GET FOCUSED!

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With CCD cameras and precision electronic focusers, you can focus much better than what is traditionally defined as the critical focus zone.

Introduction

The bar of excellence has never been higher in astrophotography. For those of us who have the courage to post the results of our labors in our images on the internet for the world to see, we expect ever growing scrutiny from a more sophisticated audience. We expect to see vibrant colors that showcase structural details, along with good framing that provides a cosmic perspective for the object. For example, the image of NGC 6164 in Fig.. 1 shows a bright, bipolar planetary nebula in the southern constellation of Norma, surrounded by an extended halo from an early expulsive event, all set in a red background rich in hydrogen emission. However, this is not sufficient for many of us. We will download the image, zoom in and explore it for interesting fine detail, as in Fig 1 Insert. Along the way, we will look for round stars, indicating that the telescope system was operating properly. We will also note if the stars are sharply focused when we zoom in. Excellent focus could make the difference between a good image and a great image that "pops".

Fig 1. NGC 6164 planetary nebula in Norma (Goldman) and Insert

Good focus is something that we often take for granted. We know it when we see it. We know that we have to work harder to achieve good focus on an f/3.5 corrected Newtonian telescope than an f/10 Ritchey-Chretien reflector. We know that some telescopes, such as closed tube refractors, may need frequent refocusing as they mechanically cool during the course of the evening. Many of us use a monochrome CCD camera for the highest possible resolution where every pixel carries information, unlike one-shot or DSLR color cameras. As such we employ filter wheels that place different filters in front of the camera for each exposure. We then combine these different data using software in our computers to produce a color image. These days, filters are made to exacting thickness tolerance and are often stated as being parfocal, so that refocusing among red, green and blue may not be required. Of course even parfocal filters will not correct offsets in color correction already present in the telescope. With possible changes in focus due to filters, color correction in the telescope optics or mechanical changes due to cooling, using a precision electronic focuser has become an essential component of an astrophotography system for optimal results. This article focuses on focus - that last little bit that can make an image great.

Critical Focus Zone?

How good does focus have to be? What is the focus tolerance within which you cannot measure or see any difference, and therefore do not have to worry about changing focus? Enter the concept of the Critical Focus Zone (CFZ). It represents a zone of focuser movement in which there is supposedly no noticeable difference in the size of your stars. CFZ is defined based upon the diameter of the first dark ring of the Airy diffraction disk, D, which is:

$$D = 2.44 * F * \lambda$$

where F is the focal ratio of the telescope (e.g., 5 for an f/5 system) and λ is the wavelength of light in microns (e.g., 550 nm green is 0.55 microns). D is an approximation of the smallest detail resolvable by this telescope. The definition of CFZ assumes that the spot size of the defocused star (measured by its full width at half maximum intensity, or FWHM) becomes no larger than this Airy disk diameter. Based upon geometric optics, the movement in focuser travel to achieve this condition requires us to multiply D by F, and because that motion goes in both directions, the CFZ is twice this value, or:

$$CFZ = 2 * F * D = 4.88 * F^2 * \lambda$$

This is the formula commonly seen in reference books and on the internet. It was derived by Sidgwick (*Amateur Astronomer's Handbook*, 4th ed., 1955, p 425). For example, at 500 nm, f/10 and f/5 systems have CFZ values of 244 and 61 microns, respectively. Thus, halving the f-ratio decreases the CFZ by a factor of 4. Hence, focus tolerance decreases rapidly with faster optics. Note that this would mean that if you are at best focus on this f/5 system, you can move 30.5 microns in one direction (½ the total CFZ) and not measure a difference in the size of the star. As we shall see below, this approach provides a value that is too large by perhaps a factor of 3, meaning that you can focus much **BETTER** than this.

Equipment

An experiment was performed using an f/5.3 Takahashi (http://www.takahashiamerica.com) FSQ-ED 4" refractor with an Apogee (www.ccd.com) U8300 CCD camera and Astrodon (www.astrodon.com) E-Series Generation 2 RGB filters in an Apogee filter wheel. This camera contains the Kodak front-illuminated, full-frame CCD, KAF8300, with 8.9 MP and 5.4 micron pixels. The plate scale was 2.1 arcsec/pixel. The telescope system was mounted on a Paramount ME (www.bisque.com). Focusing was done by removing one of the focus knobs and conecting the axle directly to a Technical Innovations (http://www.homedome.com/) Robo Focus electronic focuser on a mounting bracket. The step size (tick) of the focuser system was measured at 27 microns. The focuser was controlled by computer. Filter thicknesses were measured to be within 8 microns of each other, so they did not significantly contribute to the focus differences.

