gizmo Called RoC?

The **RoC (Radius of Curvature)** is the radius from the center point of a round circle or ball projected out from and matching a spherical mirror's surface curvature, where a single point light source will reflect back to focus.

A Spherical Mirror will focus angular light emitted form the RoC, when viewed at the RoC. It will not focus parallel infinity starlight viewed at the focal point (half the RoC), and it will have a condition called spherical aberration (different focal points from the center to the edge) with measurable zonal focal length errors.

A Parabolic Mirror is exactly opposite! It will focus parallel star light from infinity when viewed at the focal length "f" (exactly half the RoC), but not angular light originating and viewed from the RoC. This angular light from the RoC will now display the exact same spherical aberration quantities as a sphere focusing at infinity. It could be called parabolic aberration.

The Foucault test can be used to measure and polish in these predetermined spherical aberration errors viewed at the RoC, to transform a sphere into a parabola. Shop testing at the RoC is desirable, star testing is not always practical. When measuring the RoC during testing, the distance is customarily measured from the mirrors center. Every zone on the parabolic mirror has a different focal length from the RoC, so there will be a "very slight" error present when measuring at the center.

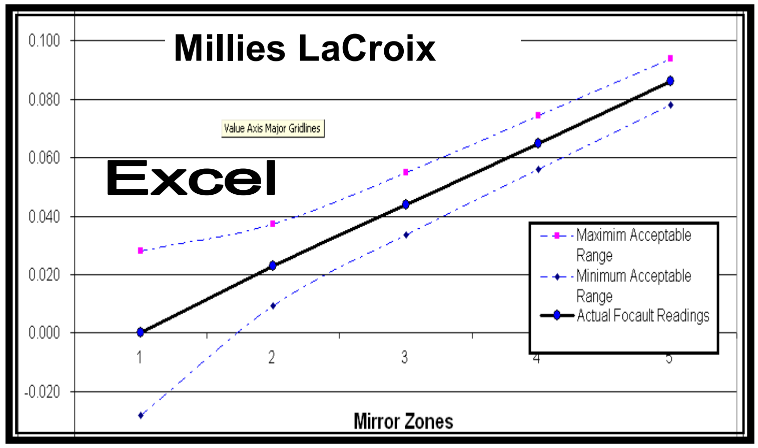


Why is the spherical RoC focal length twice the focal length of a parabola? The reason lies with parallel starlight versus angled light from the RoC. A light source from the RoC emits light at all angles and is reflected directly back equidistant from a sphere to focus at the RoC. Now consider parallel infinity light hitting a parabola, it arrives as straight-on parallel rays and is reflected at higher angles, pulling the "focus" down to half the RoC.

The more distant an angled light source is the more parallel it's light becomes, so the focus will vary accordingly. Focusing light from across the street requires moving the eyepiece outward for a longer focal length, somewhere between the infinity focus and the RoC. These in-between focal positions will show variable amounts of spherical aberration.

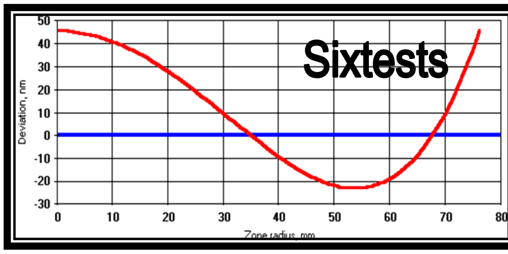
Test Data Reduction Software

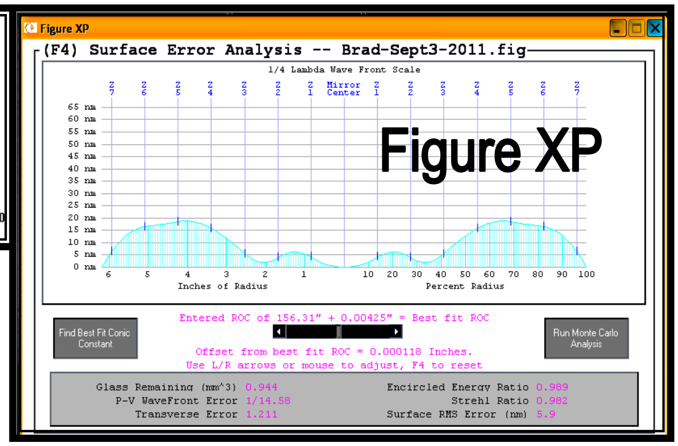
The **Millies LaCroix** chart is designed to show the diffraction limited 1/4 wave horn parameter (maximum allowable errors) of a mirrors surface, that mirror makers strive to be within. However, the final curve should be fairly smooth without severe kinks and be well centered.



It's very important to interpret the Millies LaCroix graph as the mirrors surface slope, displayed as numerical focal point locations, and not the actual surface profile!

A mirror can be figured with this slope information, but it requires extensive surface interpretation when deciding how and where to add correction. This is where **Sixtests** and **Figure XP** come in. Both free downloadable programs mathematically draw an accurate edge-on surface profile of the mirror's surface from Foucault data, making it much easier to plot a figuring solution especially towards the end of figuring. I really like Figure XP! I especially appreciate how it displays the surface profile in inches and metric, and it's ability to alter the RoC slightly to find the easiest way to figure the ideal surface profile. It's much easier knowing exactly where to remove glass, avoiding the slope measurements, and very rewarding to see the predicted changes in the following test results.

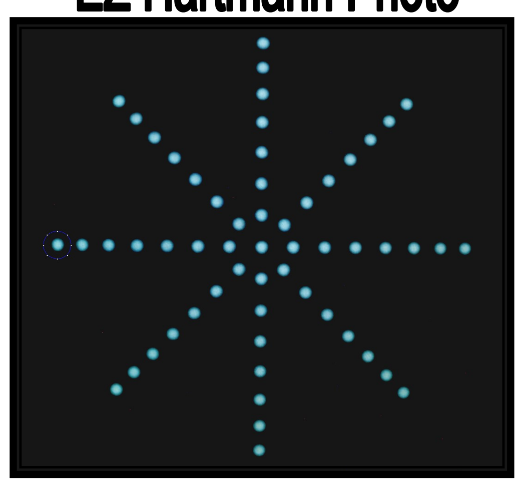


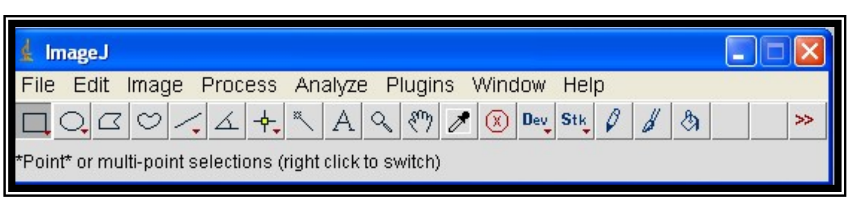


ImageJ Open Source Photo Processing Software

ImageJ is free photo processing software available for download. It was developed by the US government for scientific research, and it's open source programming which easily adapts to different requirements. ImageJ excels at ***measuring pixel locations of mirror mask zonal images and cleaning up large image files***. It determines the center of mass for each zones light image, and returns the exact pixel location of these centers. That center of mass numerical pixel location is used to calculate the mirror surface profile data.

EZ Hartmann Photo





Parabolic Mirror Testing Methods

The Foucault Test

Leon Foucault, French physicist,1819 to 1868 (passed at 49)

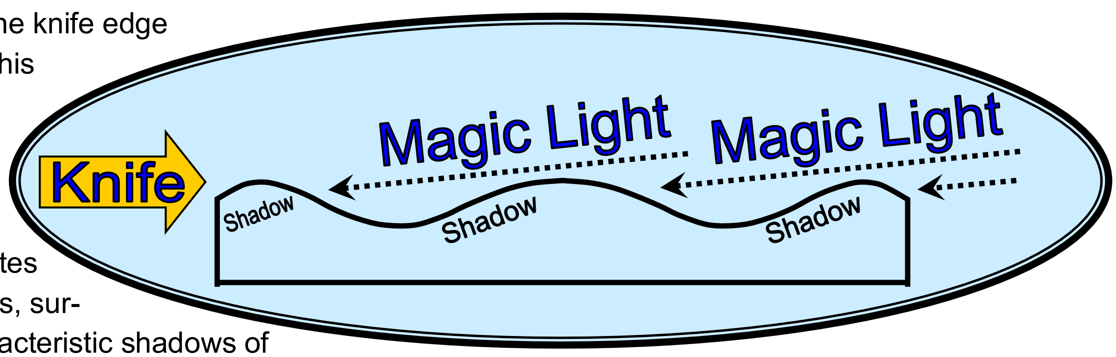
1850- Proved **light speed** is different through water and air.
1851- Used a **Foucault Pendulum** in the Pantheon in Paris to show the rotation of the Earth.
1852- Named the Gyroscope.
1855- Discovered **Eddie currents**, the extra force needed to rotate a Copper disk between magnets.
1857- Invented the **Foucault polarizer**
1858- Invented the **Foucault knife-edge test** for mirrors.
Foucault Figured the first glass mirror with a silver coating!

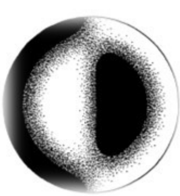
He revolutionized mirror testing and figured **the first glass mirror with a silver coating** invented by a German chemist Justus Von Liebig. Mostly guesswork before the Foucault test, by working in the dark and star testing. Foucault amplifies mirror surface defects by a factor of one million.

