A guide to fixing tilt and spacing with objective analysis

By Chris White

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*****Version 2*****

-Updated analysis in Part 1 to use current version Hocus Focus screenshots as well as analysis from a different telescope that more easily shows tilt issues.

-Added a new section (Part V) to discuss decentered sensors and the impact on tilt analysis. (The old Part V, is now Part VI.)

Part I- Fixing the dreaded tilt and backspacing error with objective analysis

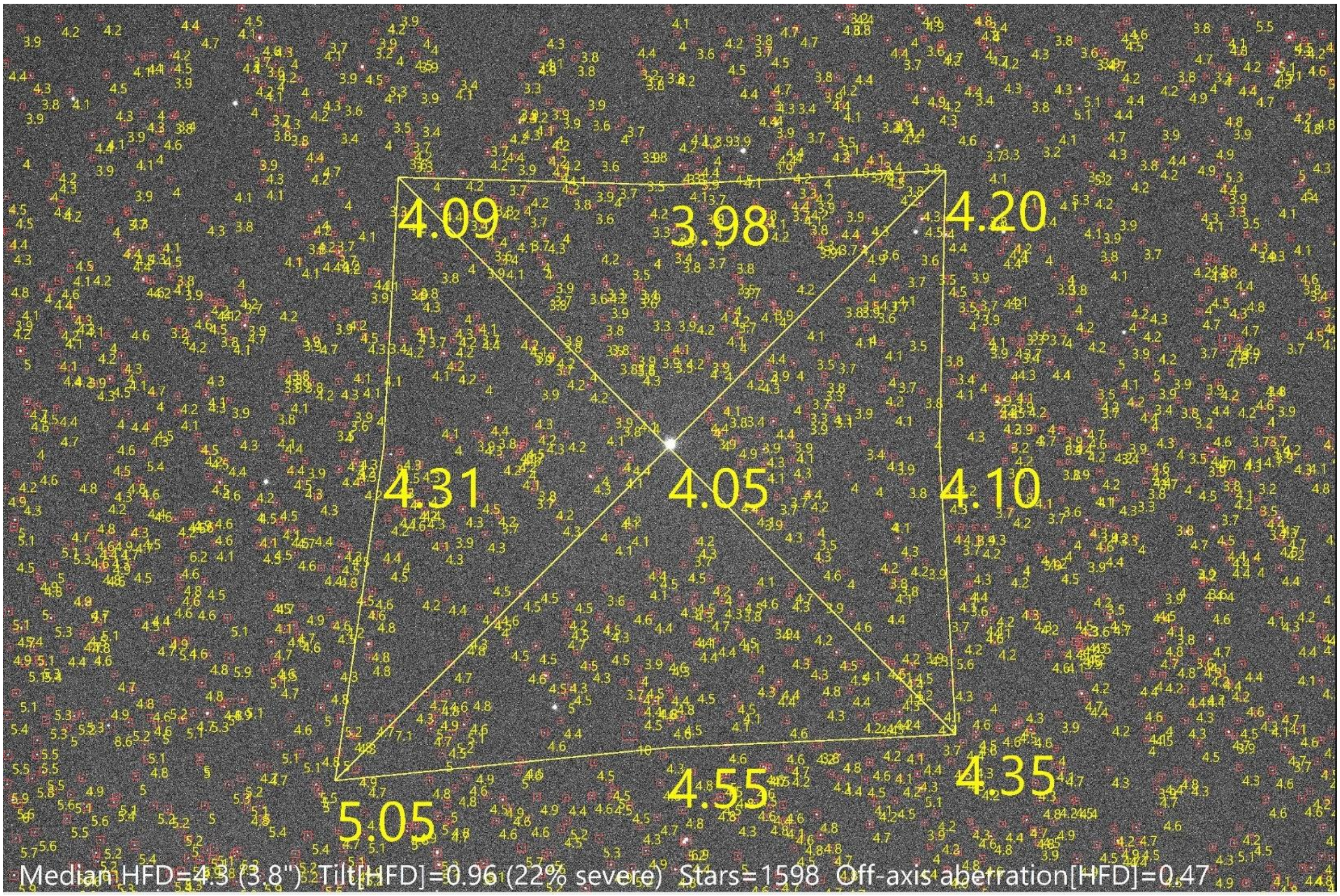
Fixing the dreaded tilt and backspacing error in optical systems with objective analysis. The curse and blessing of modern CMOS cameras is that amateur astro-imagers have easy and relatively affordable access to extremely high resolution detectors but at the same time these tiny pixel, large chip cameras create challenges with optical systems when it comes to producing a well corrected field.

The IMX455 is becoming more and more popular, and people are starting to realize that this sensor is a true torture test for optics. Even the smaller APS-C IMX571 has proven to be a challenge for most optical systems.

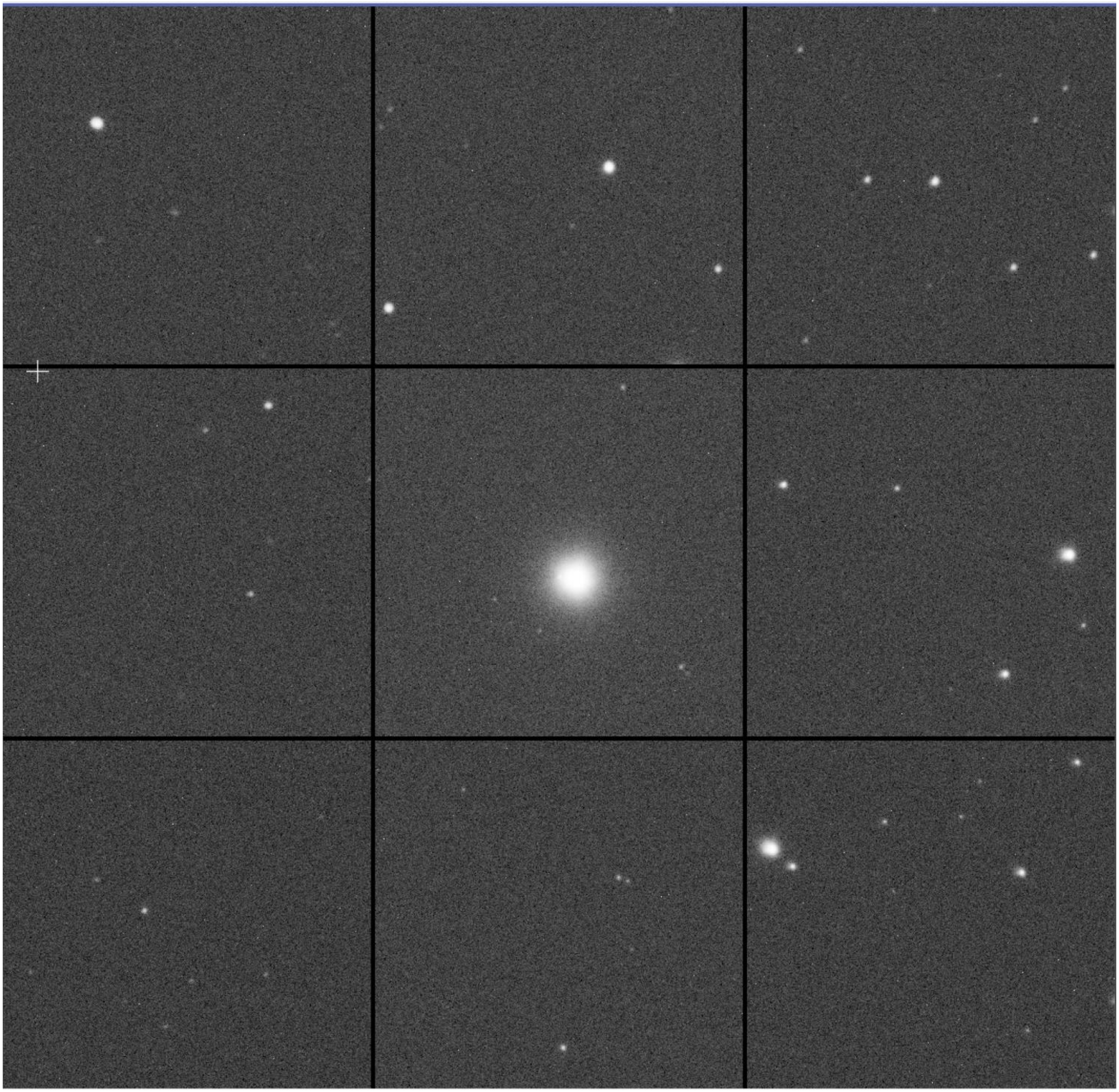
To get the most out of these high resolution, large chip cameras it may require significant effort to dial in spacing and tilt. In the past I have always used aluminum foil to shim my image trains to correct tilt, and spacing was largely a trivial task as I used smaller sensors. (Optical systems are more forgiving of spacing error with smaller chips). With large chip, modern CMOS sensors you get a compounding effect of error where field curvature (due to backspacing error or a corrected field that is smaller than the sensor) combines with tilt to create aberrated stars off-axis (further from center). The challenge here is that you might have multiple problems to address that are difficult to identify, and because these problems interact, it can get confusing as to what the solutions are. It can feel like fixing one thing makes the other thing worse, or different in a way that you didn't expect. The trial and error method of fixing tilt and spacing error is a good way to waste time and cause frustration. I will address these challenges within this article and attempt to shed some light on these issues on how to measure, and mitigate as well as share my experience in hopes that you can improve your own systems to produce better stars across the entire frame.

For this article we need to assume that your optics are well collimated. Of course, in reality any telescope can suffer from collimation error. Since these issues can be detected, and in many cases corrected with collimation tools and eyepieces, I'm going to ignore this in order to focus solely on backspacing and tilt error. We also must assume that your sensor is centered in the optical axis of your telescope. I will address the issue of a decentered sensor later, as this can be a particularly frustrating component of fixing tilt and spacing.

Please keep in mind that I am not claiming that I have developed anything here. I have simply spent countless hours exploring this topic to get the most out of my imaging system and thought that this information might be helpful to the astro-imaging community. I welcome discussion, debate, comments, and constructive criticism.

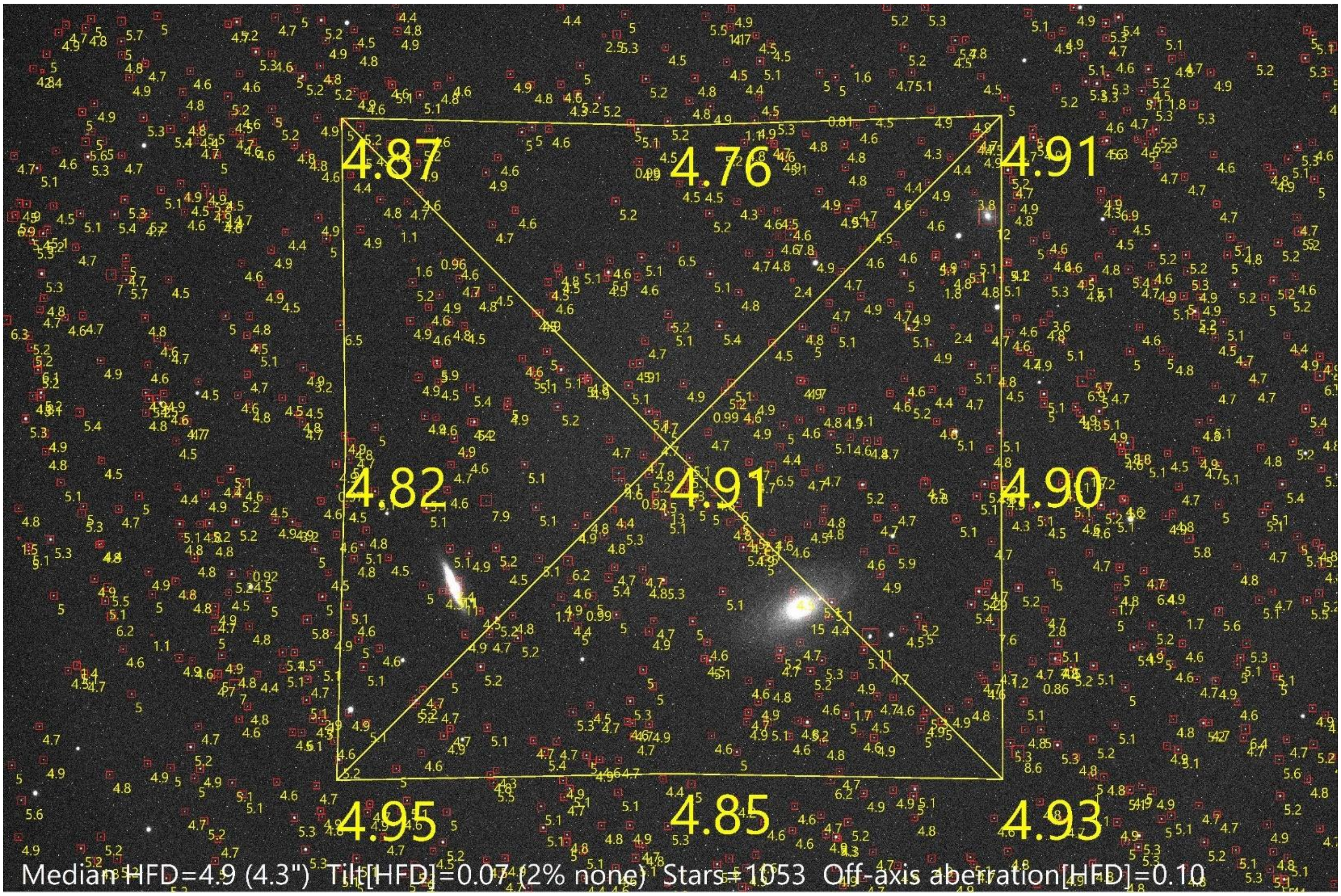


Why do we care about tilt and spacing? When tilt or spacing error is present in an imaging system it results in aberrated stars that get worse as you get farther from the center of the frame. Essentially, the stars in the corners will not look very good. Instead of round stars they might be elongated or misshapen, or even a little out of focus. You can measure this using tools like ASTAP, CCD Inspector or Nina's Hocus Focus. Above is an ASTAP analysis of an image taken with a slightly tilted image train. The numbers represent the Half-Flux Diameter (HFD) of stars across nine regions of the sensor and are represented by an octagon. The bigger the number, the larger the stars are, and presumably the worse looking they are. In this image tilt is measured at 22%, with the worse problem in the lower left of the frame. The upper left is the best, and in general the right side of the frame is somewhere in the middle, not great but not terrible. If there was not tilt present, this octagon would look more like a square with corner values all similar to one another. Below is the aberration inspector of this same frame showing the corners and the center of the frame.