Fig. 2. Experimental system

The freeware program FocusMax (http://users.bsdwebsolutions.com/~larryweber/) was used to calibrate the system by averaging five "V-Curves". This program moves the focuser on both sides of best focus while measuring the width of an appropriate star. The results are V-shaped calibrations with the bottom of the "V" representing best focus. It solves for this minimum by measuring several defocused points and then moves the electronic focuser to that point of best focus.

Measurements

All FocusMax best-focus solutions were made within 7 minutes of each other on an unsaturated star near the zenith. Separate best focus measurements were made through red, green and blue filters. Each filter was measured 3 times in the order of red, green and blue, and then the sequence was repeated to look for any time-dependent changes. The results in Robo Focus tick mark positions are summarized in Table 1 below

Image analysis was then performed by measuring the average FWHM of a field of stars using CCDInspector (www.ccdware.com) and reporting the results in arcseconds. The image sequence shown in Fig. 3 starts at the best focus (focuser position, or tick 4482) using the green filter shown in Table 1. The FWHM analysis from CCDInspector is shown in Fig. 4. The CCD sensor (~19 x 14 mm) is well within the 88 mm illuminated field of the telescope, so optical effects on the FWHM analysis (coma, astigmatism) should be minimal.

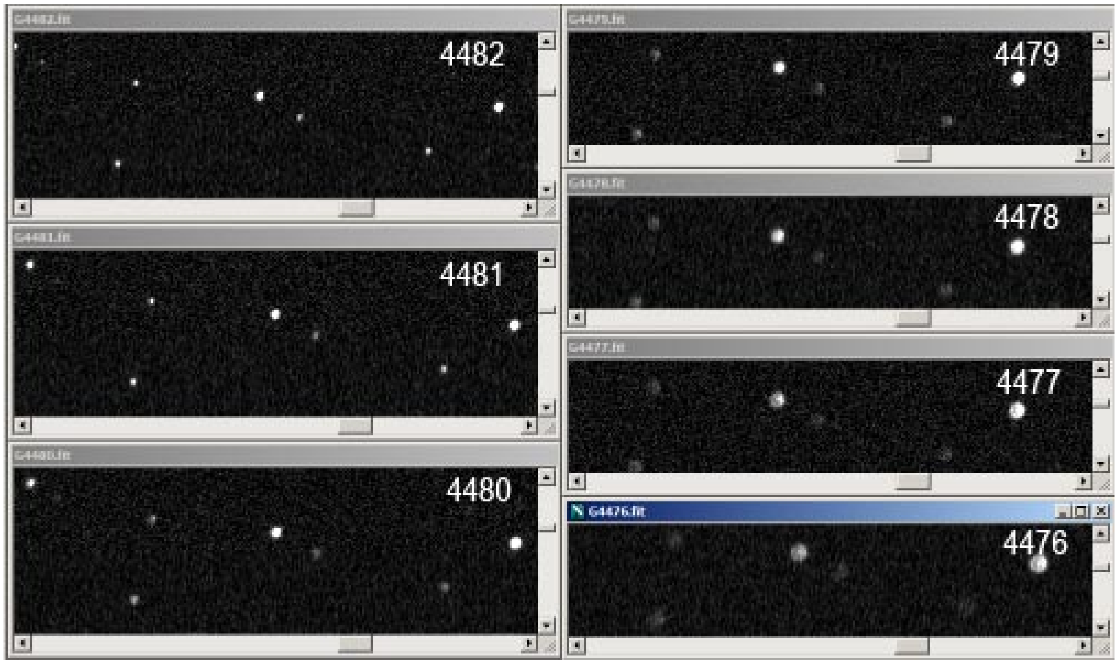


Figure 3. Star field at best focus (4482) and progressively defocused using the green filter