The Foucault test is very simple and precise, it employs a light source at the RoC, and a razor blade to intersect the reflected light from a mirror. It is an **extremely sensitive** test, able to show immeasurable glass expansion caused by touching the surface with a warm finger! It exposes minute surface relief details by casting shadows around valleys and illuminating hills. It is very **easy to use!** Simply measure the different mirror zonal focal points and compare to predetermined ideal values of a parabola.

Foucault Magic Light Shadowgram

Because a parabola has an infinite number of focal points at the RoC, when cut by a knife edge it will exhibit a circular null shadow on the mirror's surface for the radius in focus at the selected distance. It appears to expand and contract across the surface as the knife edge moved along the optical axis. This shadow is magic because light appears to originate at very low angles from only one side, the side opposite the knife edge. It illuminates the surface and creates shadows around hills and valleys, surface deformations, and the characteristic shadows of the various surface profiles. The light is magic because it ignores the fact that there are hills in the way that would normally block the low angle light from the next hill, seemingly shining right through them. When the Foucault knife is inserted in the light cone from the left, will null the crest of a parabolic zone as a magic circular shadow darkened on left side of the mirror and illuminated circle on the right side. The overall left shadow pattern appears to be the inverse of the right shadow. Again, imagine the magic light from the right illuminating the upside crest of the parabolas doughnut shaped zones and casting a shadow on the downside. It is very important to note which side the knife is intersecting the light, to correctly interpret high and low areas.





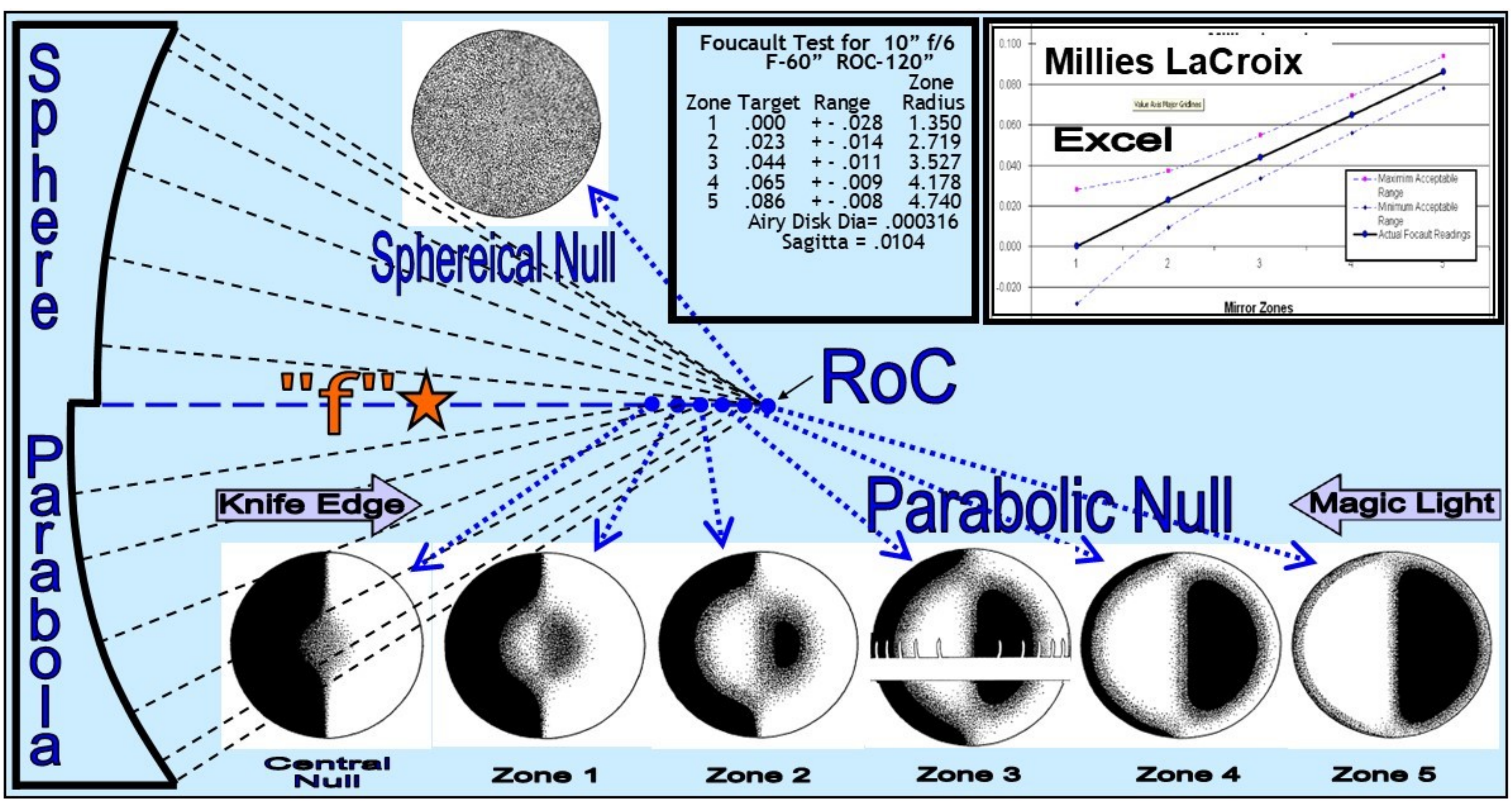
Testing and Figuring the Parabola from a Sphere

"A sphere will focus a single point "angular light" source from the RoC, a parabola will not. A parabola will focus "parallel starlight" from infinity, a sphere will not. They are exact opposites."

First, we create a sphere because it happens rather automatically during rough to fine grinding. **Then when testing at the RoC we will figure or change the surface profile to a parabola, by polishing in the spherical aberration errors that would be present in a sphere when viewing parallel starlight.** The resulting parabola will focus parallel starlight from infinity to one focal point "F" or the Central Airy Disk. ("F"=the focal point, "f"= focal length)

When testing a sphere with a light source originating from the RoC, and inserting a knife edge from the left at the exact focal point, it will cut off (null) all the light and darken the entire mirror surface. Viewed inside the RoC, the knife will first block or null the light coming from the left and darken the left side. Viewed outside the RoC, the left side knife will block the light crossing over focus from the right side leaving the right side dark. Inside and outside of focus, the sphere will display a straight vertical shadow terminator line that will remain straight as it is moved side to side with a lateral knife adjustment. This side to side movement will show edge and other surface defects just like a Ronchi screen test. If major astigmatism is present, the terminator line will lean side to side, in and out of focus.

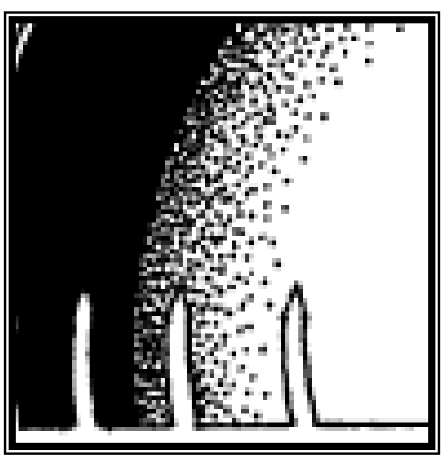
When the spherical surface is altered towards parabolic there's no longer a single focal point, but a infinite number of different focal points (nulls), one for each different radius or zone on the mirrors surface. These zonal shadows are no longer straight, they become circular in shape and the shadow on one side appears to be the inverse image of the one on the other side. Remember the magic light. Moving the knife back and forth along the optical axis will locate the different focal points or zonal nulls, the shadow will expand or contract sideways across different radius positions on the mirror. Adjust the shadow position to an exact mirror zonal radius location highlighted by an Everest pin or Couder screen mask, balance the shadow on the left and right sides, and take a focal length measurement to compare with the predetermined ideal focal points of a parabola. This information will guide us while polishing in the perfect parabola shape.



Experiences with Foucault Testing

Leon Foucault's test is simply genius. His test has enabled countless fine mirrors to be handcrafted by amateurs and professionals alike. I became totally absorbed by the whole concept and constructed my own test stage from the Stellafane plans, to test and figure my first 16" f/5 mirror. It turned out fantastic! I have claimed to be very lucky trying to show my modest side, but in truth it went as planned. Everything went smoothly as I brought the curve down to a parabola from a polished sphere, but the closer to finishing the more difficult testing became. Judging the center of the Foucault shadows is difficult at best and several repeated sets of readings, all averaged together, was the only way to get the needed accuracy. Some of the sets of readings just looked out of whack, so I would discard them in favor of others that seemed to follow the trending curve. I constantly resisted the urge to customize the readings to what I knew they should be! I had a particularly difficult time reading the outermost narrow edge zone and the center two zones with their mushy long focus f/ ratios. Each set would take me at least 15 minutes behind the knife, so a total of four sets would take an hour! Then another 30min or so to enter all those numbers and analyze the results in my computer. All this testing for results that might require 15 minutes, or less, of light polishing on the offending zone to correct! Before testing, the mirror must rest in the test stand for at least one hour to equalize temperature after figuring and adjust to its new position (varies by mirror size and thickness). Add this all up, and you have spent **about 2.75 hours for each testing and figuring session!** No wonder this mirror making takes so much patience!