As you can see, stars are not perfect in the corners of this image despite being capture a well collimated telescope with a large corrected field. It's because there is tilt present!   You may see similar stars in your images, or maybe even worse stars! I certainly have. In the past I would simply crop these out, or down sample the image so they were not as pronounced. But you don't need to do this.

Below is an image taken with the same telescope and camera, after tilt has been corrected.



So how do we get from a 22% tilted frame with obvious star issues in the corner, to a 2% tilted frame with nice round stars in the corners?

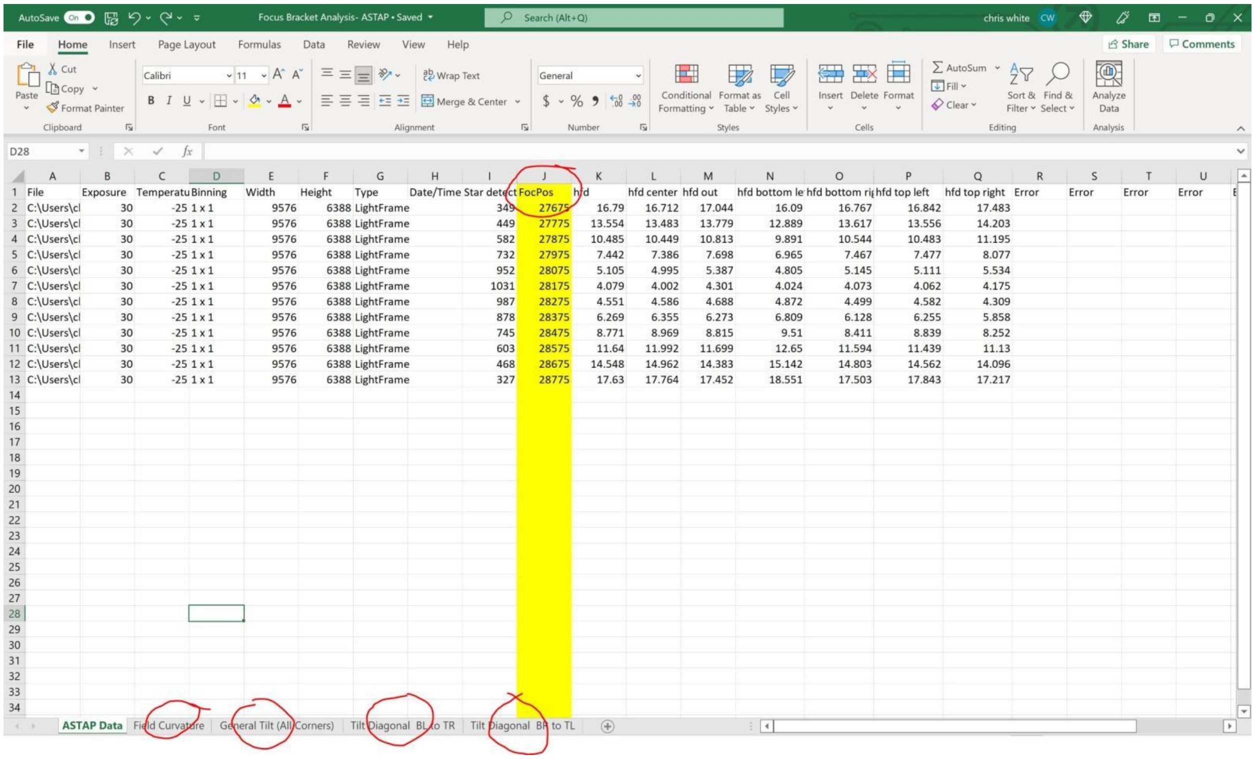
First, lets take a look at how to objectively identify that you might have an issue. To do this, you perform a focus bracket analysis from intra focus through extra focus and plot the HFD or HFR of the analyzed frames for the center and corners. As of this writing there are two ways that I know of to do this. You can capture the data manually and load it into ASTAP for analysis and then manually copy that data into excel for graphing, or you can use NINA Hocus Focus plugin to automatically capture and analyze the data.

I'll describe ASTAP first, just to explain how all this stuff works, however I generally recommend using NINA Hocus Focus as it is a much simpler method, and automatically analyzes the data to provide you with guidance on what adjustments need to be made.
The first step to performing this analysis is to capture a set of exposures (I recommend 10 to 13) through a set of focuser

positions around critical focus. How far out of focus should you go? ASTAP recommends no more than 20 hfd for the analysis. So, do a little experimentation to determine how much out of focus you need to be to have slightly less than 20 hfd stars. With the system below I'm using an AP 130GTX with an Optec Quicksync focus motor and an IMX455 based camera. For my system I captured a set of data with the focuser position range of 27700 and 28800 steps, a range of 1100 steps. My focuser has a step size of 1 micron, so this represents about 1.1mm of focuser travel.

I captured exposures for every 100 steps of travel with critical focus right in the middle and loaded them into ASTAP. (In ASTAP, click the sigma icon, then select the inspector tab. Then click browse to input your test captures.). Once your images are loaded into ASTAP, click on the Hyperbola curve fitting button. ASTAP will measure each frame and output an HFD value for stars based on focuser position for all four corners as well as the center of the frame. You can then take this data and copy and paste it into EXCEL to graph the focus curves of the center and corners of your sensor.

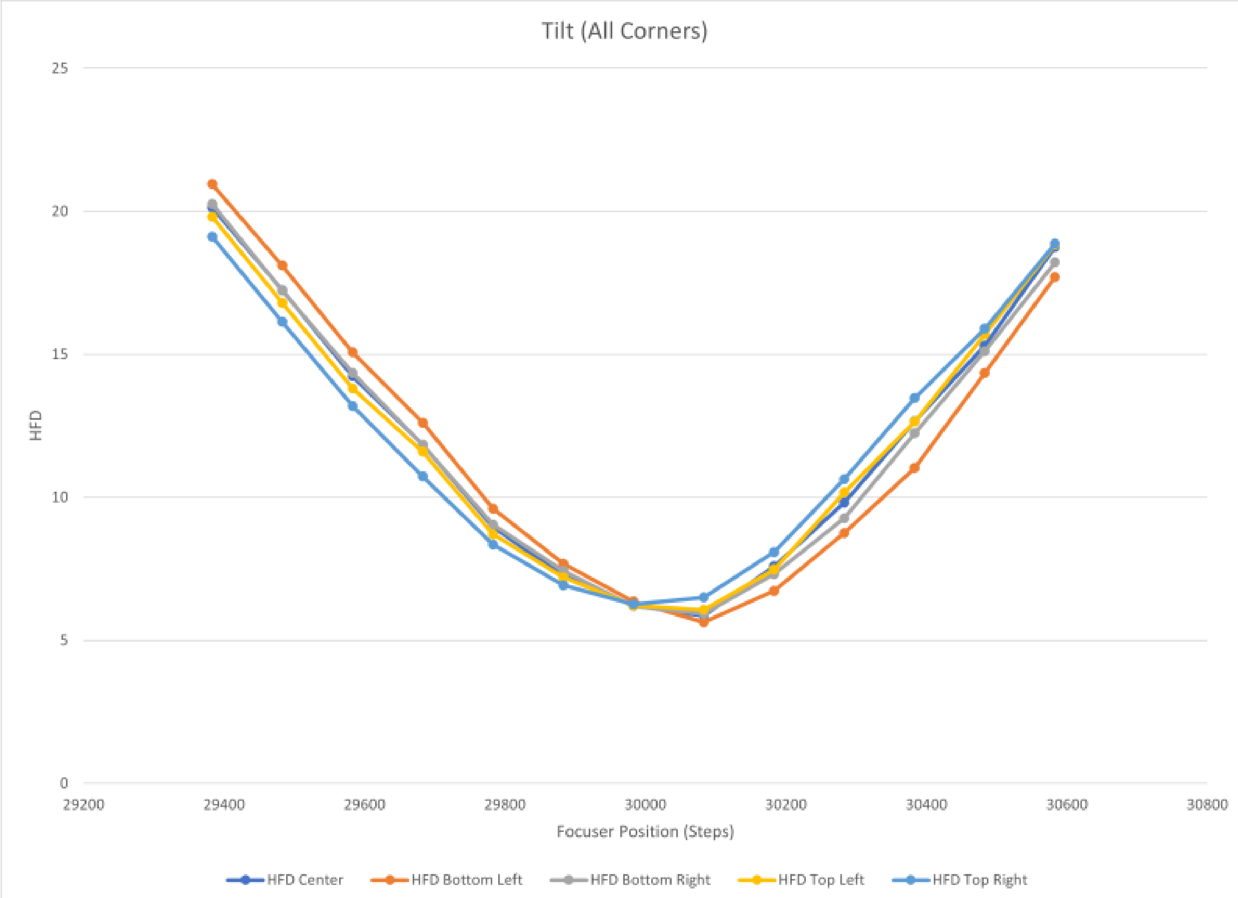
Your copied data will look something like this in excel:



File	Exposure	Temperatu	Binning	Width	Height	Type	Date/Time	Star detect	FocPos	hfd	hfd center	hfd out	hfd bottom le	hfd bottom ri	hfd top left	hfd top right	Error	Error	Error	Error
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		349	27675	16.79	16.712	17.044	16.09	16.767	16.842	17.483				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		449	27775	13.554	13.483	13.779	12.889	13.617	13.556	14.203				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		582	27875	10.485	10.449	10.813	9.891	10.544	10.483	11.195				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		732	27975	7.442	7.386	7.698	6.965	7.467	7.477	8.077				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		952	28075	5.105	4.995	5.387	4.805	5.145	5.111	5.534				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		1031	28175	4.079	4.002	4.301	4.024	4.073	4.062	4.175				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		987	28275	4.551	4.586	4.688	4.872	4.499	4.582	4.309				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		878	28375	6.269	6.355	6.273	6.809	6.128	6.255	5.858				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		745	28475	8.771	8.969	8.815	9.51	8.411	8.839	8.252				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		603	28575	11.64	11.992	11.699	12.65	11.594	11.439	11.13				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		468	28675	14.548	14.962	14.383	15.142	14.803	14.562	14.096				
C:\Users\cl	30	-25	1 x 1	9576	6388	LightFrame		327	28775	17.63	17.764	17.452	18.551	17.503	17.843	17.217				

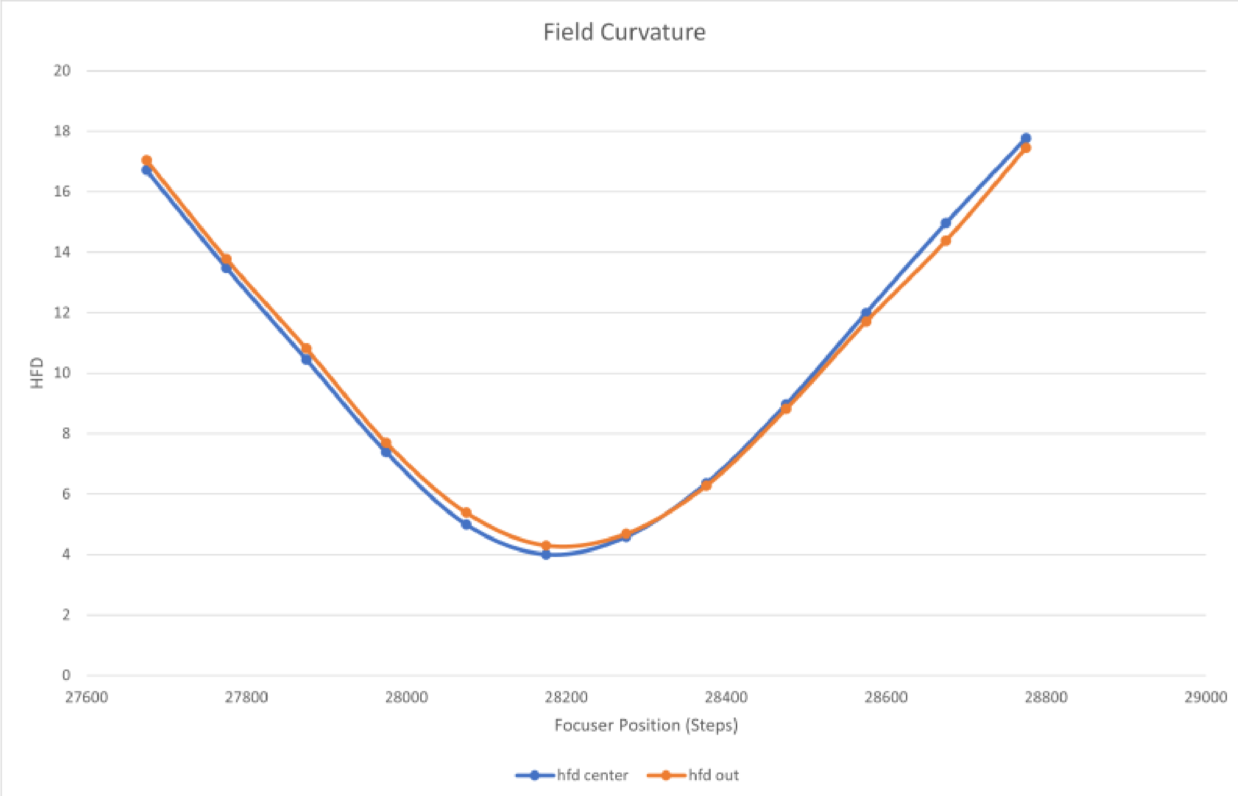
You will get a table that lists the HFD of each of the corners and center as well as the focus position. Focus position column is highlighted above. For my analysis I created separate tabs to house the graphical representation of this data.