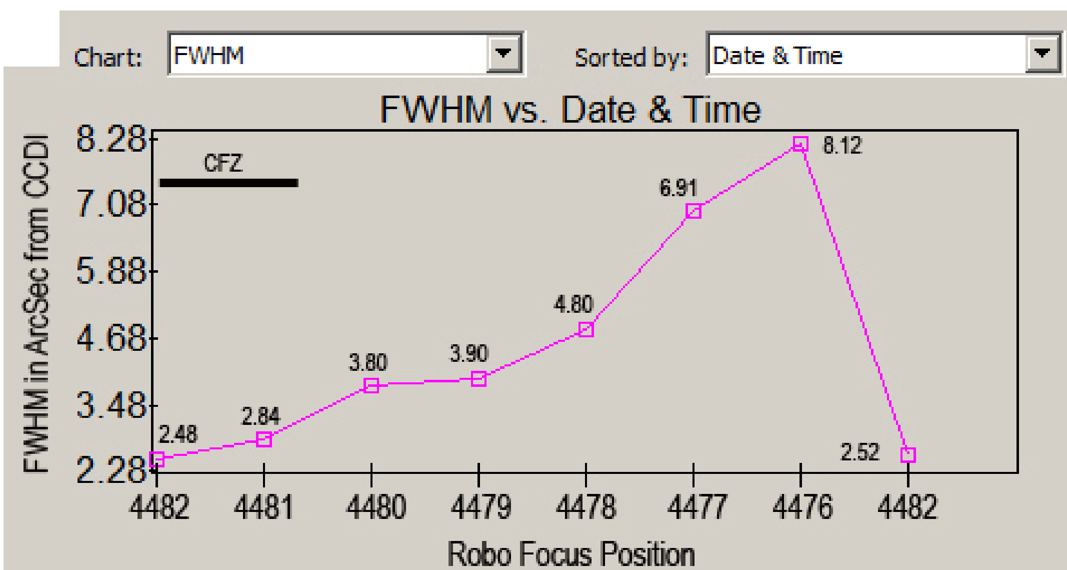


Figure 4. Average FWHM analysis of images shown in Fig. 1 using the green filter.

	Red	Green	Blue
	4481	4482	4480
	4481	4482	4480
	4481	4483	4480
	4480	4482	4481
	4481	4482	4481
	4480	4482	4481
Average (ROBO Ticks)	4480.7	4482.2	4480.5
Std. Dev.	0.5	0.4	0.5
Offset ROBO Ticks	-1.5	0.0	-1.7
Offset (mic)	-40.6	0.0	-45.1
CFZ (mic)	79.3	67.1	54.9
CFZ one direction (mic)	39.7	33.6	27.5

Table 1. Measurement of best focus reported in RoboFocus Ticks

Discussion

It is obvious visually from the images in Fig 3. that even one tick of defocus (i.e. from 4482 to 4481) enlarged the stars. The faint stars are not as sharp. CCDInspector data indicate that this difference increased the FWHM on average by 0.36” from 2.48” to 2.84”. Two ticks increased it by 1.32”. The sequence was stopped at six ticks and the focuser was returned to the starting point to check for reproducibility. It returned to within 0.04” of the initial FWHM value as shown in Fig. 4.

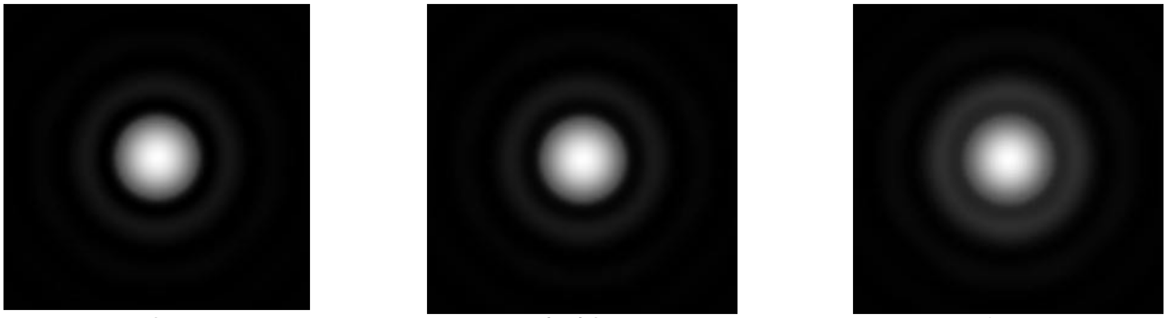
The calculated CFZ for the measurements presented in Table 1 for the green filter in one direction is 34 microns, or roughly 1.25 ticks. This is shown by the length of the horizontal bar in Fig. 4. Yet within the span of this CFZ we see an increase in FWHM of about 0.6”. This value is significantly larger than the reproducibility of the system on that night. It presents a conundrum. ***How can we measure differences within the CFZ, the zone of no focus difference?***