The Foucault shadows are fuzzy and hard to read at best, and early on I realized that there is a terminator or sharp line at the shadows edge that seemed to indicate the shadow location with greater accuracy. I would place that dark-light line in the center space between the zone markers (Everest Pins), attempting to position it at the zone center figured as an area rather than a radius. I soon discovered that I could get much grater accuracy using the Everest Pin zone locater rather than a Couder screen mask with holes cut out for each zone. I liked the open view of the whole mirror behind the Everest pins, which allowed me to more easily balance the left and right shadows and critique the entire surface condition and curve. The shadow followed the long curved horn zonal markers with a more positive positioning as I moved the tester fore and aft on the optical axis. So far so good! When running the numbers of a test series, I used the zone closest to the 75% zonal area of the mirror as a home row. It's important to note any changes when returning to that home zone from the center or edge. It's ok to adjust the side to side knife position, balancing the right and left shadows, as the test progresses to each zone. I concluded that unless the shadow balance stage adjustment was minimal and extremely accurate, it could introduce a second potential serious error and change all the lengthwise measurements accordingly. One single, very accurate test stage alignment on the optical axis, and centering of the right and left shadows significantly reduced the required side to side adjustments for the whole test and improved the accuracy.



It was very disappointing each time I returned to the 75% zone the numbers kept changing!! It was much worse in hot weather with he sun bearing down on my garage wall. It's called **"test stand creep"**, and it comes from everywhere that can be effected by thermo expansion. The floor and walls evidently move, ever so slightly, as the temperature changes! The best and most consistent testing was accomplished during a cool early morning after everything had equalized in temperature. Otherwise, the only solution was to align the shadow at the 75% zone and test the inner zones, then reset at 75% and test the outer zones. However, the consistency of the numbers always suffered testing this way! I needed a better way to test mirrors!

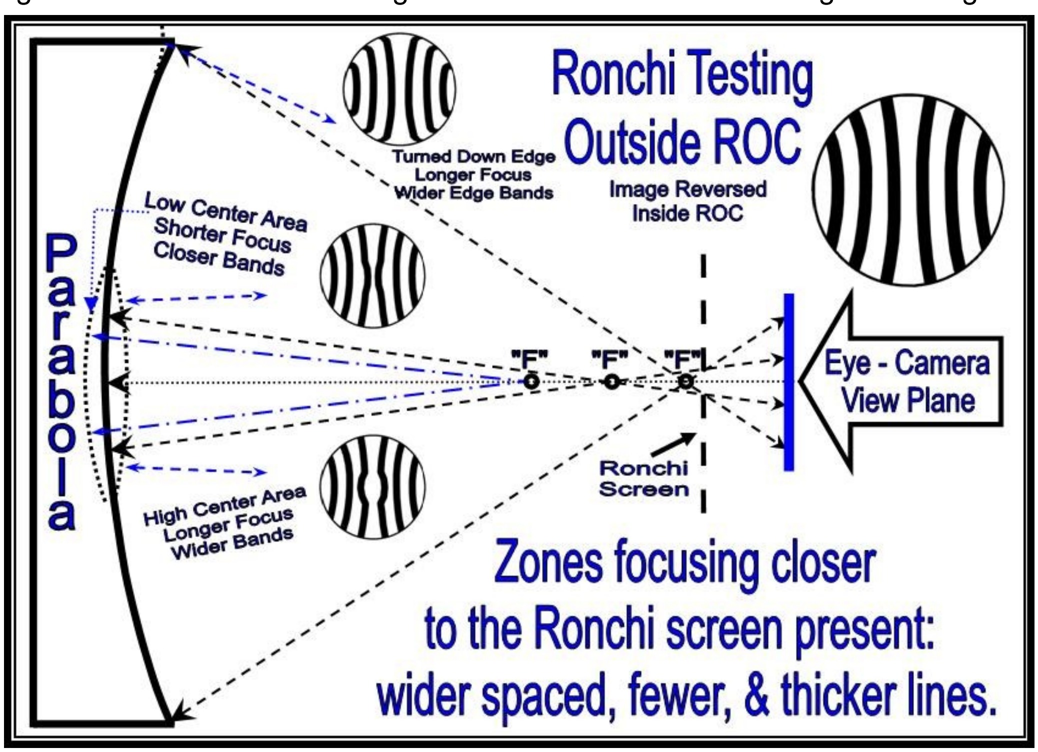
Ronchi Screen Testing

This test is very similar to Foucault with respect to the knife cutting the returning light source from the ROC, and is applied in much the same way. It's like using multiple double edged knifes that return many bar shaped shadows that start out straight with a sphere and begin to curve while figuring towards a parabola. It consists of a lined grating on mylar or glass, usually 80 to 250 lines per inch, and is viewed along the optical axis by scanning inside to outside of the RoC. It is suggested to use higher line count gratings for faster f/ratio optics, which increases the sensitivity. I prefer line counts between 80 and 100, diffraction artifacts become intolerable with higher line counts.

The closer the grating is to a mirror's zonal focus, the lines become wider, fewer, and further apart.
The parabolic surface patterns are opposite inside or outside of RoC. Sphere remains the same.

A **sphere** will focus an angled light source from the RoC, the projected light is reflected directly back equal distant to the origination point, and displays as parallel Ronchi lines. The **parabola** will not focus a single light source from the RoC, the center zones focus shorter pushing the Ronchi line centers in or out from the center, inside or outside of RoC. As the grating is moved closer to focus it intersects a smaller diameter of the light cone, displays fewer lines, and gives the impression of magnifying and expanding the lines. Outside the RoC, a turned down edge displays line ends hooked outward because the edge focuses long, they will hook inward inside the RoC. Any surface zoning will return skewed or deflected lines around the defects, a rough surface will show rough or jagged lines.

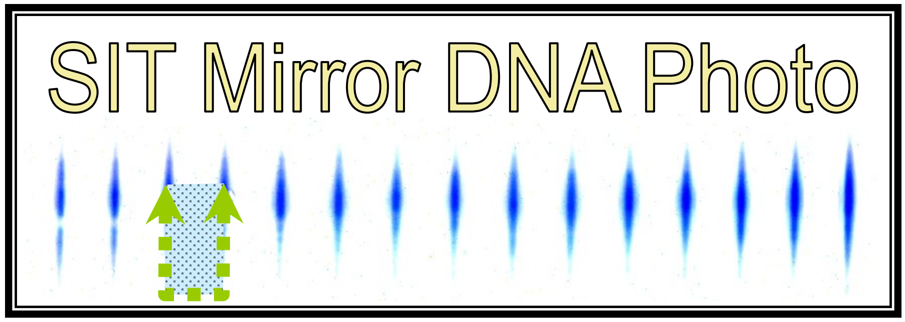
The Ronchi test is especially useful during polish and early figuring stages to locate the RoC, follow the smooth progression towards a parabola, and a great visual test for monitoring the absence of turned down edge and astigmatism. It is important to achieve smooth curved lines with well defined edges, indicating the mirror surface is smooth and zone free. The Ronchi test results are called **"qualitative",** because they don't provide the optician hard data for an exact surface profile. For final figuring, Foucault results provide the necessary mathematical **"quantitative"** surface measurements.



Using a Ronchi screen over a telescope eyepiece while viewing parallel starlight, will return straight spherical-like lines from a parabolic mirror, because the entire parabola will focus to the same point with infinity light.

Slit Image Test

Several years ago a friend dropped by with his 12.5” f/5 mirror that was polished out spherical, with a great edge, that needed to be finished. We proceeded to figure to a parabola using my Foucault tester under the previously described conditions. Everything went well considering, and we finished up in a reasonable time. During this time I had been working on the ATM effort with Bill Thomas from a neighboring astronomy club, and he introduced me to his new **Slit Image Test (SIT), yubagold.com.** I immediately thought the SIT was a huge improvement over Foucault. It captures a single digital camera photo of projected slits of light from a single light source reflected back from a series of holes cut in a mask across the mirror. The resulting photo bears a strong visual resemblance to DNA protein helix markers, and I like to call it the mirrors DNA. The test results are computed from the known exact mirror mask zonal hole locations, the ROC, and the pixel distances between the slit images on the photo measured with ImageJ software.

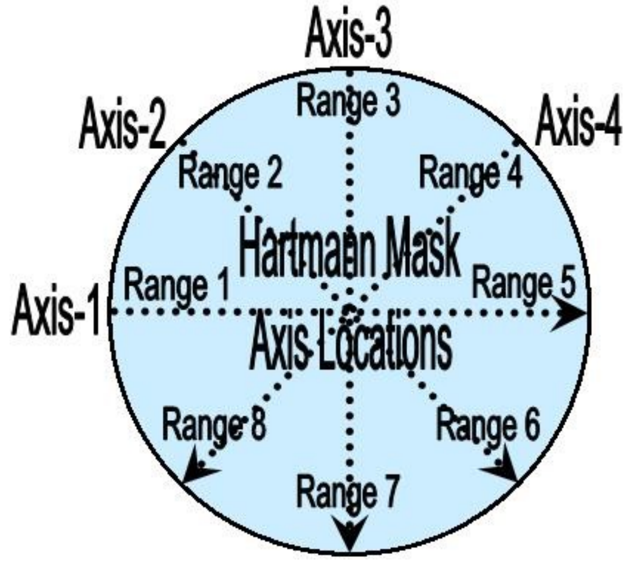


We retested the 12.5” mirror with the SIT test, and it barely passed the 1/4 wave Miles Lacroix tolerance! The areas I mentioned earlier that I found hard to read with Foucault, were the areas the SIT showed long. OK, which test do I believe?? I had no experience with the SIT and after all Foucault had been around a while longer than the SIT test!