First, lets take a look at what a graph looks like that shows each of the corners and center HFD values for each focuser position:



I’m going to break this down so it makes more sense. What you are looking at is HFD on the Y axis and focuser position on the X axis. Each line represents a different corner along with the center. These 5 lines are labeled at the bottom. This is showing what the HFD of stars are at specific focuser positions for specific areas of the frame. What you need to know, is that in a perfect system that is tilt free, with perfect backspacing, each of these lines would stack together to form one single visual line. This is because with an optimized system the center and corners arrive at their optimal focus position at the same time. Because these lines don’t stack, it is a visual representation of tilt and backspacing error in the system. Lets separate some of these lines out to illustrate how the sensor is positioned relative to the optical axis of the telescope.

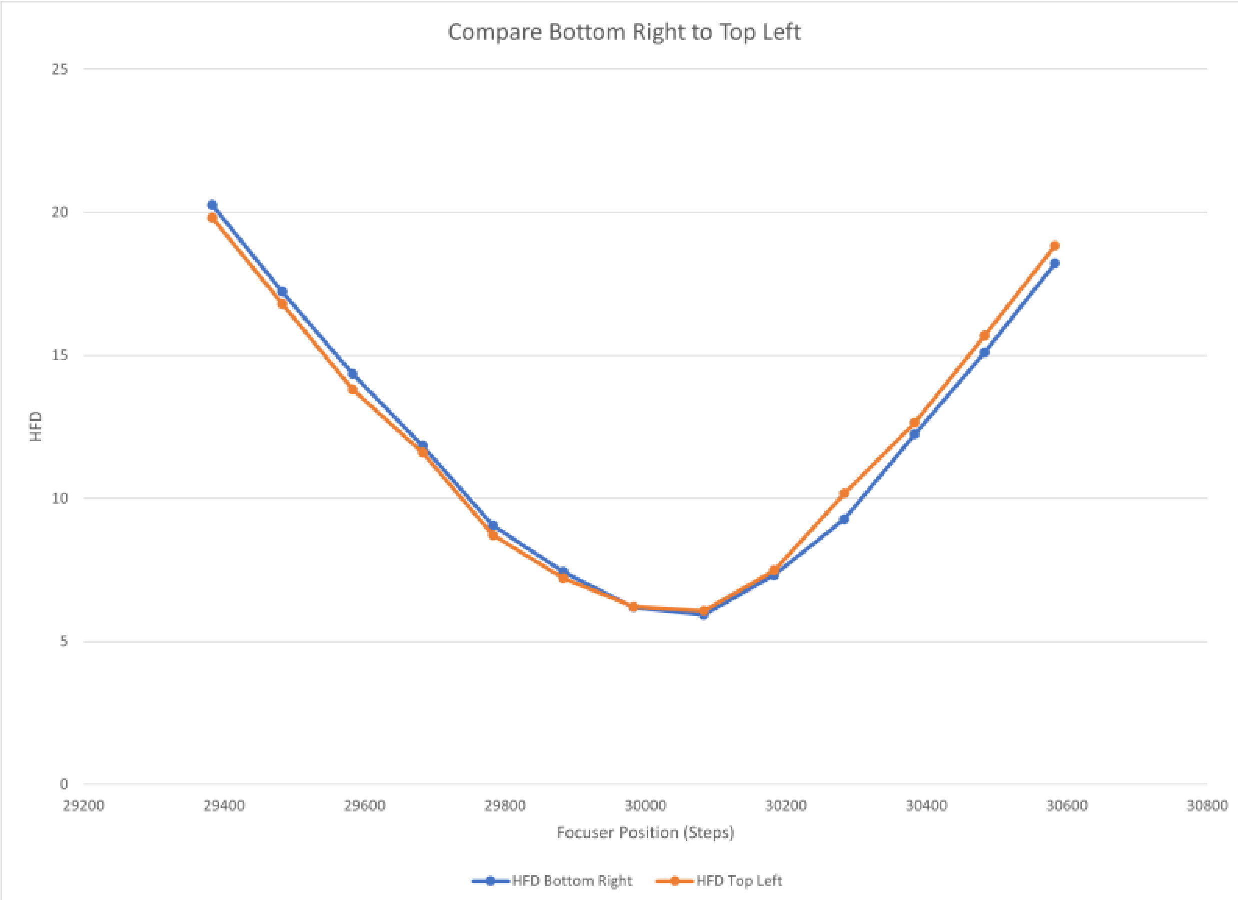
First, lets take a look at the center curve, plotted with an average of the corner curves. Below you will see a graphical representation of backspacing error, or field curvature. Assuming that the optics are capable of producing a flat field for the sensor size you are using, you should be able to perfectly dial in spacing to achieve that flat field. This would be graphically represented as a perfect stacking of the lines of corner average and center HFD.



While these lines do look pretty close, it's clear that the orange line (corners) is shifted slightly right of the blue line (center). In other words, the corners achieve optimal focus at a focuser position that is slightly further out than where the center achieves optimal focus. Remember, that a perfectly spaced system would achieve optimal focus for the center and corners at the SAME EXACT focuser position (and represented graphically by the lines stacking). So in the example above, there is backspacing error present. Roland Christen has published a guide to optimizing backspacing. In a nut shell, what he has said that if you 1) focus the center of your frame and find that 2) your corner stars exhibit field curvature that if you 3) move the focuser out slightly and corner stars improve that you need to reduce your spacing or 4) move the focuser in slightly and corner stars improve that you need to increase your spacing. What you see above is a graphical representation of Roland's advice. In the case above, moving the focuser out improved corner stars, so backspacing needs to be reduced. Note the inverse relationship. If outfocus improves corner stars, you need to reduce spacing, and vice versa.

So the last graph shows what backspacing error would look like. Lets take a look at some of the individual corners to understand how the sensor is tilted. The first graph showed all corners and center on the same graph, which does get a little bit confusing. When we isolate the bottom left and top right curves for example, its easy to see how the sensor is tilted.

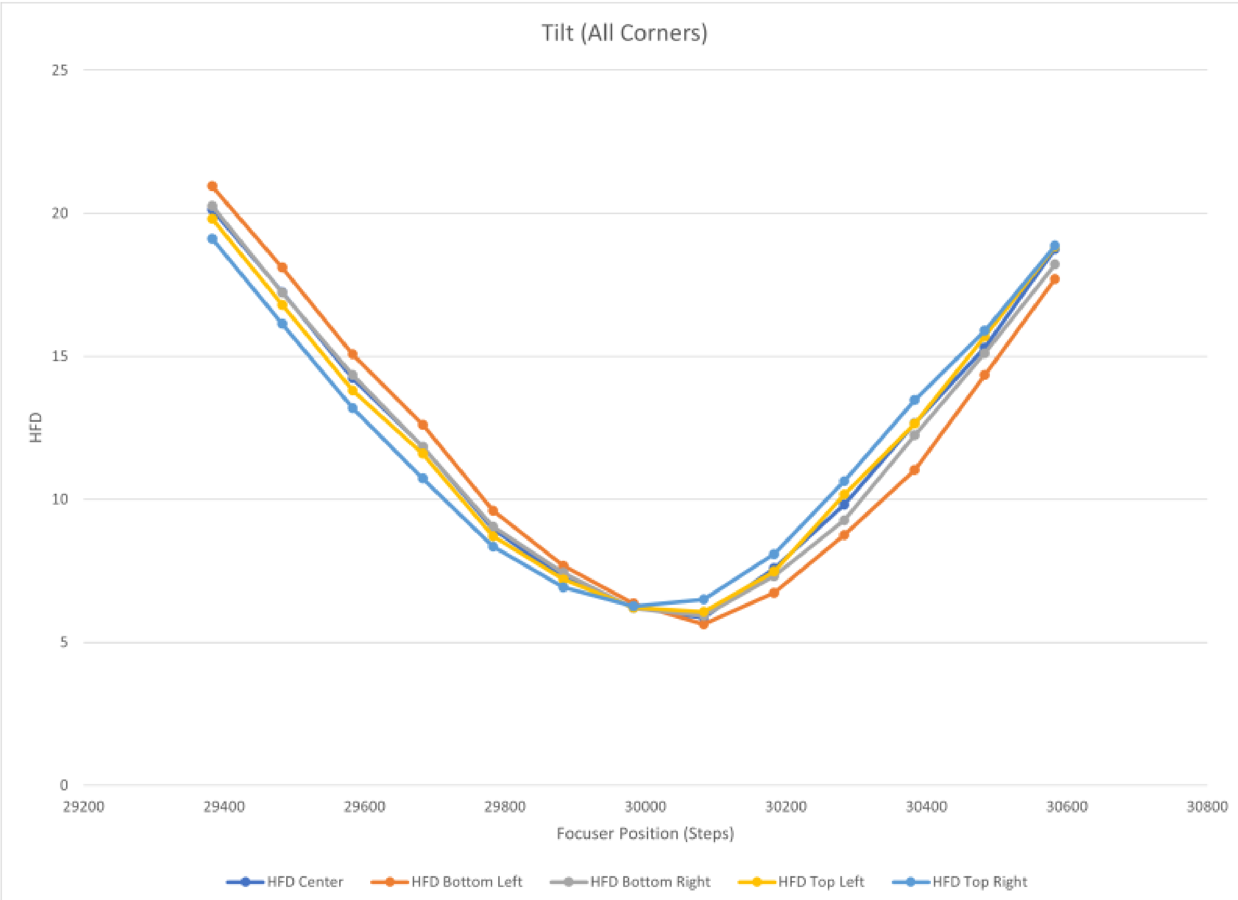
It's pretty obvious that these two points of the sensor do not arrive at the focal plane at the same focuser position. If they did, the lines would stack. The top right corner of the sensor is actually tilted closer to the Optics than the bottom left.



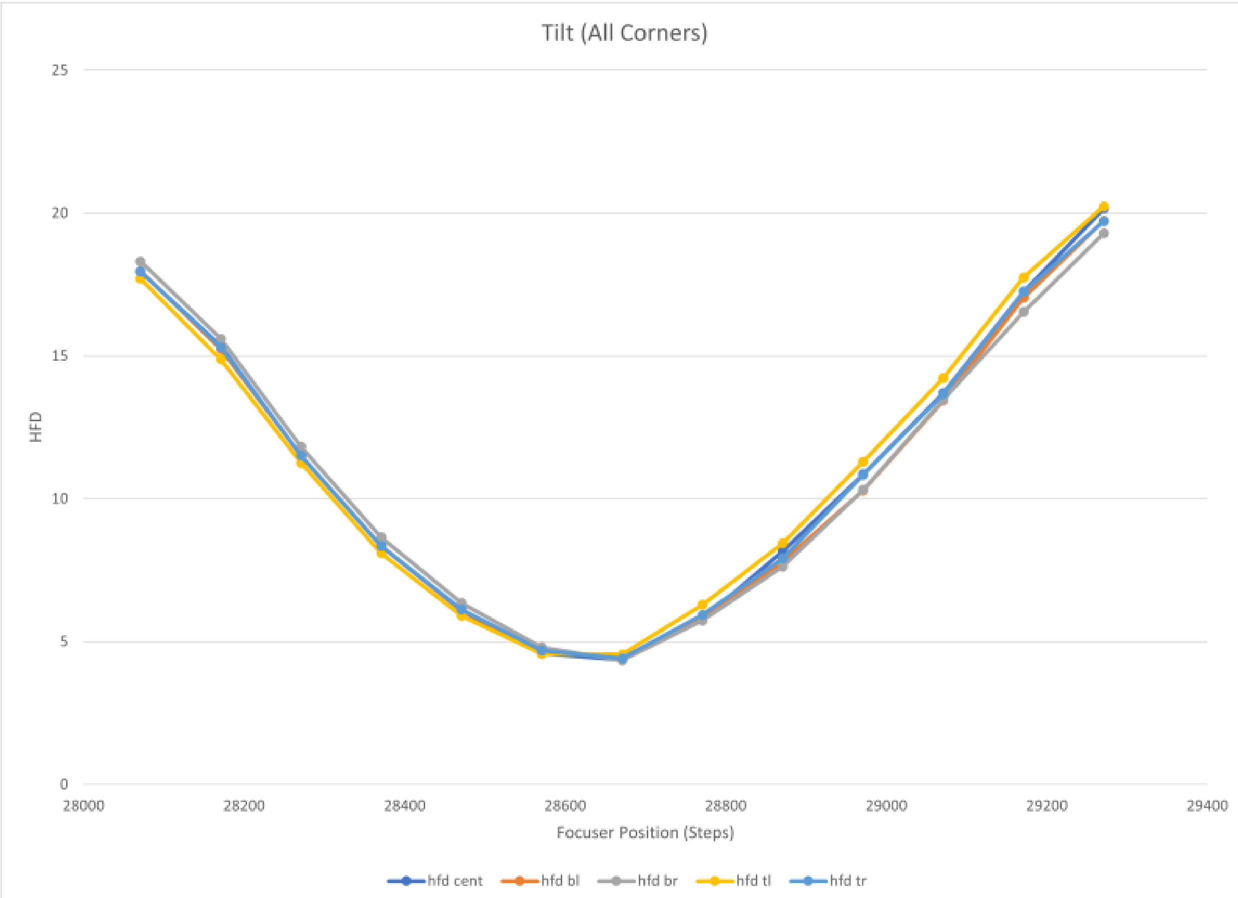
When we compare the bottom right to the top left we see that these two corners are pretty well aligned. The curves stack and optimum focuser position is the same. So the sensor is NOT tilted from the bottom right to the top left.