The answer comes from the fact that the previous calculation of CFZ was overly simplistic. Suiter (Suiter, H. R., *Star Testing Astronomical Telescopes*, 3rd ed., page 78) indicated that there is no absolute CFZ, and derived an expression relating focuser movement to the resulting number of acceptable wavelengths of optical aberration:

$$\Delta f = 8 * F^2 * \Delta n * \lambda$$

where Δf is the change in focuser position that results from an optical aberration of Δn wavelengths. So, what does this mean in practical terms? Let’s take a value a 2.5 times the reproducibility suggested from our measurements and consider a change in FWHM of 0.1”. This represents 6 microns (6000 nm) of focuser travel, which is about 10 wavelengths for green light. If n is allowed to go from +1/10 to -1/10 (i.e. maximum optical aberration of 1/10 λ), Δn = 1/5 = 0.2, Suiter’s expression becomes $1.6 * F^2 * \lambda$. This becomes 25 microns for the green filter, but in one direction is about 12 microns. This is approximately 1/3 of the CFZ value and more consistent with our measured results. Sidgwicks formula corresponds to about 4 wavelengths of aberration (Δn = ¼ = 0.5).

How do we tell which is applicable? The freeware program Aberrator (http://aberrator.astronomy.net) provides the answer. This program was used to simulate the diffraction patterns of a 106 mm f/5.3 telescope at 0, 1/10 λ and 1/4 λ of defocusing aberration.



0 1/10 λ ¼ λ

Fig. 5. Focus aberration modeled by Aberrator

It is clear from Fig. 5 that aberration is barely visible at 1/10 λ , but becomes obvious at 1/4 λ, where a significant amount of light has moved to the first bright diffraction ring and which should result in a measurable increase in FWHM. 1/4 λ corresponds to the CFZ as it was originally defined. Since we measured significant increases in FWHM at this 1/4 λ point combined with the fact that there is clear aberration in the Aberrator image, we must conclude that the CFZ overestimates detectable changes in focus by about a factor of three. We would be better off using Suiter's derivation for 1/10 λ, which becomes (in one focuser direction):

$$0.8 * F^2 * \lambda$$

Thus, for f/10/, f/7, f/5 and f/3.5 optical systems at 500 nm, these new values become ~ 40, 20, 10 and 5 microns, respectively. To put this in perspective, let's consider a set of 3 mm thick filters with a good thickness tolerance of +/-0.05 mm (+/- 50 microns). Thus, they can differ in thickness up to 100 microns. About 1/3 of this value translates into focus shift due to light refraction[1], or about 33 microns, which is larger than all the values listed above except for f/10. Thus, even filters specified with a good thickness tolerance may not be parfocal with optics faster than about f/9. Lastly, to provide an additional perspective, a human hair is approximately 50 microns thick. So, telescope systems must be focused to better than the width of a human hair for sharp stars using this updated CFZ. A good quality electronic focuser becomes critical for success.

Conclusions

It appears that we can and should focus our telescopes considerably finer, perhaps by three times better than the value described by the traditional CFZ, especially with our electronic focusers and CCD cameras. Without this realization, we would conclude from our tests that the slight differences in focus among the red, green and blue filters due to microscopic variation in filter thickness are within the CFZ. We would simply focus on one filter and use that focus position for all filters. But, that would be a mistake. Our results suggest that these finer differences are real and we should change focus when changing filters in order to maintain optimal image quality. Many current data acquisition programs have the means to enter filter focus offsets for electronic focusers. Thus, it

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[1] For example a 3mm thick glass filter or chamber window in the CCD camera will increase the backfocus as measured from the telescope by 1mm.

becomes easier, for our example, to focus on the green filter, and adjust the focus by -1 tick when using the blue or red filter without further measurement. This saves time. Furthermore, these data acquisition programs can automatically refocus on a prescribed schedule to ensure optimum focus throughout an evening as optical systems cool and mechanically change focus. This much smaller range of optimal focus may mean that filters previously thought to be parfocal, good optical systems with excellent color correction, may need to be refocused, even at f/5. The need for a precision electronic focuser becomes even more important. You should calibrate your system on a good night of seeing and set the resolution of your focuser accordingly. In short, it is clear that modern amateur telescope systems can achieve better focus than previously thought.