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New Critical Focus Zone

GoldAstro has undertaken research into a replacement for the traditional Critical Focus Zone which has known theoretical and practical problems. This potential replacement is called the New Critical Focus Zone.

In theory, in the absence of astronomical seeing, the GoldFocus Focusing System can measure focus right down to perfect focus. In practice, in the presence of astronomical seeing, GoldFocus can measure focus down to very near perfect focus with very reliable accuracy. Therefore, the traditional Critical Focus Zone assertion that certain focus errors are non-measurable must be revised.

The New Critical Focus Zone recognizes that all focus error is measurable. Instead of non-measurable focus errors as in Critical Focus Zone, the New Critical Focus Zone uses a criteria of whether focus has a negligible impact on image quality. What constitutes negligible impact is subjective and is related to the goals and purposes of the astronomer or astroimager.

The New Critical Focus Zone uses a "tolerance" for focus error designated by the astroimager. The focus error tolerance represents an acceptable percentage deviation from the best possible focus as measured by the FWHM of the image. For example, if astronomical seeing conditions are 3.0 arc seconds and an astroimager wishes to achieve a focus tolerance of 10 percent, then the astroimager is willing to accept 0.3 arc seconds as additional focus error (10 per cent of 3.0) up to 3.3 arc seconds (3.0 plus 0.3) of total seeing in the image.

Most experienced astroimagers can visually discern focus errors on the order of 15-20 per cent tolerance, by eye and without the aid of any measurement. For example, they can visually discern 3.45-3.60 arc seconds FWHM compared to 3.0 arc seconds FWHM. Thus, from a practical standpoint, most astroimagers will desire a focus error tolerance of 10-15 percent or lower, perhaps even as small as 1-3 percent.

Again, the focus error tolerance is up to the astroimager to choose as appropriate to his needs.

The New Critical Focus Zone is the range of travel on the focuser draw tube (as it is for the traditional Critical Focus Zone) which falls within the focus error tolerance desired by the astroimager. The New Critical Focus Zone (denoted NCFZ) is closely approximated by the formula:

$$\mathbf{NCFZ} = \mathbf{0.00225} \cdot \boldsymbol{\theta}_{\mathbf{FWHM}} \cdot \sqrt{\boldsymbol{\tau}} \cdot \boldsymbol{A} \cdot \boldsymbol{f}^{2}$$

NCFZ - New Critical Focus Zone (micrometers)
$\boldsymbol{\theta}_{\mathbf{FWHM}}$ - total seeing (arc seconds)
$\boldsymbol{\tau}$ - focus tolerance as a percentage of total seeing (unitless)
$\boldsymbol{A}$ - telescope aperture (millimeters)
$\boldsymbol{f}$ - effective imaging system f/ratio (unitless)
0.00225 - constant (micrometers per arc second per millimeter)

Suppose your telescope diffraction limit and astronomical seeing conditions combine for a total seeing of 3.0 arc seconds and that you have a tolerance of 15 percent for focus error. Suppose your telescope has an aperture of 106 mm and your imaging f/ratio is f/5. Your NCFZ is:

$$\mathbf{NCFZ} = \mathbf{0.00225 \cdot 3.0 \cdot \sqrt{15} \cdot 106 \cdot 5^2} = \mathbf{69\ micrometers}$$

The above NCFZ means that starting from a point of near perfect focus, you can focus in or out up to about 35 micrometers (half of 69 micrometers) without adding more than 0.45 arc seconds (15 percent of 3.0) to your image's total seeing, up to 3.45 arc seconds.

The New Critical Focus Zone can also be used to analyze the diffraction limited focus behavior of your telescope. The same 106 mm telescope will have a diffraction limit of 1.1 arc seconds in green light (550 nm). The theoretical diffraction limited NCFZ is:

$$\mathbf{NCFZ} = \mathbf{0.00225 \cdot 1.1 \cdot \sqrt{15} \cdot 106 \cdot 5^2} = \mathbf{25\ micrometers}$$

You will note that the traditional Critical Focus Zone for this telescope in green light (550 nm) is about 67 micrometers and that the traditional Critical Focus Zone is always stated for diffraction limited. The above results are further evidence of the problems in the traditional Critical Focus Zone which claims the focus error is not measurable at 67 micrometers.

The NCFZ shows that the focus error is visually observable at 25 micrometers for the diffraction limited case, contrary to the traditional Critical Focus Zone claiming it is non-measurable at 67 micrometers.

Likewise, NCFZ shows that the focus error is visually observable at 69 micrometers in the presence of 3.0 arc second total seeing, contrary to the traditional Critical Focus Zone claiming it is non-measurable at 67 micrometers for perfect astronomical seeing (i.e., under much better conditions than 3.0 arc seconds seeing).

Accuracy of NCFZ

The reader should be made aware that the interaction between diffraction limited images (Airy disks), astronomical seeing, and focus produce mathematical relationships which are called a non-closed form in the mathematical jargon. Non-closed form means there is no simple and direct equation which can be solved to produce exact results, a situation fairly common in the theory of optics.