These three graphs give us a pretty nice visual representation of how the sensor is tilted relative to the optical axis as well as how much backspacing error there is. Keep in mind that when I am describing a tilted sensor, that I am not suggesting that the camera is defective and has a tilted sensor. I am describing the position of the sensor relative to the optical axis. The source of tilt could be the camera, the filter wheel, the OAG, spacers, etc… It doesn't really matter what the source of tilt is, they would all be represented by this type of graphical analysis.

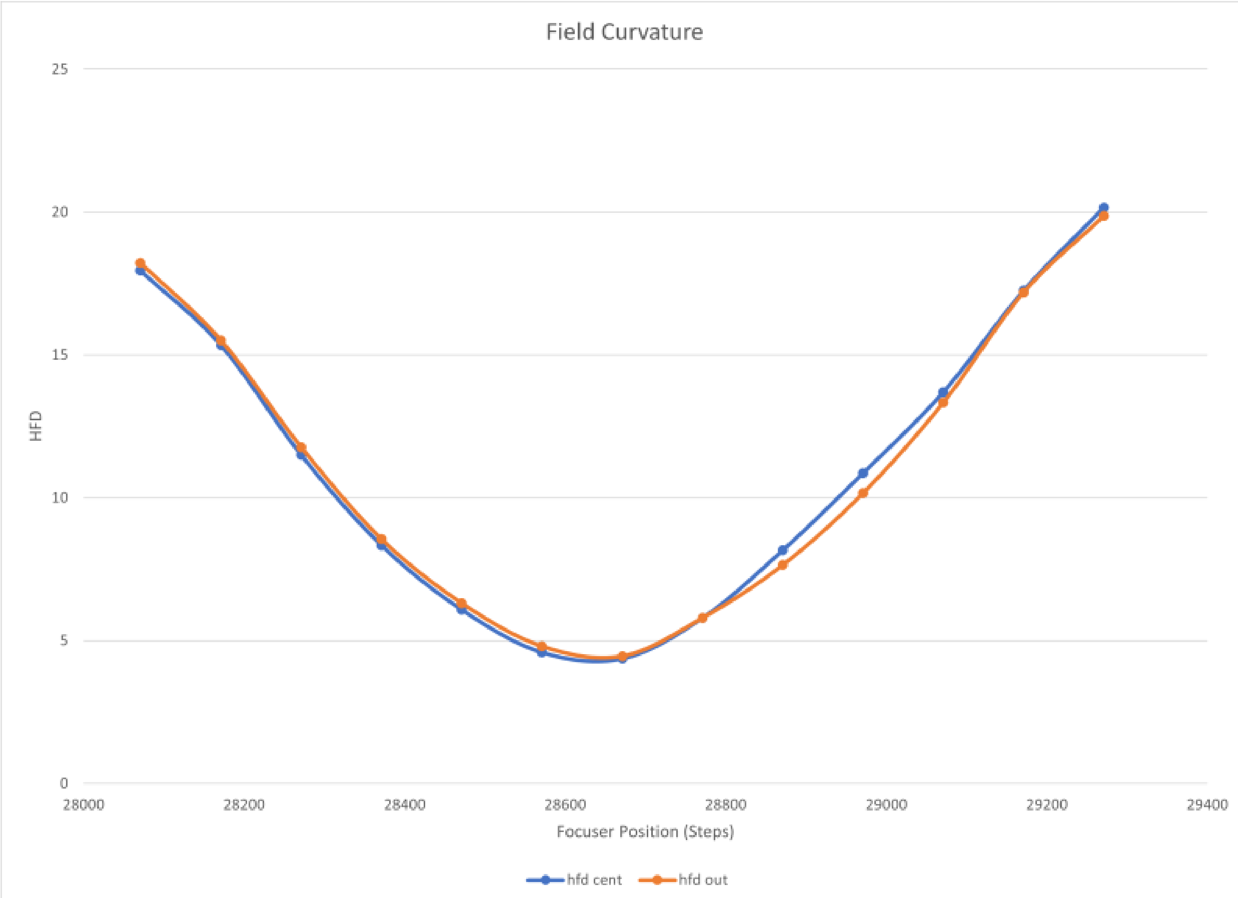
So what happens to the focus graphs for this equipment when we correct for tilt and backspacing? Once again, here is the original plot of all corners and center before correction:



And here is the graph after correcting for tilt using a Gerd Neumann CTU and reducing the backspacing by 2mm.



As you can see, the corrected result is much less cluttered! And the corrected backspacing graph is here:



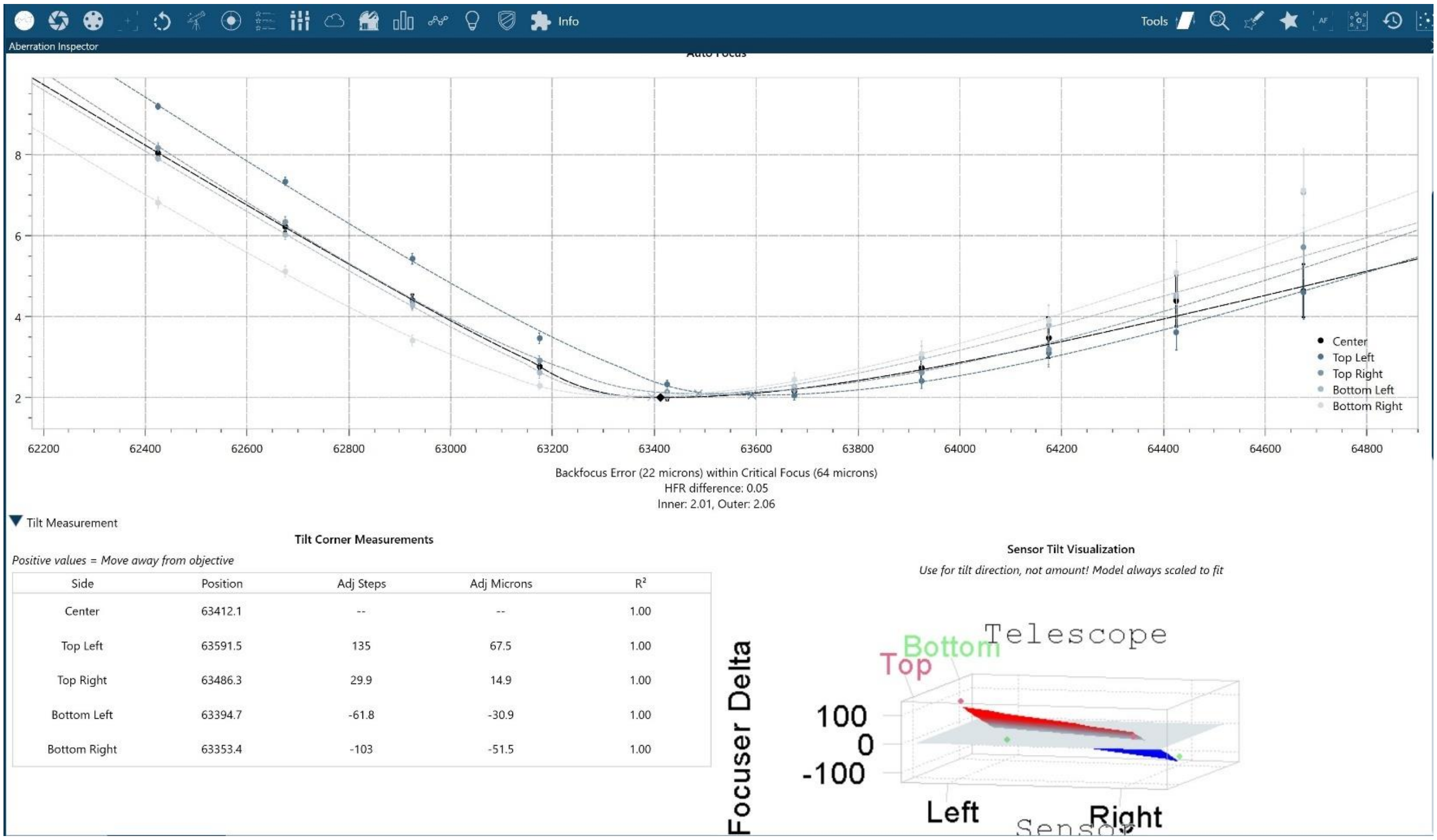
Notice how these graphs stack, suggesting a much more accurate backspacing. Not only are all of these improvements seen graphically, but the improvements can also be seen in the stars.

I highly recommend that you take a look at ASTAP. It's a wonderful piece of free software, authored by Han Kleijn and offers many more features than the two that I have briefly touched on here. You can also see the full documentation on his website to discuss how the field is evaluated for the image inspector tools. In addition to providing the HFD data in a table, there is an output of results that can be interpreted as a guide for you to square your sensor. Despite the power of ASTAP, currently I am recommending a plugin for NINA called Hocus Focus to perform this analysis. I've received many emails over the last year by people striving to improve their images, and because NINA has a plugin that automatically captures, analyzes and outputs sensor plane adjustments… it's just so MUCH easier for you (and me if I am helping you!)

To use Hocus Focus connect your gear, slew to an area of the sky where there is decent density of stars and initiate an autofocus run. Hocus Focus will then output a graph of the curve analysis (the same thing I created manually in Excel) as well as a table showing the focuser position delta between each corner and the center and an output of backspacing error.

The graph is a great visual representation of whether your sensor is orthogonal to the optical axis, but the table is where the magic is. If the corresponding number is positive it tells you that you need to increase the backspacing for that corner, If it is negative you need to reduce the backspacing for that corner. The numbers themselves are derived by calculating the difference between optimal focuser position (in steps) for center and corners. The numbers in this chart are optical differences based on the specific backspacing that you are using. So if it says 20 microns, that is not telling you that you need to move only 20 microns, but rather use this as a RELATIVE value when compared to the other corners. Use the positive and negative assignment as your guide.

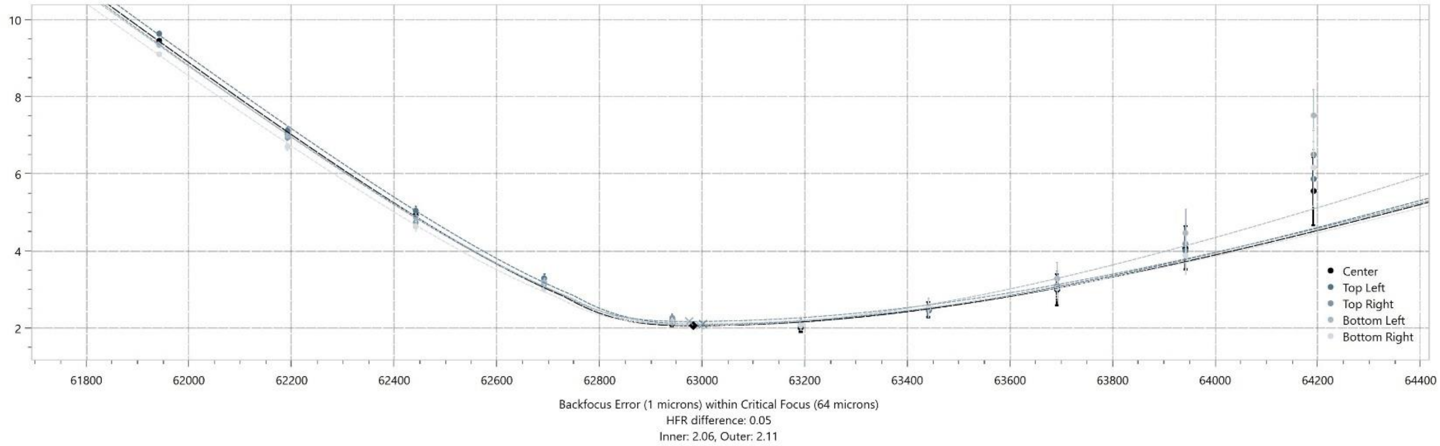
Below you can see the output of analysis for My AP 130GTX with the Field Flattener and a QHY600 camera with IMX455 sensor. This first output was run without any tilt adjustments made and an approximate backspacing estimate.



Side	Position	Adj Steps	Adj Microns	R^2
Center	63412.1	--	--	1.00
Top Left	63591.5	135	67.5	1.00
Top Right	63486.3	29.9	14.9	1.00
Bottom Left	63394.7	-61.8	-30.9	1.00
Bottom Right	63353.4	-103	-51.5	1.00

As you can see, the graph is a bit cluttered. Its obvious by looking at the graph that there is tilt and backspacing error. When you look at the table below you can see that there is guidance on which direction to move each corner of the sensor (in or out). It's suggesting that I move the top left out, the top right out by a smaller amount, the bottom left in and the bottom right in by a larger amount. If the system was tilt free and backspacing optimal, all of these values would be very close to zero. Zero representing, no difference in HFR measurement between the corners and the center. There is also a suggestion directly below the graph that states I need to move the sensor away from the optics. Pretty straight forward. I made an adjustment with my tilt device and ran the focus analysis again. After two focus runs with tilt adjustments, I was able to achieve the result below.

TIP: I always recommend you work on tilt first and ignore backspacing. You will always get a more accurate backspacing recommendation when there is less tilt in play. At the beginning you may visit tilt and spacing in an iterative approach, as changing spacers and using shims has the potential to impact tilt. So, spend a little time getting the tilt better, then follow the backspacing guidance and tweak tilt again if needed. Don't agonize over this stuff, just strive to make improvements and don't forget to make pretty pictures along the way!



▼ Tilt Measurement

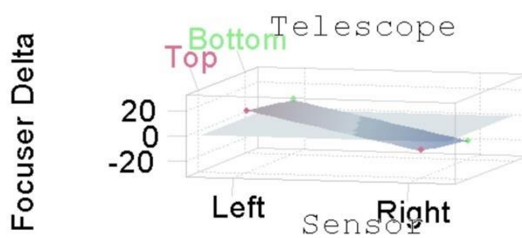
Tilt Corner Measurements

Positive values = Move away from objective

Side	Position	Adj Steps	Adj Microns	R^2
Center	62983	--	--	1.00
Top Left	63001.9	16.7	8.3	1.00
Top Right	62974.9	-10.3	-5.2	1.00
Bottom Left	62996.5	11.3	5.7	1.00
Bottom Right	62967.5	-17.7	-8.8	1.00

Sensor Tilt Visualization

Use for tilt direction, not amount! Model always scaled to fit



As you can see in this second image, the curves all stack nicely, corresponding to optimal spacing and tilt, and the table below has numbers getting much closer to zero.