The SIT camera captures a single image of mask hole locations across one radius, so no test stand creep can rear its ugly head. The camera is recording the image instead of the eye, making it possible to use several more smaller zones for a given size mirror, producing a much more accurate surface profile. It can accurately read a zone located much closer to the outer edge than with Foucault. The accuracy of Foucault readings have been estimated between +-.050, I believe the SIT accuracy is down around +- .002!! There are no human judgment errors as to where the shadow lies from test to test, or with different individuals doing the test. No eye fatigue, handy for those occasional late nights before with little sleep. The test results were repeatable, almost exactly, time after time so only one test run was needed! Once the tester is laser aligned to the optical centerline, simply move the camera back until all the zone slit images fill the entire CCD. The RoC should be rechecked often to keep it within a generous 1/8” tolerance. Did I mention that I didn’t need to enter the test numbers manually? Simply copy the results from ImageJ or Photo Shop and paste them in Excel. No more potential entry errors! The SIT Excel spreadsheet computes the pixel location information and plots the curve on a Miles LaCroix chart. It also outputs Foucault data for FigureXP. For me it was an absolute no brainier, I had to incorporate the SIT test with it’s obvious advantages! We decided to refigure the 12.5” mirror using the SIT test. After waiting an hour or so for mirror to stabilize temperature on the test stand, testing took about 15 minutes from start to finish, computer processing about 15 minutes, and final figuring about 15 minutes for a total of less than 1.75 hours!!! Now I could spend an eight hour day testing and figuring, and easily get in 4 sessions instead of 3, **faster than Foucault and far more accurate!** It’s really a blast to have this continuity between testing and figuring, quickly getting desired results that agree with the last plotted figuring solution.

EZ Hartmann Test **by Lonnie Robinson**

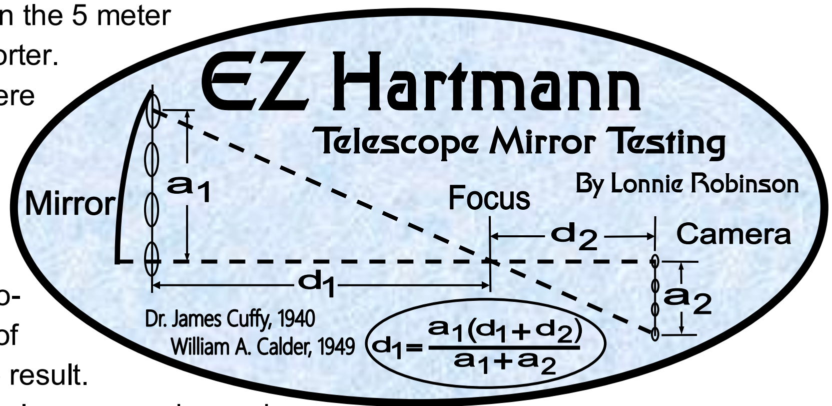
In use, the Foucault test was extremely difficult to obtain repetitive numbers. The SIT is a giant step forward in accuracy, repeatability, and ease of use. However, I soon realized the need for an all mirror test, one that would return data for the whole mirror from a single photo. It's just amazing how much is missed with a single axis test! I tried with some success using the SIT by rotating and testing the mirror at four different axis positions and hand correcting each axis, but that was problematic because it averaged the left and right side results of each axis. This method proved to be exhausting, requiring a fresh setup and test for each axis, and introduced error potential from individual setups. However, it did demonstrate a real need for an all axis test, exposing unknown errors everywhere on the mirror. Countless great mirrors have been successfully made using Foucault even though it only returns data for one half of a single mirror axis and assumes the rest of the surface is identical. It's possible, although unlikely, to accurately figure a mirror with a single axis test using exacting machine procedures, and ending up with correct slopes over the entire surface.



In my ongoing quest for an all mirror test, I took a serious look at the Hartmann test invented around 1900 by a German astronomer Johannes Franz Hartmann. It employed an all mirror mask with many holes of known locations, used two photographs, one inside of focus and a second behind it, and parallel starlight for the light source. This test used the triangulation of starlight image locations in the two photos, to plot errors on the mirrors curve and compared it to a perfect mirror. It was mainly used by large observatories to star test their operational telescopes, to determine in-service finished mirror accuracy and adjust the mirror cells. Hartmann was largely perceived by the amateur only for use on large operating observatory telescopes, and seemed too complex to implement with two photographs. These are likely the major reasons it hasn't been used widely in the ATM community.

In about 2010, I came across a great article describing Hartmann testing in a 1940 publication called **Amateur Telescope**. Included in the periodical was an article titled Observatories by Albert G. Ingalls (Amateur Telescope Making), and included in that article was **The Hartmann Method of Testing, From Amateur to Pro,** written by Dr. Cuffy. The article began by describing how the amateur has all but ignored the great potential of the Hartmann test. He then described a simplified Hartmann in-shop test that only requires one photo behind the RoC instead of two, and substituted the customary second photo with known mirror mask hole locations. The entire process was described from the mask hole size and locations, camera mounted perpendicular to the mirror, the use of a pinhole light source at the RoC, how to measure the photo light image locations, to a complete description of the principal formula using equal triangles. Years before digital cameras, he described using a photo enlarger to project the expanded photograph of light positions along long strips of paper and physically measuring their locations. Performing the test in the workshop with angled light from a pinhole light source at the RoC, allowed the use of the same parabolic formulas employed with Foucault testing. He went on to suggest the amateur can easily use this method at any stage of mirror making. Currently, there are several applications and references of single photo Hartmann like tests similar to the one described by Dr. Cuffy in 1940; Amateur Telescope Making by Inglalls, Star Testing by Suiter, 2D Hartmann by Burrows, Spot Testing by Sherman, Slit Image Test by Thomas, SCOTS Reverse Hartmann at the Richard F. Caris Mirror Lab, Hartmann Test by Micro, and probably more. Dr. Cuffy used his simplified Hartmann method to successfully test the optical surface of the 36" f/5 mirror in the Goethe Link Observatory, in Brooklyn, Indiana.

A major technological advance that greatly improved all telescope mirror testing was the Digital Camera. Film was cumbersome at best requiring the optician to physically measure the separation of points of starlight reflected from different mirror locations. Digital capture allowed the precise computer measurement of the pinhole light images X & Y pixel locations with available software, it's fast and extremely accurate. One of the earliest Hartmann tests utilizing a CCD camera instead of film was conducted on the 5 meter 200 inch Hale telescope mirror in 1985 by Alain C. Porter. Mirror testing was never the same after that. Now there are many mirror tests using Digital cameras, a predominate one is called SCOTS (Software Configurable Optical Test System) developed by the University of Arizona's Richard F. Caris Mirror Lab. It's called a reverse Hartmann because the zone locations are projected from a computer monitor to the mirror instead of using a mask, and a single camera photo records the result. They claim its accuracy rivals Interferometry and is far less expensive and easier to conduct.



I was totally inspired by Dr. Cuffy's article and decided to implement his suggested Hartmann shop test with roots back to early 1900, create my own Excel worksheet, and call it the EZ Hartmann. The EZ Hartmann evaluates four different axis', eight different ranges, and returns all that data for the entire surface from a single digital photo. Dr. Cuffy's formula for locating the focal points of each zone (d1) proved easy to apply with simple geometry, and the addition of a few standard Foucault formulas for finding the desired zonal focal points and the maximum allowable 1/4 wave mirror tolerance completed the process. The test results are plotted in Miles LaCroix charts and the Foucault data is extracted for import into FigureXP. Being cursed as a perfectionist, I crave having all the data possible! EZ Hartmann has significantly increased the likelihood of crafting an excellent mirror!

Making the EZ Hartmann mask requires great precision, the hole locations and the camera pixel locations must be highly accurate! Please don't let this precision scare you away, with a little effort it's doable and very rewarding. I use .060 ABS sheets for the mask and a router cutting jig similar to the one suggested by Bill Thomas. Taking the mask jig to the next level, I added a brass router cutter guide bushing in the fixture base, and a guide ball bearing on the router bit that fits snuggly in the bushing. This arrangement removed most all of the plunge router slop, and enabled cutting mask hole locations within +- .005. The mask jig's accuracy was again improved dramatically with the addition of a 36" digital read out scale (a DRO), connected to the router base plate. Early on I used a 3" dial indicator, but it required resetting after each hole increasing the error potential. The Hartmann mask is made by using a square sheet of .060 ABS, cutting the first row of holes and then rotating it around the center hole to the next axis. When all the holes are finished the entire mask is cut round in the router jig, 1" larger than the mirror, by rotating it around a pinned center hole while advancing it into a fixed 1/4" router straight bit. Only three mask holder mounts on the mirror are necessary, the long arms over the mask face help keep it hanging flat. The nylon bolts near the center can be shimmed to gently touch the mirror to help keep the mask flat, and covered with electrical tape to protect the mirrors surface. The ultimate mask cutter would be a CNC Router, which is on my bucket list!