The NCFZ formula presented here is a good approximation to the exact NCFZ and can be easily calculated with a hand-held calculator. The NCFZ formula should be accurate to a relative error of about +/- 0.04 times the computed NCFZ. For example, a computed NCFZ of 50 micrometers should be accurate to about +/- 0.04 times 50 micrometers, or about +/- 2 micrometers.

Discussion

Following is a discussion of the NCFZ, the factors it involves, and other factors related to focus and imaging.

θ_{FWHM} - total seeing (arc seconds) - The total seeing sets the baseline for the smallest size of image detail which is possible with perfect focus for the given seeing conditions. The total seeing is the combined contribution of the diffraction limit of your telescope and the astronomical seeing. These two are not directly additive. A good rule of thumb when astronomical seeing is 2 arc seconds or higher is:

$$\theta_{FWHM} = 0.2 \cdot \theta_{limit} + \theta_{seeing}$$

> θ_{FWHM} - total seeing (arc seconds)
> θ_{limit} - telescope diffraction limit (arc seconds)
> θ_{seeing} - astronomical seeing (arc seconds)

For example, if the diffraction limit is 1.0 arc second and astronomical seeing is 3.0 arc seconds, then total seeing will be approximately 3.2 arc seconds (0.2 · 1.0 + 3.0).

In light of the above rule of thumb, notice that total seeing is dominated by astronomical seeing and only moderately affected by diffraction limits. Most astroimagers are accustomed to estimating their astronomical seeing or perhaps use available forecast services for seeing conditions, either of which are usually stated in arc seconds as required for the NCFZ formula. Alternatively, if you have means to measure the FWHM of star images taken through your imaging setup, you should use that FWHM measure. Be sure to use a FWHM measure converted to arc seconds and do not use FWHM measured as pixels or micrometers. See also the discussion of CCD pixel size, below.

The NCFZ formula is accurate across a range of about 0.4 to 6.0 arc seconds total seeing. Note that 0.4 arc second seeing is a practical limit for earth-based observing, so NCFZ applies to the best earth-based observing sites, as well as to poor 6.0 arc seconds seeing.

τ - focus tolerance as a percentage of total seeing (unitless) - As mentioned above, the focus error tolerance is chosen by the astroimager to meet his own needs. Given that a tolerance of 15-20 per cent of FWHM is visually noticeable to most observers, the focus error tolerance chosen by most astroimagers will most likely be 10-15 per cent or less. With a good focuser, tolerances as low as 3-5 per cent are possible. With an top-quality focuser, even 1-2 per cent focus error is achievable. For example, 1 per cent focus error tolerance would mean imaging at 3.03 arc seconds seeing or better when actual seeing conditions are 3.0 arc seconds, which clearly pushes image quality to its practical limit. Choose a focus error tolerance which is consistent with your imaging needs and the quality of your focuser.

The NCFZ formula is accurate across a range from 0 to about 20 per cent focus error tolerance.

A - telescope aperture (millimeters) - Aperture, together with f/ratio, scales arc second seeing and focus errors to the physical linear size of your telescope. Larger apertures give larger NCFZ, meaning larger aperture telescopes are easier to focus than smaller aperture telescopes. All other things being equal, the same focuser mounted on a large telescope will have an easier time focusing than on a smaller telescope.

The NCFZ formula is accurate for all apertures.

f - effective imaging system f/ratio (unitless) - The f/ratio scales the physical linear size of focus error on the CCD focal surface to the travel distance of the focuser draw tube. As with aperture, larger f/ratio (slower) telescopes are easier to focus than smaller f/ratio (faster) telescopes.

The NCFZ formula is accurate for all f/ratios.

Focal length - Because focal length equals aperture times f/ratio, both of which are in the formula, the NCFZ does depend upon focal length. Refer to aperture and f/ratio for discussion.

The NCFZ formula is accurate for all focal lengths.

Light wavelength - The wavelength of light has an effect on the diffraction limit of the telescope at that wavelength and therefore is included in total seeing, which is in the formula. See total seeing for discussion.

The NCFZ formula is accurate for all light wavelengths.

CCD pixel size - The physical pixel size of the CCD in relation to the telescope focal length determines whether images are under-, over-, or critically-sampled. Many amateur imaging setups are under-sampled by a factor of several times when considered at the diffraction limit of the telescope. However, when total seeing is accounted, these same imaging setups are often very close to critically-sampled. An under-sampled imaging setup will experience total seeing higher than critically-sampled setups due to a loss of image detail at the pixel level. If your setup is under-sampled at the actual total seeing conditions, then it is important that you use a FWHM measured by your imaging setup in order that it reflects your imaging setup's actual seeing. You will also note that the higher FWHM of an under-sampled setup causes a higher NCFZ, meaning under-sampled imaging setups are easier to focus than critically-sampled setups.

The NCFZ formula is accurate for all CCD pixel sizes assuming the total seeing used in the formula is representative of the total seeing measured in images taken using that CCD pixel size.

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