The nice thing about NINA Hocus Focus, is that it will allow you to objectively achieve a result that is the best your optical system can achieve. There is no guesswork on where to make an adjustment. If you have ever sat out under the stars and tried to adjust a tilt device through trial and error you have no doubt experienced the frustration of confusing and conflicting results when looking at a single in-focus frame. Now, you can simply execute a focus run and follow the guidance of Hocus Focus to dial in your equipment. Hocus Focus was written by George Hilios and is a fast evolving plug-in that continues to offer additional features as well as settings so you can refine your focus runs to achieve your specific goals.

There are several tilt devices available and depending on how much backspacing you have available in your image train, as well as your budget, you can decide if any will work for you. I’ve personally used the ZWO tilt plate, the Gerd CTU, the Octopi Precision Tilt and Spacing Device, and the Photon Cage.

- ZWO Tilt Plate: This is a standard feature on many of the ZWO cameras. It uses a 3-point push/pull collimation system. It is a crude method for adjusting tilt as the threads on the adjustment screws are quite coarse, and the location of the screws does not provide easy access with some image trains. While it may get you there, if you are serious about fixing tilt I recommend an aftermarket device. An additional consideration with the ZWO tilt plate, is that the material is very soft and can strip with too much force on the screws. I have seen several reports of this problem. Additionally, the manufacturing is not very precise and I have seen significant variability in thickness of up to 0.1mm when measuring with my micrometer. These tilt plates could very well be a significant source of the tilt you are trying to fix.
- Gerd CTU: The Gerd CTU is an excellent device. It has a high resolution three point collimation system that allows 200microns of precision with every screw rotation. It costs about $300, and the only downside is that it takes up 17.3mm minimum of backspacing. As of this writing I believe that Gerd Neumann has or is planning to release a slimmer version for those who don’t have enough spacing for the original device. The benefit of this device is that you access the adjustment screws from the side, so no matter what you have for accessories in your image train, you will easily be able to make adjustments. It is a little tricky as there are three points for

adjustment, yet ASTAP and Hocus Focus provide guidance for adjustments based on each corner. ASTAP does offer a single frame tilt evaluation model that does display three points, and you can rotate this to match up with how your device is installed, but in my opinion using a four-point tilt adjuster is much easier.

- Octopi Astro Device: The Octopi uses a four-point collimation system which utilizes ultra-high resolution screws. As far as I know these are the highest resolution screw in any tilt device and offers 127 microns of adjustment for every revolution. It's easy to make very small adjustments that are repeatable and reliable. A quarter turn is only about 30 microns. A major benefit of the Octopi is that it only takes up about 3mm of backspacing, so it will fit within most image trains, even those that have a lower backspacing allowance. It also offers precision backspacing adjustments with up to 5mm of travel. One thing to be careful of, is that because the Octopi has a centering feature where you can move your sensor laterally across the optical axis, you can easily have a decentered chip. This decentering can be very problematic with tilt and spacing analysis and you need to make sure that your chip is centered before working on tilt and spacing. See Part V of this article for more information. Price is around $700.
- Photon Cage: The Photon Cage also uses a four-point collimation system with high resolution screws. One revolution on these screws is about 200 microns. It uses a traditional push/pull design and is extremely easy to use. It has a low profile that fits tightly around the camera and is very light weight. It only takes up about 3mm of backspacing and offers a backspacing adjustment that is separate from the tilt screws. As of this writing I am a new user of the Photon Cage, but I find it to be an excellent tool. Price on this is also around $700

While I am not going to go so far as to endorse a specific device, I will say the Photon Cage and the Octopi are both excellent choices if you want the most control over tilt and spacing adjustments. When paired with analysis programs like ASTAP and Hocus Focus they will give you the best user experience and the best results with fixing tilt and spacing error.

Whether you manually evaluate your data with ASTAP or automatically with NINA, these software tools will allow you to objectively measure and correct tilt and spacing to achieve the best result your optics and sensor combination will allow. I've described the logic and process here, and tried to keep things simple. There are additional considerations however that are worth discussing, such as how to use single frame ASTAP analysis as a guide, and what to watch out for as well as considerations on how to best approach dialing in a field where the sensor is larger than the corrected field and what compromises can be made, depending on your goals.

Part II- When your Sensor is too large for your corrected field.

There is once scenario that I'd like to discuss, where there is more than one "optimal" backspacing. I've presented that optimal backspacing is achieved when the corner curves are perfectly aligned with the center curve, which is true, however this assumption is with the good faith that your corrected field is large enough to accommodate the size of your camera sensor. What happens when your sensor is LARGER than the corrected field? How does this analysis potentially fall short with achieving an optimal result?

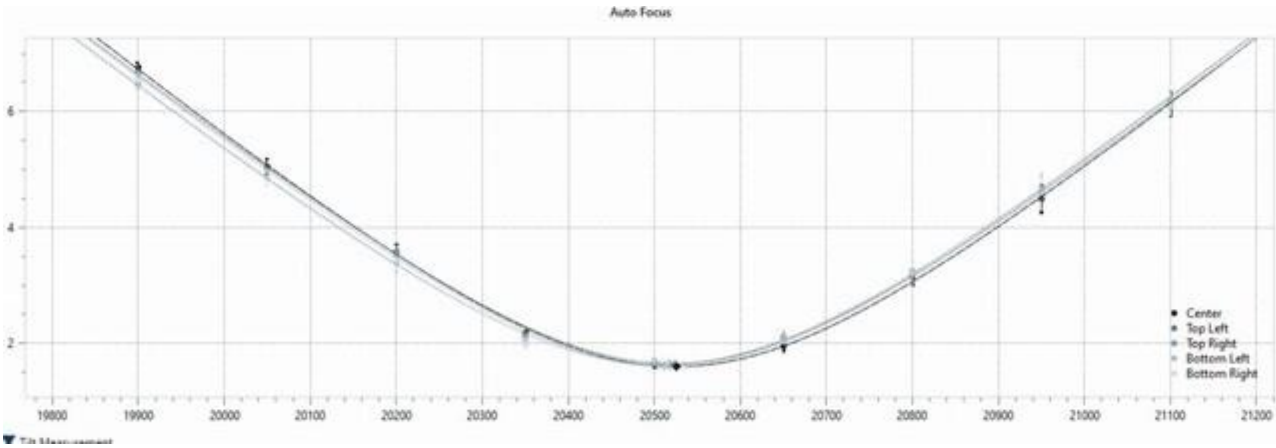
Ultimately, it really depends on what your goals are. Do you want to optimize for corner star quality by choosing a backspacing that might be a compromise of star quality across the entire field, or do you want to optimize for the corrected field your telescope is able to produce at the expense of the corners, knowing that you can just crop these out? This is one of those scenarios where you cant have your cake and eat it too. If you want the least bad corner stars possible, it will be at a slight detriment to the rest of the field. Conversely, if you want perfect stars as far out as the optics will support, your corner will suffer. You cant beat physics here. You can try focus offsets and spacing offsets to try and cheat the physics, but the optics will only deliver what they can.

My AP130GTX with the QTCC Reducer and the IMX455 chip falls into this exact scenario. The corrected field is not large enough to accommodate this chip. So, I decided to see what was the best result I could get if I:

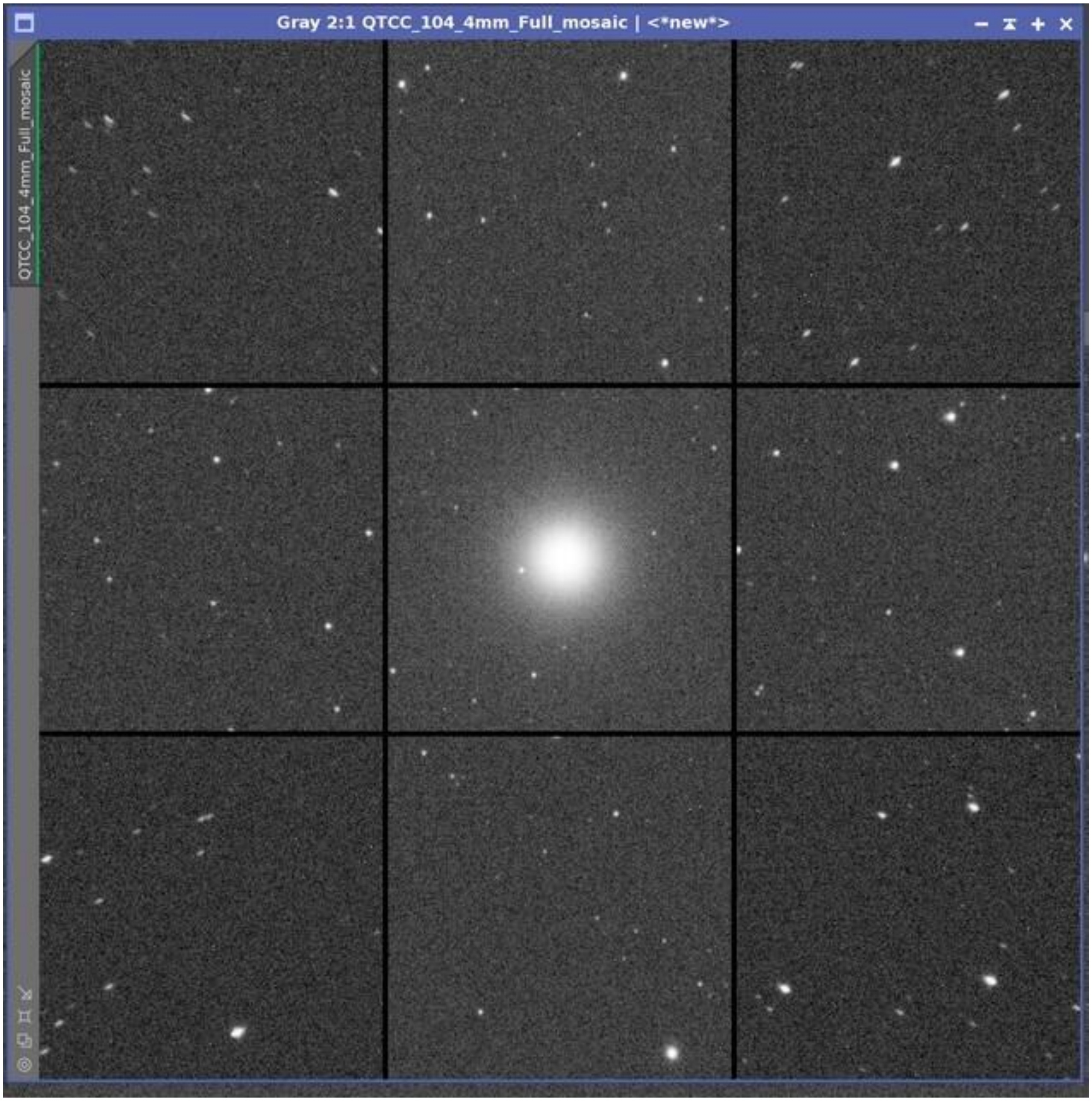
1) Set backspacing to optimize for the corrected field that the telescope with reducer could deliver (smaller area than the chip), or...
2) Set backspacing to optimize for the corners.

When you use the NINA Hocus Focus Analysis with default settings, it will direct your backspacing for the first option. It will advise you to adjust backspacing so that all of the curves align, which corresponds to optimizing for the corrected field of the telescope. If this is your goal, you dont need to get fancy with anything, just follow NINA's advice with the understanding that you will end up with excellent stars across the corrected field and just crop out the bad stars in the corners.

This is what the NINA graph looks like when you are optimizing for the corrected field of the scope. This is with 104.4mm of backspacing.



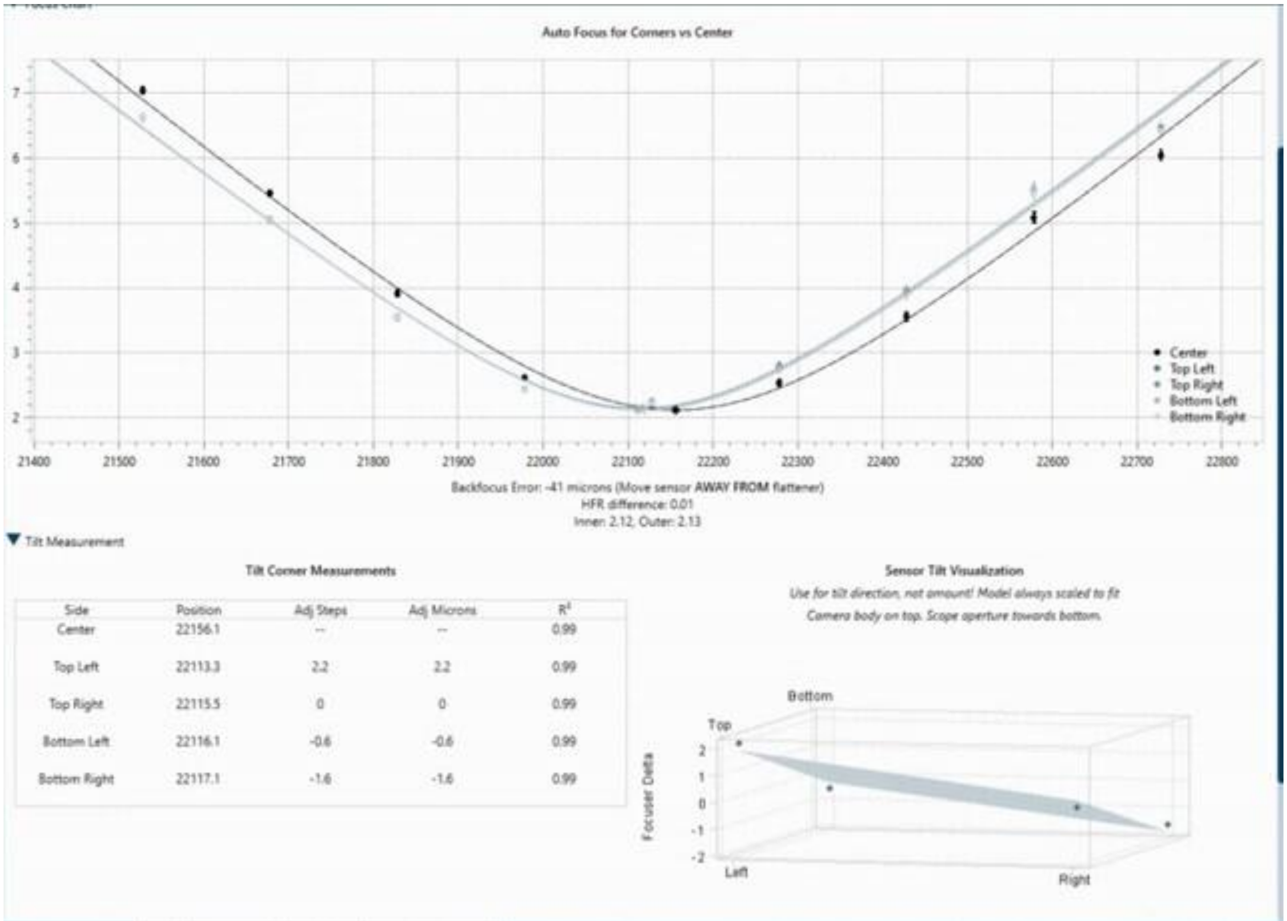
All of the curves for corners and center align nicely. There is almost no tilt, and spacing error is negligible. However, you will see that the corner stars look absolutely terrible!