The EZ Hartmann offers many advantages over a single axis test.

One of the most important is the ability to detect and target **astigmatism** anywhere on the mirror. Besides displaying four non-averaged Miles LaCroix charts for all four axes and eight independent ranges, it compares the pixel distances across opposing zones. Any difference in neighboring same zone pixel counts indicates different focal points, the definition of astigmatism.

The four Miles LaCroix charts, can teach anyone how to bring down the curve evenly across the entire mirror, any errors that show up as you progress are corrected by adjusting your timing and figuring positions as you proceed. In my opinion, serious errors are unavoidable when figuring by hand, the machine has the ability to figure a surface of revolution equally all around the mirror but only if used properly. It can also smooth things if they get out of control. EZ Hartmann outputs Foucault data for each of the eight ranges, each axis average, and overall mirror averages, making it possible to chart the surface profile for any location on the mirror with FigureXP.

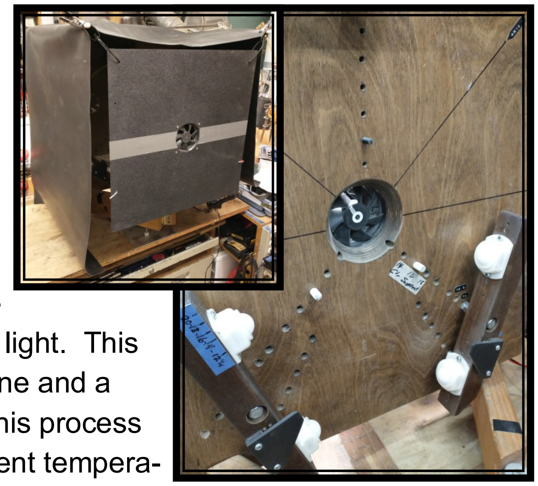
There is a very rewarding learning curve starting with Foucault and ending with Hartmann or perhaps Interferometry. Foucault teaches the necessary basics of mirror testing, and should be explored before progressing to other tests. The Ronchi screen is used with all tests showing progress toward a parabola, edge and surface condition. Each test you master will give you invaluable knowledge to apply to the next test. Photographic tests like the Hartmann vastly improve Foucault's issues, one photo producing numerical non-judgmental results for the entire mirror. EZ Hartmann takes accurate mirror testing to the next level, and challenges the mirror maker!

You can only make a mirror as accurate as your test results!

Mirror XYZ Test Stage & Camera

Temperature Changes & Testing

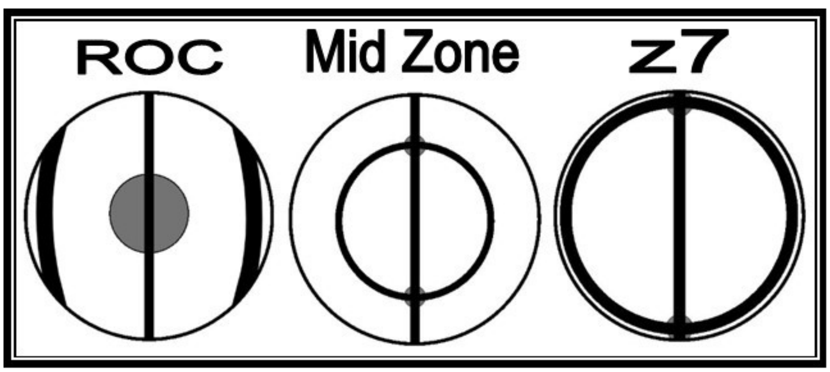
Remember all the stories about ATM'ers testing in cool and stable basements with enclosed tunnels to prevent air currents? Well, indeed temperature changes will be your worst enemy. We discussed test stand creep with Foucault, and how photographs help eliminate it. We still need to watch air currents, which are averaged out in long exposures. The major issue left when testing is temperature equalization in the glass itself, mirrors change temperature very slowly from the center outward, so it is vastly important to allow the overall temperature to equalize. Minor temperature related issues will also effect the curve; not removing the mask during cool down, cleaning solution evaporating and cooling the surface right before testing, touching with warm fingers, nearby furnace or hot water heater running, anything that varies the air temperature period! My first idea to solve this issue was realizing there was no air circulation between the mirror and my test stand. This caused unequal stabilization, so I added a small 12v exhaust fan



centered behind the mirror. Since I don't have an air-conditioned test room or a basement, my solution for consistent testing was to add an additional fan located in front of the mirror's center blowing on the front surface. The front fan is located about 18" away, far enough for the moving air to expand over the mirrors diameter for even gentle coverage. If the fan targets a specific area on the glass, it can cool the mirror unevenly, so I used a 6v power supply with the 12v fans to reduce the speed and disperse the cooling air even more. The mirror test stand is shrouded with rubber shelf lining material around the sides to duct the airflow, and also serves to stop stray external light. This arrangement has produced very consistent test results after approximately one and a half hour of cool down, regardless of room temperature changes. I verified this process by comparing fan results to early morning benchmark no-fan tests at consistent temperatures, and achieving repeatable results all day long. It's a serious challenge getting your head around the extremely small tolerances of mirror making.

Trust but Verify All Test Results! Remember the Hubble!

Hubble nearly failed because the mirror test results were not confirmed! Taking the time to star test, or even a quick visual view would have exposed the error. I use Foucault measurements for a sanity cross check, it is far less accurate than EZ Hartmann but verifies I'm in the ball park. On a regular basis I use the Ronchi screen to verify the overall figuring progress by moving the stage to z0, the RoC null, and take an indicator reading. At z0, the Ronchi expands to a single line which then becomes a double edged knife test similar to a wire test. It displays an expanding pie like shape as the stage is moved along the optical axis away from the RoC. Then take a reading at the outer z7 null, like Foucault this distance from z0 to z7 gives the overall progress towards a parabola. It also provides astigmatism data, by critiquing the round zonal null shape. Make sure the circular shadow ends complete to the vertical line, an open ended "S" shape indicates astig, and watching for any lean in the vertical line that swaps position in-out of fucus.



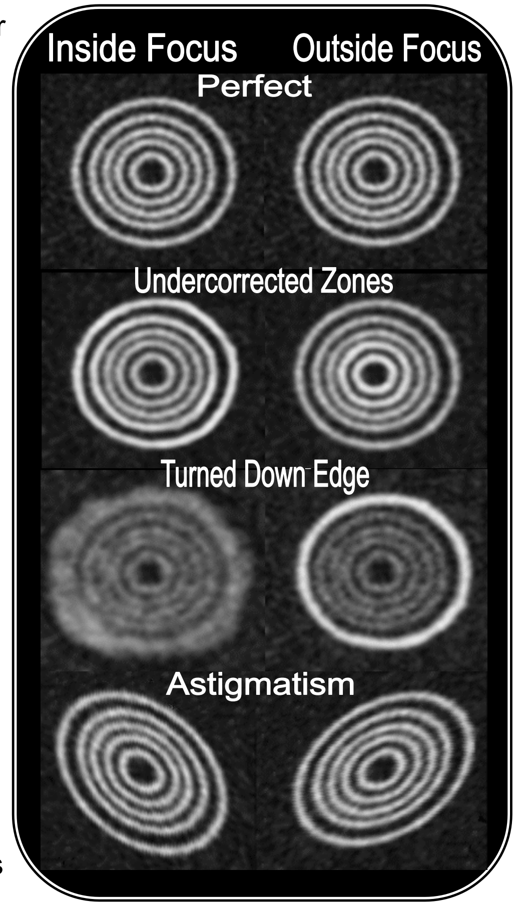
I also tried with great success, a suggestion from Everest Pin testing to run the knife or wire test in reverse when the mirror is finalized. Set the stage dial indicator to the required focal point distance for each zone and then check the shadow locations. This can be done with the Hartmann mask too, each zone position will null the mask opening. Surprisingly accurate and refreshing viewpoint for verifying a finished mirror! And then last, but not least, perform the star test for absolute conformation.

Star Testing, the Final Mirror Test

Star Testing is the cold hearted critical critique of all your efforts at mirror making. The goal is to have identical defocused diffraction patterns both inside and outside of focus. A perfect mirror is very rare and this test is extremely sensitive, so the trick is to learn just how much perfection is necessary. Remember to equalize mirror temperature before testing!

This "out of focus" diffraction pattern will expose the telltale signs of stray light, light from a particular zone that may be focusing long or short, a long zone focus will brighten a diffraction ring outside of focus. It will expose the oval swapping elongated shapes of astigmatism. It will show a dull fuzzy outer ring inside focus, and bright ring outside, tattling on a turned down edge. It will disclose a rough surface with erratic lines.

Good easy stuff except for **one major issue, enjoying a perfect night of seeing that will provide a steady star diffraction image!**



As a mirror maker, I like to visualize the round diffraction pattern much like a Foucault or wire test. Each ring "roughly" represents a circular radius zone of the mirrors surface, and the whole pattern is the entire objective right to the edge. When a mirrors zone is focusing light longer than ideal focus (because of a surface error), the light is displaced to brighten the corresponding diffraction ring outside of focus and leaving it darker inside of focus. A TDE focuses long and brightens the outermost ring outside of focus. The size and brightness of the secondary mirror breakout shadow should be the same size equidistant in and out of focus. If not, it will indicate over or under correction. The mirror is under corrected if the diagonal shadow breaks out early inside focus (longer focusing inner areas, pushing the secondary shadow balance point outward). Now you can see how the out of focus diffraction pattern, used in star testing, can tell us a lot about mirror quality.