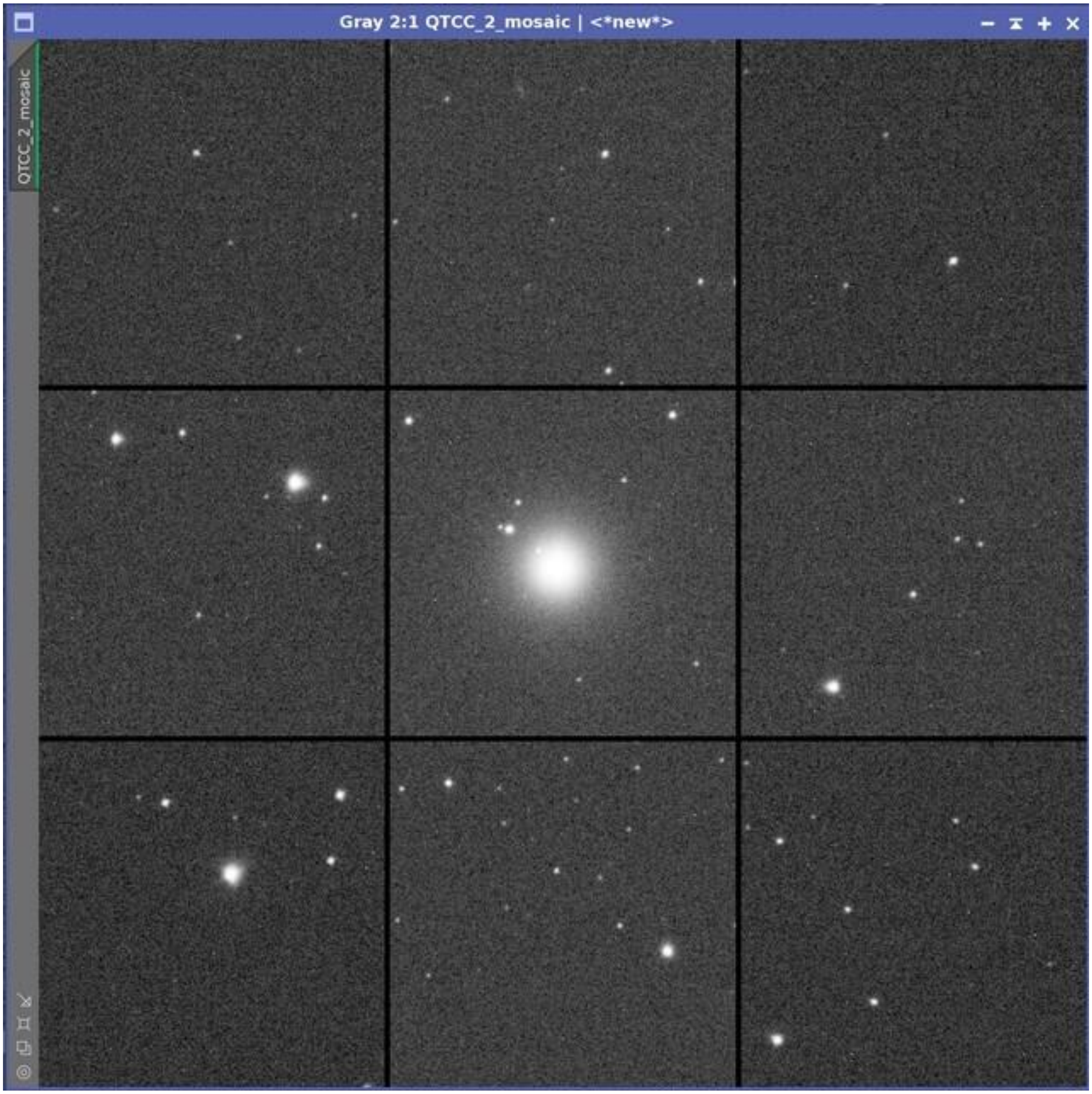


Corners suffer from severe astigmatism, elongation, etc... They just look awful. If you evaluate the full frame however, you will notice that stars look excellent for about 80% of the frame, then they deteriorate quickly from there. If you just crop these out, you get excellent performance for the corrected field of the scope.

If you want to find the optimal backspacing that will improve corner stars you will need to do a little trial and error. What I did was reduce spacing by about 0.1mm at a time, until I found the spacing where corner stars were the best. I found this to be at 103.5mm of spacing. Here corner stars looked much better.

Note however, that the NINA graph shows backspacing error. Which of course there is! I was intentionally introducing backspacing error to try and improve corner stars.





You might look at this new result and say that it looks much better. And I agree, the extreme corners look much better. However, when you evaluate the entire frame you will notice that in order to get the least bad corner stars, you had to give up on star quality further on-axis. In other words, the entire frame suffers from mild field curvature due to this spacing error.   It's seen as a flare on the on-axis side of brighter stars.

Whats the best choice? That's up to you.   Which goal above are you trying to achieve? The best corner stars possible, or the best stars possible across the CORRECTED FIELD OF THE TELESCOPE?

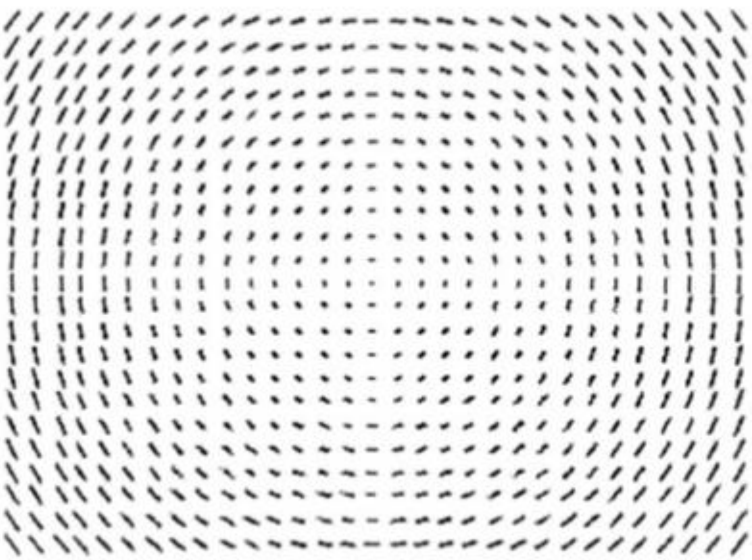
With this I think it's helpful to take a look at the full frame test images. I have included them here for download: https://www.dropbox.com/sh/pzj7p3dyki2n55f/AADlNguuisLplPHUkf6j-XRma?dl=0

File names are self explanatory.

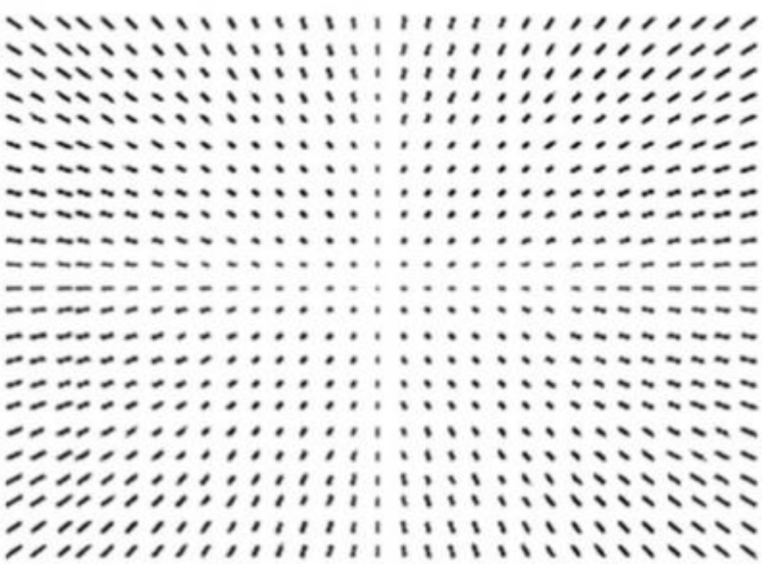
A note on the typical backspacing reference that I have seen posted literally hundreds of times over the years. I really DO NOT like this diagram.

Flattener/Reducer Star Patterns

For REFRACTORS:



If stars appear to form arcs or concentric circles around the center, the distance between the flattener and CCD must be REDUCED.



If stars appear to radiate out from the center, the distance between the flattener and CCD must be INCREASED.

I'm going to repeat it, I really DO NOT like this diagram. There are multiple reasons I do not recommend it.

1) Your focus position can obscure what your corner stars actually look like. If you have any focus error, the offset can change the shape of your stars. You can make your stars look like they radiate out from center or around the center simply by changing focus position.
2) If your corrected field is too small for the sensor, this guide will only help you optimize your field for the corners. This

might not be your goal! It doesnt help you reduce and eliminate field curvature, it simply helps you to get better corner stars. For me, I would prefer a better overall field and to crop out the corners.
3) If you have any other error such as tilt error, it really confuses things.

My recommendation is to ignore this diagram entirely. NINA and ASTAP provide much more robust tools for analysis.

By the way, I did a test integration where I optimized my QTCC reducer for the corrected field (at the expense of the corners). In case you want to see it, here it is:

Click for full resolution.

Corners look terrible, but for the 80% of the frame that fits within the corrected field... it looks really great!

Part III- The pitfalls of using single frame analysis when measuring tilt

I thought I would add a section on single frame analysis. Has anyone out there used a single frame to evaluate their field? I have! There are pitfalls that you should be aware of, and I'm going to expose them here to hopefully help you avoid some of the frustration that I have experienced in the past.

If you take a single frame and look at the corners, then make an adjustment, then look at the corners and things unexpectedly got worse... you are not alone. If you then go in the other direction, and things still get worse... well, that is a recipe for CONFUSION! Now you've spent potentially hours with a trial-and-error method of adjusting spacing or tilt and things seem no better than they were when you started. Plus, because of inconsistent results after adjustments, now you really don’t know how to fix it.

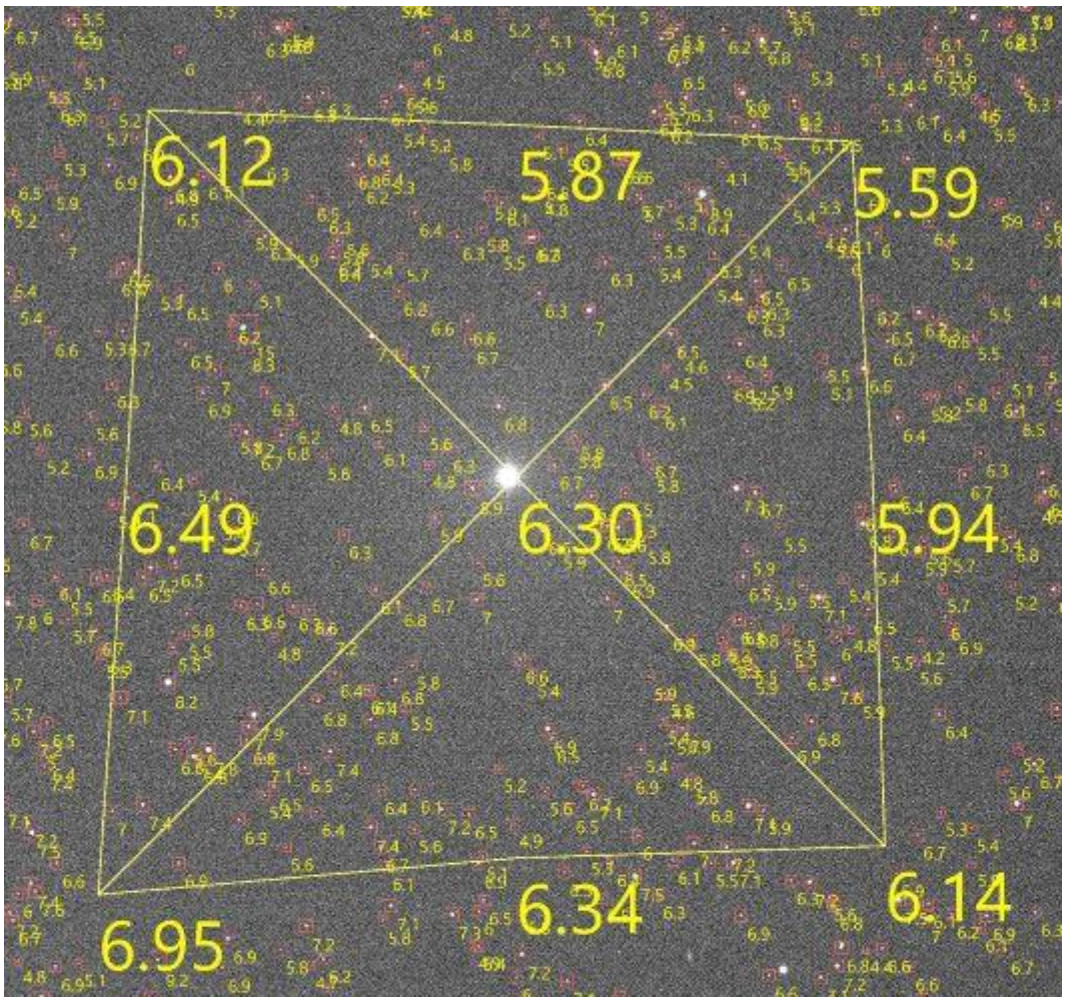
Why does this happen?

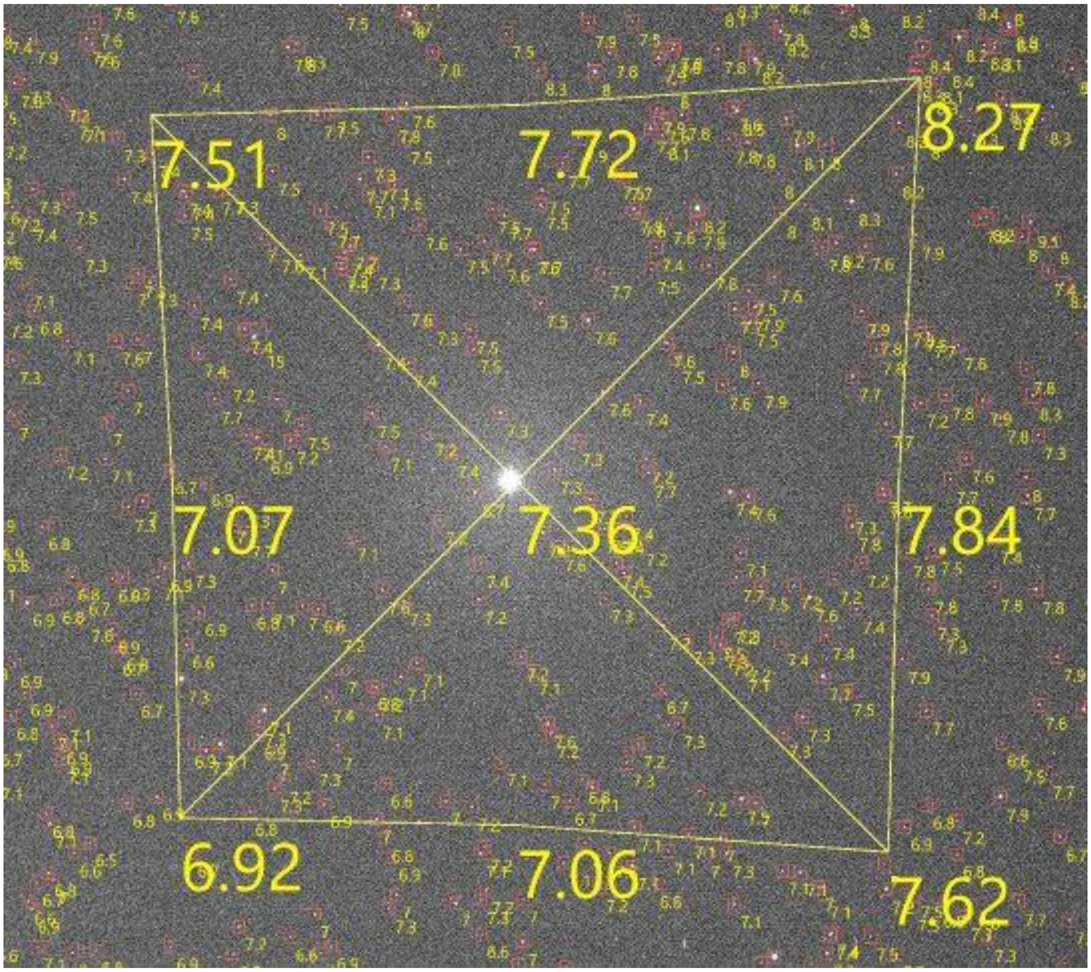
The answer FOCUS. Focus plays an interesting role in this process. It has the ability to mask, mitigate and even invert the results you get after making an adjustment. It becomes critical to focus exactly the same way with the same precision, in between adjustments. This is easier said than done. I've used many different focus methods out there, including full field focus from SGP, NINA, Voyager as well as single star focusing with Voyager. The problem is, if you run two focus runs back to back... you might not get the same exact result. This is especially true with full field focusing. Depending on how robust the algorithm is the results might be quite different. I'm not talking about whether a frame is in focus or not, I'm talking about a slight variability in focuser position as the software attempts to find the best fit focus position for the entire field. With my 1 micron step focuser that can result in over 50 steps of variability if I run the focus routine back to back. That’s why when creating filter offsets for focusing, you take the average of several focus runs.

This small amount of variability might not be immediately apparent, but off-axis (towards the corners) this variability can interact with field curvature and produce some unexpected results. Take for example the concept that you can use focus position to improve corner stars when backspacing is not perfect. You can run a focus routine, end up with a step position of 30,000 and notice elongated stars in the corners. Simply by moving the focuser 50 steps to 30,050 position you notice that the corner stars become round. OK. So you then reduce your backspacing a little bit and run the test again. Now your stars look even worse! This could be because of focus position variability. The same phenomenon can make tilt look worse, even though you might have actually improved it with an adjustment.

As you move through the critical focus position, field aberrations from tilt and spacing actually invert. That's why it is so confusing. If you are slightly intra focus the problem looks like it might be in the lower left, but then when you are slightly extra focus the problem is in the upper right. Well, with tilt... the problem is indeed in both places but if you have the wrong assumptions it can lead you down the wrong path. By the way, fixing the lower left would also fix the upper right, but the problem is, you just don't know which direction to move the corner. Do you move it in or out? Additionally, a tilted sensor does not have independent corners. When you adjust one corner, you are adjusting all corners. You just need to know how this interaction occurs to know that you are still moving in the right direction.

Here is a visual example.   The first is 100 steps inside focus and the second is 100 steps outside focus.





Notice something interesting? The tilt model inverts as you pass from inside focus to outside focus.

If you are not using an autofocus routine that can precisely achieve the same exact focus position (within say 10 or 20 microns) then this could be a reason why single frame analysis (whether with ASTAP or visual) is confusing you. The only method of focus that I have found to be repeatable enough for single frame analysis is Voyager's single star method. I can reliably get close enough to the same focus position where I get consistent results for single frame analysis.

This is why I am recommending the focus bracket analysis, in particular the NINA Hocus Focus Plug-in for this kind of work. It doesn't matter how consistent the focus routine is, because you are analyzing a full focus range for determining how to adjust your sensor. It is a far more robust model than the more confusing single frame approach. That said, now that you know what to look for and why you might get inconsistent results, you might find the single frame approach more useful. Before George wrote Hocus Focus, I got pretty adept at using the single frame approach, however now... I just use Hocus Focus. It's so much easier, and it's free so there is no reason not to give it a try.

***Special consideration. The scenario above is particularly relevant when your sensor size and resolution is pushing up against (or exceeding) the corrected field of your telescope. If you are using a small sensor relative to your corrected field, you might not have too many issues getting your system dialed in. But for those of you using IMX455 or IMX571 chips, there is a good chance this is why you are struggling.

***Another note... I suggest precision to within 10 or 20 microns when repeating focus runs. This is really kind of an arbitrary suggestion. 10 to 20 microns might be literally NOTHING to an f10 system, but at f2... it could be massive. So what I should have stated was that you need to have enough repeatable focus precision for YOUR system to make the single frame analysis method effective.

Part IV- Effectively using single frame analysis to address tilt

OK, so you still want to try the single frame analysis even though it can be confusing and unreliable.

I outlined the pitfalls in an earlier post and will mention them again here:

1) If you are not consistent with your focus you will get very different results from test frame to test frame. This can confuse you into thinking you have made tilt worse when you may not have.
2) As you move from in-focus through critical focus into out-focus, the tilt model inverts. This can confuse you into thinking that you have overshot your correction, or that you are not seeing an improvement.

Here's how you use single frame analysis:

Tilt exists, and can be measured whether you are in focus or out of focus. If you have ZERO tilt in the system, all corners of the ASTAP analysis will match whether you are in focus or not. The fact that the tilt effect is amplified with defocus, actually means you to have a more clear measurement if you are slightly defocused.

So with single frame analysis in ASTAP, your goal is to get all four corners to be pretty much the same HFD measurement. As long as the four corners get closer to each other AFTER you have made an adjustment... you are improving the tilt on your field! That's it. Just get the corners to match, and your tilt will get better, regardless of focus quality.

I will repeat this concept. A tilt free sensor will show no tilt at critical focus, as well as no tilt with a defocused system. This is easily seen in the NINA Hocus Focus Analysis. If your corner curves all stack you have no tilt right? Well, look closely... if the corner curves stack, then the individual plots stack. So for a tilt free system, all four corner plots will match at every point along the curve.

As long as you are aware of the possibility of confusing and conflicting results, the single frame analysis can be used as a simple guide to a tilt free system. Just get the corner HFD values as close to one another as possible. Of course, it is more precise to use a full focus bracket analysis for tilt mitigation, but that doesn't mean that's the only way.

CAVEAT for backspacing: You MUST be at critical focus for any backspacing assumptions. For backspacing you are comparing the corner HFD to the center HFD. Any amount of Defocus will throw this measurement off significantly.

Part V- A case study on a decentered sensor. This might apply to you!

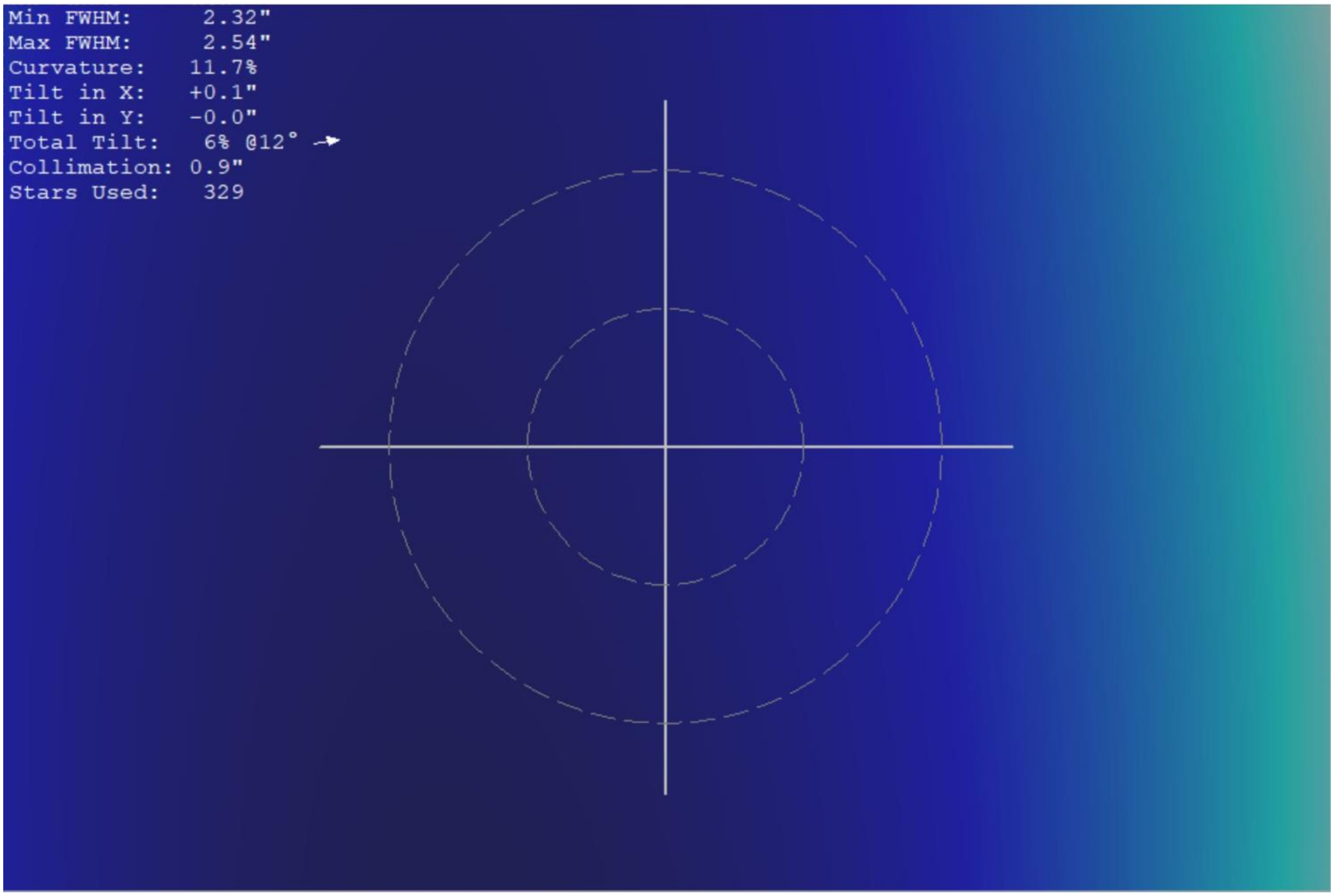
Recently, I had a scenario where I was mitigating tilt and spacing on a new field flattener for my 130GTX telescope. I spent several hours a few nights in a row running Hocus Focus and mitigating tilt and could not seem to get a good field. There was one edge of the image that always seemed to have bad stars, and no matter how much I adjusted the tilt I could not get them to improve much. In fact, the stars on the opposite side of the frame started looking worse and worse. Finally, it hit me that what I was seeing, should not have been possible! I use a single star focusing method which places a bright star in the center of the frame and achieves focus using a very robust and reproducible routine. Because the center of the frame is at critical focus, any tilt in the system would "pivot" around that central point. If I had bad stars on one edge of the frame because they were too close to the optics, I would also have bad stars on the other side of the frame because those stars would be too far from the optics. It should not be possible to have bad stars on one side, and good stars on the other side… unless… there was something asymmetric with field curvature. There are only three things I can think of that could cause this. Optical defects, a sensor that is warped, or a sensor that is not centered with the optical axis of the telescope. The first two are extremely unlikely. My scope had recently been back to Roland Christen for cleaning and collimation. The camera has been used successfully on other optical systems. That left me with a decentered chip as being the most likely culprit.