John Dobson used the star test to figure his mirrors. He had a simple rule: Move the eyepiece outward from focus; those areas of the mirror that appear excessively bright, or have bright rings, are focusing longer and need more polishing to increase the slope and bring the focal point lower. The opposite is true for inside focus.

The star test is the final word on your mirrors surface quality! Star testing with an uncoated mirror, installed in your telescope, is a great way to confirm your mirror before sending it off to for aluminizing. You can get some really stunning views of bright objects without the aluminum! The total uncoated mirror light grasp is about 4% of an aluminized one, making an uncoated 16" about equal to an aluminized 3.2" (20% of diameter) but with a 16"s resolution. My 16"s resolution showed amazing detail on the Moon without needing a filter, and Saturn was tack sharp. Try using Polaris to star test with your Dob, because it moves very little in the sky.

Mirror Quality	PTV Wave	Strehl Ratio	Airy Disk % light energy	Diffraction Rings % light energy	RMS	Usable Power Per Square Inch
Perfect Optics ***"Seldom attained"***	0	1	84%	16%	0	
Excellent Optics **Francon Criterion**	1/16	.99	83%	17%	1/54	35-50x
Very Good Optics! **Our Target Quality**	1/8	.95	80%	20%	1/27	25-35x
Good Optics **Rayleigh Limit "Diffraction Limited"**	1/4	.80	68%	32%	1/14	25x
Poor Optics	1/2	.40	40%	60%	1/7	15-25x
Bad Optics?	1	.10	10%	90%	1/3	12x

Mirror Quality Yardsticks

The Strehl Ratio is an excellent indicator of overall mirror quality (contrast & resolution) The Strehl ratio describes how much reflected light energy from the mirror is concentrated in the central Airy disk and how much is deflected out to the diffraction rings. The Francon Criterion at .99 Strehl or 1/16 wave PTV, is the point that any further improvement will not be visual. Notice there is very little improvement to the Airy disk light energy after **"Very Good Optics" at 1/8 wave PTV or .95 Strehl**, therefore most experts recommend at least this level for a quality optic. **The Rayleigh limit at .80 Strehl ratio, or 1/4 wave, is considered a minimum to be called Diffraction Limited. This is the point where diffraction limits maximum amount of light that the airy disk can**

hold, the point where improving the optic has very little impact on the image in “good seeing”. Again, this 1/4 wave Raleigh limit is depicted as the tolerance horn in the Millies LaCroix graph. Making a mirror to a higher tolerance, 95 Strehl 1/8 wave or more, allows a little more room to hold unsteady air light scatter inside a 1/4 wave Airy disk. This is especially true for obtaining high power views, like planetary detail, and higher Strehl ratios help support higher magnification.

Mirror Machine Basics

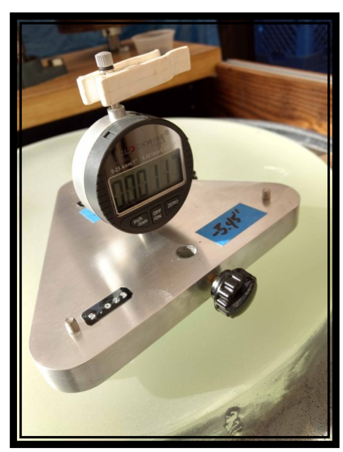
All the terms used to describe mirror machine actions can be confusing to say the least! There are speed and position settings for the turntable and arm sweep, then the tool action is described by overhang and offset positioned with the arm. Many times the arm is described as the quill, the swivel connection point to the tool.

Turntable & Arm speed relationship

Turntable & Arm speed relationship is very important. The arm sweep speed must be properly adjusted to prevent continuous machine repetition errors over the same spot of the mirror. Observe a couple movable index markers on the turntable and adjust the arm speed to advance the tool about 1/5 to 1/7 the mirrors circumference after each rotation, and make sure it does not repeat any position. I’ve been using a 7” advance (1/7th of circumference per rotation) for a 16” mirror’s 50.24” circumference with good success. This can be a major source of astigmatism if not adjusted and maintained properly.

Tile Tools & Pitch Laps for Grinding, Polish, & Figuring

A plaster and tile tool, 75% of the mirror diameter, is cast to fit the mirror’s surface curve. It’s used for grinding with grits from 40 silicone carbide to 3 micron aluminum oxide. Polish is accomplished with a pitch tool the same size as the grinding tool, with a solid back preferably 1/2” aluminum. Several pitch figuring tool sizes are needed in steps of about 1” to 1.5” decreasing diameters, and it’s advisable to use the same thickness aluminum backing material for all figuring tools for consistent weight when adjusting surface psi. Figuring tools are roughly sized at 60% of the zone being figured, starting with 60% of the mirror’s OD. Larger tools push the work further outwards, smaller ones toward the center. The idea is the correct curvature of the tools circumference better fits the curve of the zone, they are used in sequential sweeps to bring down the curve to parabolic. Very fast mirrors may require smaller tools for the deeper curves.



Spherometer

A spherometer is a giant leap forward from using coins to measure the sagitta. It allows very accurate measurements and projected final focal lengths. I’m happy with my latest spherometer design, it employs a 1/2” aluminum triangular base footprint with two hole locations for the digital dial indicator, and has ball bearing feet. It can measure at the tool center or close to the edge, the edge is my most used position. The .0001” digital dial indicator has many advantages; zero on a surface calibration plate, and read the actual dimension directly with a one ten thousandth inch accuracy.

Fixed Post "Neutral Position" for Grind & Polish

Tools sized at 75% of the mirror's diameter are used for grind and polish with a "fixed post" method. The arm position is fixed to maintain a constant overhang with a small slow eccentric motion added (+- .5") to reduce zoning. The machine table speed is set to about 65rpm. The overhang is near 15% of the tool, but it is adjusted in-or-out to maintain the desired curve and RoC. Decreasing the overhang will lower the RoC, increasing overhang raises it. We are looking for the **"neutral position"**, where there are no further changes in the RoC. Establish the curve early in rough grinding and maintain this overhang neutral position and turntable rpm from grind to polish. Turntable speed is proportional to overhang, more overhang is needed with slower speeds, so keep it constant. Tool size will change overhang requirements, larger tools push the work outward, so keep them equal sized as well. Rough grinding grits are able to make major curve changes that fine grits can't, so it's very important to establish the final curve early on. Finer grits and polish are used to remove previous rough grit scratches and smooth, not to make major changes in the curve. Any late changes in the neutral position result in the tool trying to cut a new curve and this creates a chaotic surface.

Astigmatism Causes & Prevention

Astigmatism is defined as having different focal points originating from different sides of a mirror from the same zone, a twist in the figured surface, which will destroy a perfect image. It can manifest anywhere on the surface, across any zone. It is caused by uneven grinding or polishing of one part of the mirror in reference to the other side. Early prevention is called for, confirm your mirror is astigmatism free at the beginning and end of polish, any astigmatism is unacceptable! It will destroy all your figuring efforts.

Astigmatism

Begin prevention by checking your glass for internal stress before grinding. Use a blue monitor screen located behind a transparent mirror blank, and view it through a single direction polarizing filter. Severe stress will display a Maltese cross like shadow in the center, and it will manifest as dark lines. Stressed glass can change shape as surface tension is released during grinding and polish, constantly changing the curve and raising havoc.

Thin mirrors may flex unevenly when grinding or polishing pressure is applied, resulting in an uneven surface. Make sure they have a stable flat supporting surface. Any condition that prevents the mirror from running flat and true on the machine can cause astigmatism. Prevention is doable: The turntable must run true, the mat used under the mirror must be a consistent thickness, and the glass must be perfectly round with a flat back and even thickness. The mirror blank should be centered on the turntable before each work session and run true in all directions within +- .005. Any time a mirror's center of rotation is changed, the tools will try to create a different curve and leave a chaotic surface. Anything causing up-down osculation can increase the work on the uphill side, again causing astigmatism.

Machine polishing and figuring tools must have a random action over the mirror to distribute work evenly and prevent repetitive machine errors that can easily introduce astigmatism. It's advisable to index the turntable and watch the arm sweep, making sure they both don't arrive at the same location every few turns or they will create repetition errors!

The mat under the mirror must be even thickness, just thick enough to compensate for any pressure points that could distort the glass. A time honored prevention is rotating the blank in the opposite direction after each session, and placing a thick shag carpet underneath. These ideas probably originated from the past when untrue blanks and inaccurate turntables were the normal, as an attempt to average out errors. If the mirror blank and turntable are true, only a thin rubber mat is required and no rotation is necessary. Rotating an out of round blank on uneven carpet forces the tool to attempt forming a new curve, rotating may average the error but there is still an error. Amateurs working around the barrel are probably lucky with this because hand grinding and polish can be very random without centering requirements!

Check for major astigmatism often by moving the Ronchi or Foucault inside of focus and then quickly outside. Watch for any line shifting direction, leaning left and right of straight up. Expand the Ronchi to a single line at ROC, back out slightly to form a round pie shaped image (it becomes a wire test). The circular null pattern should be exactly round, make sure the ends of the circular null connect to the central line and don't form an "S" pattern, if they are open at one end it indicates astigmatism.

Important; be sure to run a second test after rotating the mirror 90 degrees on the test stand, you may have picked a good area of the mirror! Make sure astigmatism follows the mirror rotation, and isn't a result of the test stand supports causing potato-chipping (bending) of the glass.

The ball bearing test is useful too. Reflect a flash light beam off a 1/4" ball bearing mounted on the test stage centerline at the RoC, the reflection from the ball is sent to the mirror and back again to a low power eyepiece. It makes it easy to see any out of round condition that rotates and shifts position passing through focus, while watching for rotating image spikes.

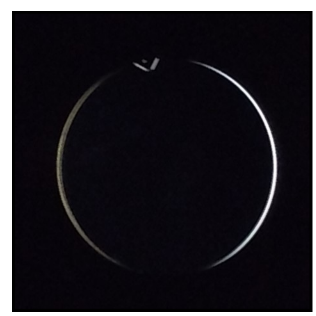
The EZ Hartmann test excels at exposing astigmatism anywhere on the mirror, and it provides quantitative data for severity and location. It's important to note astigmatism can occur anywhere on the mirror, not just the entire mirror, it can manifest as different focal points around any shared zone.

TDE Causes and Prevention

Preventing TDE, has been called "the holy grail of mirror making". A good edge must be accomplished by the end of polish, and TDE is very difficult, if not impossible, to correct during figuring. Maintaining the neutral position from grind through polish, helps make a good edge highly probable. If it was caused by grinding it likely can't be corrected with polish. The idea here is establishing a good edge at polish, maintain it through figuring, definitely not a last minute fix!

Some other causes are; too much overhang, too much tool weight, improper sized lap, incorrect pitch hardness, incorrect turntable speed altering the overhang effect, mirror not centered correctly on machine causing the tool to attempt creating a new curve, just to name a few.

Balanced Edge Ring of Fire



Describing Machine Arm Actions in Figuring

The tool position is set by the arm and is described with the following terms:

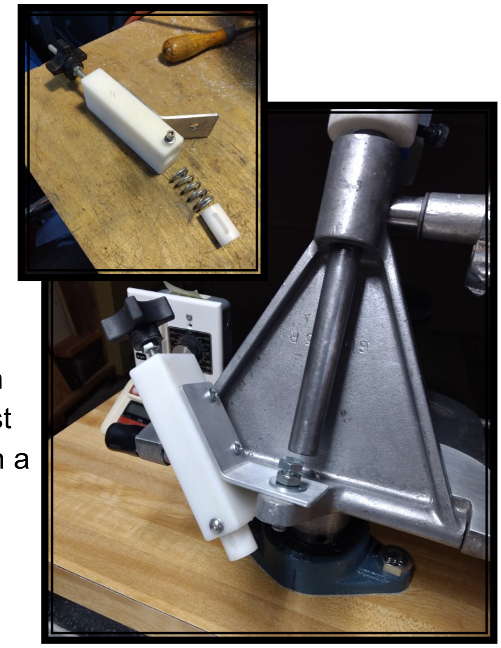
Overhang; The distance the tool hangs over the mirrors edge or over the target zone. Keep maximum overhang less than 20% of the tool diameter to protect a good edge.

Offset; The distance from the mirrors center to the tool's sweep centerline, adjusted by moving the tool outward along the quill arm. Note; Different offsets change the tools overhang over the edge or zone, and must be adjusted to maintain a consistent overhang. Increased offsets make the tool act larger, pushing the correction and smoothing action outward between zones.

The Lap "Sweet Spot"

It has been determined that 20% (of the lap diameter) inward from the laps edge, is the point where the most work is accomplished. This "Sweet Spot" is used to target specific areas for correction on the mirror. I like to Sharpie mark my tools with a circle at that position. As the work progresses inward, zone positions are located by measuring the distance from the mirror's edge to the tools Sweet Spot, a chart of these distances is helpful.

Tool Weight



Weight is added to the arm over the tool, to set the surface working pressure. It's important to use a constant weight per square inch for each different size tool, small tools can quickly get overweight. I found it necessary to counterbalance my quill with a spring to weigh less than a pound, to meet the low extra weight requirements of very small tools. My tools are all made the same using 1/2" aluminum, so they are equal in square inch weight. I like to figure with .052 oz per square inch added weight (including Quill weight). A nine inch tool needs 2.5 lbs. extra added weight, a 6" only .75 lbs. For polishing, suggest adding about 1.42 to 2.84 ounces per square inch of tool, I add 10 to 20 lbs. on a 12" tool.

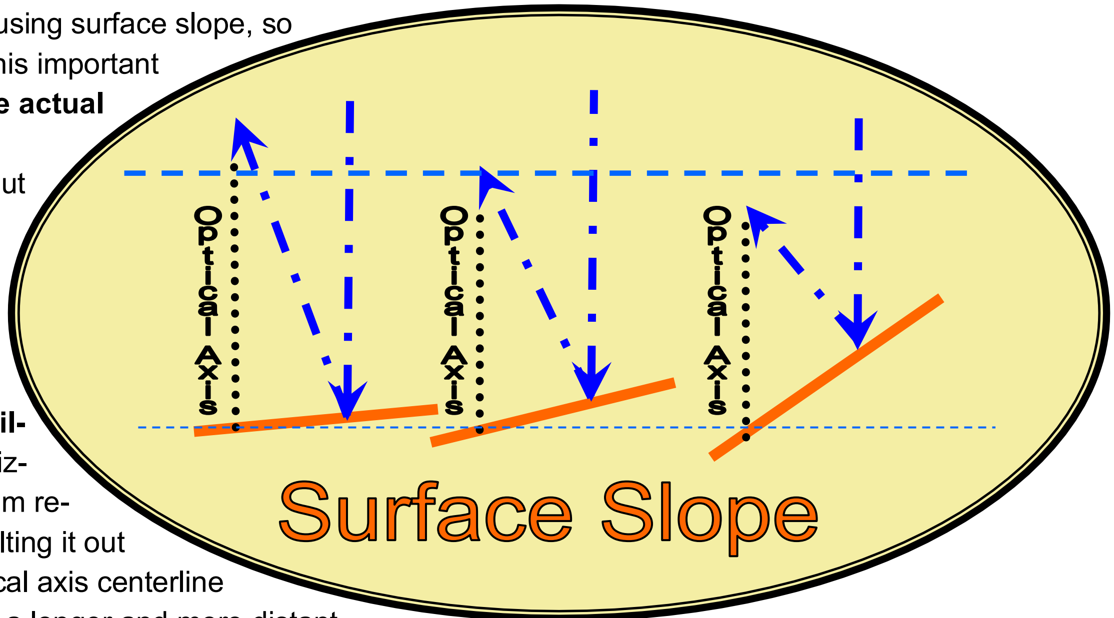
Surface Smoothness

Carl Zambuto mirrors are famous for a smooth surface and the resulting high contrast images. His success begins with proper smoothing after polish, and figuring with several different laps sized to fit different zones, constant offset adjustments to smooth between zones, softer pitch, low arm weight, slow turntable and fast arm speeds, and very thin CEO (Cerium Oxide polishing powder) mixtures.

A rough surface can be caused during polish, resulting from too aggressive, to heavy, or erratic lap action. "Dog Biscuit" is a term used to describe a rippled surface. It's preventable by using the proper pitch temperature range, tool weight, lower speeds, adequate surface moisture, thin CEO mixture, and pressing the lap to the curve and conditioning the lap surface often. It helps smoothness to reduce the turntable speed and lap weight towards the end of polish. Use small laps sparingly with their more aggressive action, and maintain equal weight per square inch keeping the surface action of all laps equal. Figuring from the center out is a good option, especially during the final figuring stages, this gives the larger laps a chance to smooth and clean up zones left by smaller ones. Apply the Ronchi and Foucault test to check for smoothness, Foucault is especially sensitive at showing surface defects. The shadow lines should display smooth gradual curves, not jagged and rough. Remember the magic light shadows. Again, sweep the Foucault knife or Ronchi screen left and right across the mirror surface to look for surface roughness and turned down edge problems. Surface roughness scatters light everywhere, and destroys the sharpness and contrast of the images. It is the one mirror quality that that isn't quantified in test results, and it's up to the mirror maker to keep a watchful eye!