I disassembled my image train and looked at everything to see if there were any alignment issues that could have caused this. I found that the Octopi Device that I was using had a couple of manufacturing issues. The Aperture was offset slightly from the barrel clamp that holds the camera, and the mounting holes around this aperture were offset as well. The combined offset added up to 0.65mm of decentering, which does not sound like much but with a large sensor and 3.76um pixels, it doesn't take much to cause a significant issue. (The Octopi has a feature that allows for centering your sensor on the optical axis)

So, if you have been working on tilt adjustments and no matter how much you adjust it you can't fix one of your corners or sides, take a look at whether your chip is centered on the optical axis of your telescope. Chances are, this is why you are having issues!

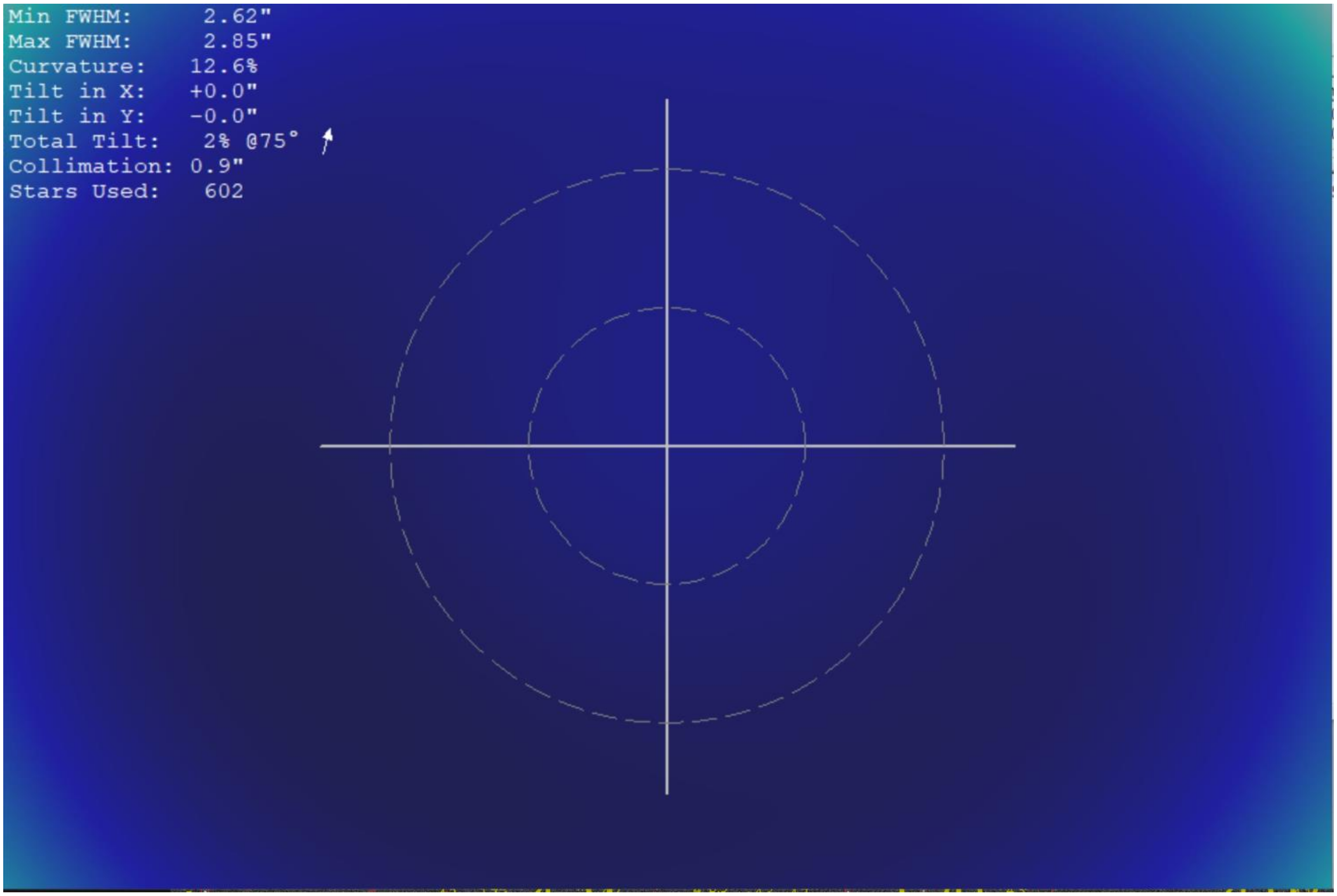
Not only was I not able to fix my stars, the Hocus Focus Analysis was unusually inaccurate. The direction of adjustments were incorrect, and there was not much measurable change in error in between adjustments. Normally, even tiny adjustments are correctly measured with Hocus Focus.

In my case, this is what the CCDI heat map of my sensor looked like when it was decentered:



Once I realized the issue and centered my chip, not only did Hocus Focus become much more accurate, my corner stars got much better and I was able to measure this improvement with CCDI, which showed a much more symmetrical impact of field curvature.

After centering my sensor:

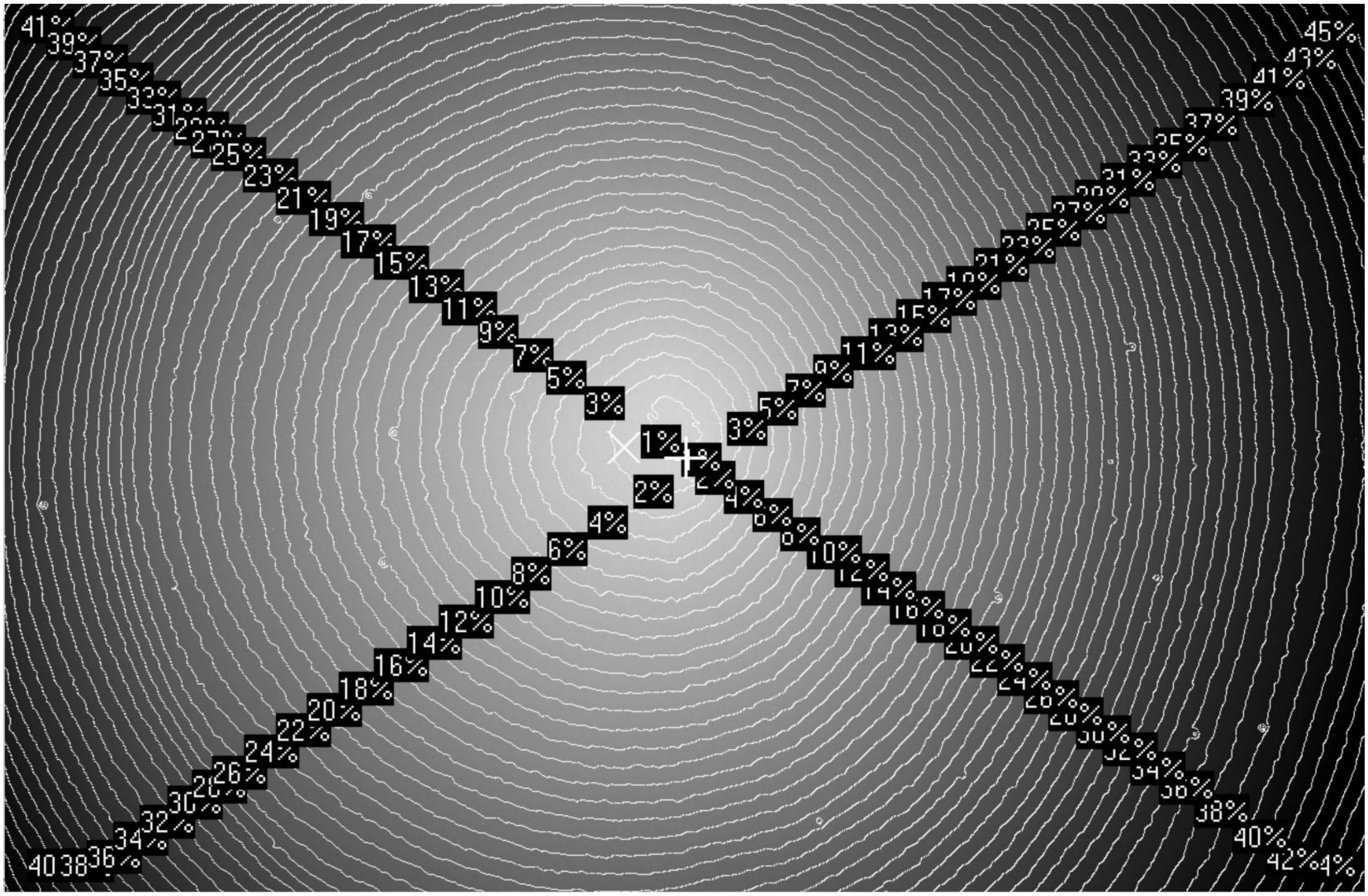


So, if you are having trouble with one side of your frame, or one corner that never seems to get better no matter how much fiddling you do… make sure that your chip is centered on your optical axis. If it is offset, even a small amount it may have a detrimental effect on your image quality, as well as your sanity.

How do you determine if your image is centered? This really depends on your image train. In my case, the source of centering error was in the Octopi device. So my sensor was offset from the Optical axis as well as the rest of the image train including my filters. In my case, I could use flat frames and measure fall off to see if it is symmetrical. If your decentering is caused by something else in your image train, you might also be able to use the flats method as long as the vignetting you get is caused by the telescope and/or corrective optics and NOT your filters. If your sensor AND your filters are both decentered, and the filters cause your vignetting, it would give you a false negative. You might be decentered, but your vignetting is not.

Since I don't have a lot of experience with decentered chips, it's difficult for me to give guidance on how to identify it. I spoke to Keith at Octopi Astro, and he told me that he now uses homing sensors on his mill to achieve a much tighter tolerance than the "old days" when the device first came out. It's also possible that the centering feature may not be centered when a camera is installed. The Octopi has a feature where you can shift your sensor laterally or up and down if the sensor is not centered on the optical axis. So, if you have an Octopi device, it is critical that you check to make sure your sensor is centered before attempting to fix tilt and spacing. Whether the device itself has a slight manufacturing intolerance or the sensor position is not centered, it would have this same effect in your images. You can easily fix this issue by centering your sensor within the vignetting of your flat frame.

This is what the flat frame looks like for a decentered sensor using the CCDI flat frame analyzer. This was taken with a Takahashi Epsilon, and with 45% light fall off in the corners of a full frame sensor, it is obvious that the sensor is not centered.



On the left side of the frame light fall-off is about 40%, while on the right side of the frame it is around 45%. If the sensor is centered on the optical axis, vignetting would be symmetrical.

Part VI- The grain of salt

None of this objective analysis is perfect. NINA provides a recommendation for corner tilt adjustment that is based on the average of all four corners optimal HFR. Essentially, the output is the delta between the corner and the average of all of the corners. In theory this should work as if you reduce the delta to zero between the respective corners and the average.... you have a tilt free field. In practice this does not always work. You may will find yourself see-sawing around this average value but never able to dial it in perfectly to produce a visually tilt free image even if the analysis says it is tilt free.

ASTAP uses the center HFD as the reference and the output values for corner analysis is the delta between each corner respectively and the center. In my testing I have found HFD to be slightly more accurate than HFR for tilt analysis, but even if the analysis says your images are tilt free... a visual inspection may reveal that they are not.

I suspect that the problem is that neither HFR and HFD are perfect proxies for determining tilt. If the image circle was infinitely large, you would see tilt as a larger (but still round) star. This doesn't happen in real life however, as field curvature plays a role. With tilt and field curvature you end up with eccentric stars or astigmatism, and this confuses HFR and HFD measurement as a tighter more well focused highly eccentric star can have a lower HFR/HFD than a perfectly round but slightly larger star.

All of this said, both Hocus Focus and ASTAP will get you very close, which is 90 percent of the battle. The final 10%, should you choose to tackle perfection relies on visual analysis and fine tuning to get the star profiles that you want.

The most important component of all of this is to take your time and try to understand exactly what is going on here as you dial in spacing and tilt. Just turning screws and hoping to get lucky will not end well. We're talking microns here.

I hope that all of this is helpful. Feel free to share this guide.

Special thanks to:

George Hilios- NINA contributor and author of the Hocus Focus plugin. This is a game changing piece of software that empowers average astro-imagers from beginner to advanced to tackled the complicated topics of tilt and spacing.

Han Kleijn- Author of ASTAP. Providing focus bracket hyperbolic curve analysis as well as robust single frame analysis for tilt.

Bill Long- Owner of Dark Matters Astro. Bill and I have been working on tilt and spacing issues together for over a year now, and this collaboration has shaped my discovery and understanding of the topic at hand.

John Hayes- Adjunct Research Professor, College of Optical Sciences, University of Arizona. I've emailed John many times with optical questions, and he has been extremely generous with his time and expertise to help me better understand my observations.

If you have any questions, feel free to reach out at chris@overcastrobservatory.com

My website is: www.overcastobservatory.com

My Astrobin is: https://www.astrobin.com/users/Overcast_Observatory/