Plotting & Figuring the Parabolic Curve

Understanding the Mirrors Surface & Plotting a Figuring Solution

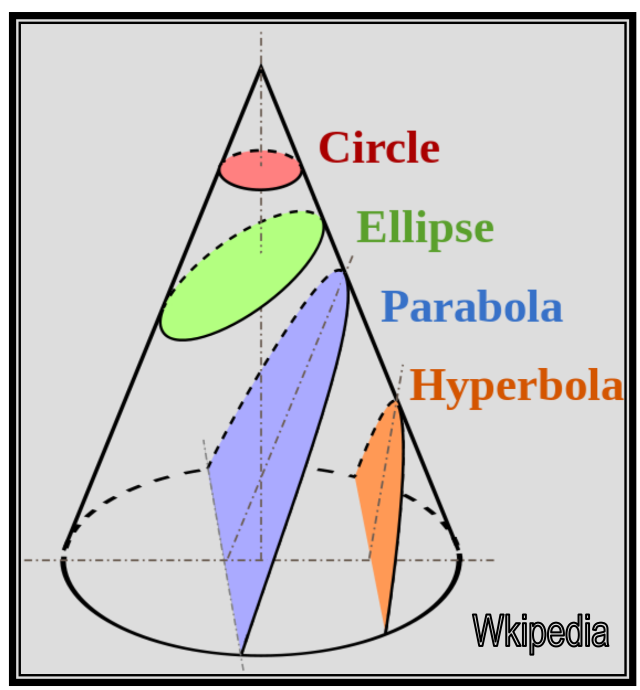


It's difficult to figure a mirror using surface slope, so lets talk about how to interpret this important data. **Slope does not show the actual glass surface edge-on profile**, where the glass is high or low, but shows the resulting focal point distance of the light reflected from a particular surface zone. The Foucault, SIT, and EZ Hartmann tests chart this slope information and it's plotted on **Millies LaCroix charts**. Try visualizing a zone's slope as a light beam reflection off a small flat mirror. Tilting it out (more open) away from the optical axis centerline will reflect the light further out to a longer and more distant focal point. When this small mirror is tilted inward, towards the optical centerline (more closed), the light is reflected inward to a lower focal point. I find it useful to use the palm of my hand to simulate the slope by tilting it and visualizing where a reflected light beam is going. This way I can decide where to increase or decrease the surface curvature (slope). It is important to consider the focal point of the mirror's "exact center" is actually the height of the glass, because the light is reflected directly back. As you move outward away from the center it becomes surface slope.

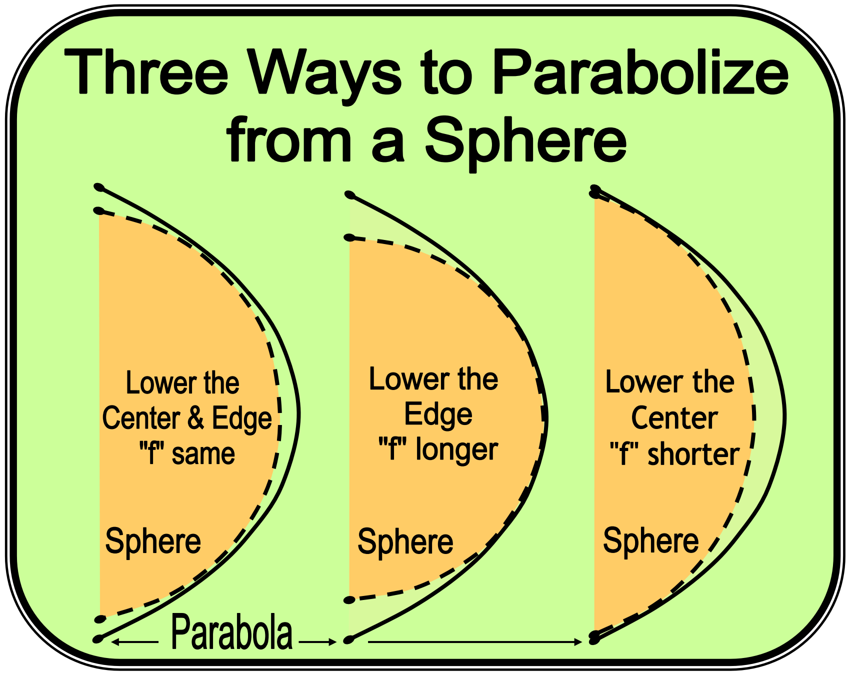
Conic Sections

As a mirror maker, conic sections need not be advanced math, but they give us a general idea of where our curve is progressing. It is particularly interesting that there is only one shape called a circle and only one shape for a parabola. They both can be any size but only one shape. **The parabola is the curve we want to create on our Newtonian mirror, to focus at infinity.**

There are countless different elliptical shapes and countless different hyperbolic shapes. We only need to know how to progress from the sphere (circle) to the desired parabola. Most often we simply describe over figuring a mirror as going hyperbolic, and under figuring as going elliptical.



Three Ways to Parabolize from a Sphere



1-Lower the center and the edge. Maintains constant focal length.
2-Lower the edge. Increases focal length.
3-Lower the center. Decreases focal length. (Most desirable because it leaves the more perfect outer zones and edge intact!)

Machine Figuring

There are many advantages in using the machine to figure a mirror, it is capable of maintaining a surface of revolution, even work distributed all around the mirror, and it can create a very smooth surface. Carl Zambuto has developed a process for machine figuring, and has shared it with the ATM community. He uses laps equal to about 60% of a given zone to be worked, starting at the outer edge and working his way to the center with progressively smaller laps that fit each zone, a slow turntable speed, and a fast arm sweep. It's important to start with a lap 60% of the outer zone, to effectively work and maintain the edge while starting the figuring process. Run sessions of decreasing lap size in figuring sweeps toward the center, timed to lower the overall curve evenly in predicted amounts, and adjust durations for any previous irregular curve changes. If figuring fails, lift the curve by polishing back towards a sphere just enough to restart figuring, and make sure to control the edge as you go. Test often during polishing, there should be no issues with TDE or astigmatism at the end of polish. Strive to maintain a good edge throughout figuring, the edge is very difficult to correct during figuring! Cold press the lap often for good contact. It is a good idea to slightly warm the lap and let the machine work it into contact to begin each session. This avoids expanding the glass surface when pressing a warm lap on a fixed position, always allow the glass time to temperature stabilize before figuring! **Keep the lap speed, weight, moisture, temperature, and lap overhang under control!**

The Mirrorcratic Oath; First Do No Harm

Move Slowly When Handling & Keep Everything Clean

Creating a precision optics requires a lot of thoughtful behavior changes to keep the glass safe and free from scratches and breakage. When carrying mirror blanks, it's wise to **move slowly and deliberate**, hold tight, eliminating the potential of a sudden jar dislodging it from your grasp. Preplan a safe landing place free of any debris, survey your upper storage areas for any stuff that could fall on the optic, assure bolts and nuts are covered or made of nylon, and **remember Murphy's Law**.

Cleanliness is vastly important, a wise suggestion is **let low laying surface dirt lie.** You have probably read about storing coarser grits below finer ones, on different shelf's, again keeping the coarse stuff at the bottom where it hopefully remains. I have had success keeping the mirrors surface clean, and not touching the turntable where the heavy stuff ends up. Lap pitch is super sticky and will pick up most anything, when not in use I keep my laps in clean plastic project boxes with secure lids. Try keeping surfaces clean where you sit the water sprayer or CEO bottle, keep CEO powder in a closed container double bagged inside, and watch for any external dirt that can be picked up. Consider other sources of contamination like the quill arm, surrounding shelf's, clean from the top down where heavy contaminates end up and won't fall on the optics. I like using a brush to clean between tiles and pitch groves, but always use a brush dedicated to a particular grit, keep them clean between use, coarse grits can easily hide in brushes! I use a stainless steel wire brush to condition my laps, storing it in a container with a lid keeps it clean.

It's suggested to let CEO soak overnight to remove scratch causing clumps, but I haven't found this to be an issue? However, make sure to shake and mix well for each use, I use a stainless steel nut in the CEO for an agitator. I never assume my mirrors are clean before a polish or figuring session, always re-clean to remove any unseen dust particles. It's not a good idea to work outdoors or with any wind blowing through your shop, because windblown air can carry a lot of gritty stuff! A real surprise discovery was a scratch source in my Sharpies, they tend to be used at all stages of grinding and will pick up all sorts of contaminates in the tip. I now have a clean box for "new" Sharpies, to be used only when marking the surface during figuring. Always dust off your clothes, another place for stuff to hide.

Conclusion

Mirror Magic part I has been a brief outline describing basic optics, testing, machining, and figuring Dobsonian telescope mirrors. Armed with this knowledge, it will be easier to apply the next **Mirror Magic** articles that will delve into the more technical ideas of machine mirror making and detailed EZ Hartmann testing of parabolic mirrors.

I am an amateur mirror maker who is always learning and asking questions, reserving the right to be wrong, and requesting the opportunity to correct any errors. Please trust but verify all information.

***The views and opinions expressed in this article are those of the author only.**
***Warning: Be advised that mirror making is very contagious and highly addictive!**

All the best,
Lonnie Robinson

Recommended Websites & Books

How to Use a Polishing Machine; Exceptional illustrated mirror machine instruction, a must view site!
http://www.astrosurf.com/gap47/T400/Machine/Utilisation_machines/utlisation_machines_eng.htm .
Mirror-o-Matic group; http://www.mirror-o-matic.com/ .
Zambuto mirror group; https://zambutomirrors.com/
Understanding Foucault by Dave Harbour Very basic and necessary understanding of the Foucault test
The Dobsonian Telescope by Kriege and Berry Apendix B: Grinding, Polishing, & Figuring Large Thin Mirrors
Amateur Telescope Making Book 1 by Ingalls Simplified Hartmann Testing & timeless mirror making procedures
A Manual for Amateur Telescope Makers by Lecleire A modern approach to mirror making
Star Testing Astronomical Telescopes by Suiter Appendix A: Foucault, **Hartmann**, & Ronchi testing
How to Make a Telescope by Texereau An old standard reference from 1919

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Conclusion

There is a lot of magic in mirror making!