On Axis Guiding
and
Real Time Autofocus Solutions

Southwest Astrophotography Seminar 2014

Dr. Gaston Baudat

Innovations Foresight, LLC
Astro-photography challenges

A target must stay still for successful long exposures. Accurate tracking and optimal focus are critical. A $1/2$ arc” error is visible under good seeing conditions.

Common problems:

- Polar alignment, King’s rate, ...
- Mount mechanic and periodic errors, ...
- Flexure(s), mirror/optics motions, ...
- Focus shifts with temperature, ...
- And more...

Auto-guiding & periodic refocusing are often required!
- **Periodic errors (PE):**
  
  *PEC helps but not necessary enough.*  
  *Active guiding is likely.*

- **Polar alignment error:**
  
  *Drift & field rotation.*
  
  *10 arc’ error, f=2 m, t=5’, fov=1°, @+35° elev.*
  
  *Trail=8 microns, or 0.83 arc”.*

- **Flexure(s):**
  
  *OTA(s), mount, ..., difficult to track and fix.*
  
  *Active guiding may help (same optical axis)*
Common focus errors

-Temperature changes:

OTA contraction, C11-Aluminium: \( \sim 350\mu m / ^{\circ}C \) (0.014”/ \(^{\circ}C\)).

CFZ = +/-134 \( \mu m \) @ F/10 -> focusing every \(^{\circ}C\) or less with good seeing ( +/-44 \( \mu m \) @ 1/10 \( \lambda \) error). Human hair \( \varnothing \sim 100\mu m \).

Mirror Radii: Optical powers, different thermal inertias.

- Mirror shift, flexure(s):

Mirror shifts with location or meridian flip. Alignment of optics may be altered.

Out of focus could lead to other aberrations
Image quality: FWHM

FWHM (Full Width at Half Maximum), correlated to PSF:

From space, diffraction limited (Airy disk) \[ FWHM = 2 \cdot 10^4 \frac{\lambda}{D} \text{ arc}'' \]
D = 0.3m, \( \lambda = 550\text{nm} \), -> 0.39 arc” (Rayleigh's limit)

From Earth, seeing limited (Gaussian like) \[ FWHM = 0.5 \text{ to } 3 \text{arc}'' \]
Image quality: Absolute Roundness

$$\text{ARDN} = \frac{(\text{Major FWHM} - \text{Minor FWHM})}{(\text{Major FWHM} + \text{Minor FWHM})}$$

An ARDN < 0.1 (10%) is not perceived by human inspection
How much tracking error is too much?

Rule of thumb: \textbf{RMS tracking error $< \frac{1}{4} \text{FWHM}_{\text{seeing}}$}

RMS tracking error v.s. seeing for a absolute roundness $< 10\%$ (Exposure $> 1$ second)

<table>
<thead>
<tr>
<th>Seeing</th>
<th>Excellent 0.5 arc”</th>
<th>Good 1.0 arc”</th>
<th>Average 2.0 arc”</th>
<th>Poor 3.0 arc”</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS error</td>
<td>0.13 arc”</td>
<td>0.25 arc”</td>
<td>0.50 arc”</td>
<td>0.75 arc”</td>
</tr>
</tbody>
</table>
How much focus error is too much?

Wave front error:

FE $\lambda/3$: $\pm 2.44 \times F^2 \times \lambda = \text{CFZ}$  (Rayleigh's limit, angular resolution)

FE for $\lambda/10$: $\pm 0.8 \times F^2 \times \lambda = \sim 1/3 \text{ CFZ}$

**Rule of thumb:** Focus error $< \lambda/10$
On-Axis Guiding (ONAG®)

Concept: Split incoming light (Visible v.s. NIR)

- Same scope, same aperture, no-flexure.
- Large field of view (on and off-axis).
- No rotation (same flat frames, stay in focus).
- Seeing effects significantly reduced in NIR.
- Allow for true real time auto-focus (SharpLock).
ONAG® XT overview

Multi-coated dichroic mirror: Laser aligned at factory
Weight: <800g (1.8 lbs)
Reflection (visible 350nm-750nm): >98% typical
Transmission (NIR 750nm-1800nm): >90% typical
X/Y stage exploration circle (guider): Ø 44mm (1.7"")
The black body law describes star spectrums

\[ I(\lambda, T) = \frac{2hC^2}{\lambda^5} \left( \frac{hC}{e^{kT\lambda} - 1} \right) \]

Star spectral classification

<table>
<thead>
<tr>
<th>Class</th>
<th>Surface T °K</th>
<th>% of stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>&gt;33,000</td>
<td>0.00004</td>
</tr>
<tr>
<td>B</td>
<td>10,000-33,000</td>
<td>0.13</td>
</tr>
<tr>
<td>A</td>
<td>7,500-10,000</td>
<td>0.6</td>
</tr>
<tr>
<td>F</td>
<td>6,000-7,500</td>
<td>3</td>
</tr>
<tr>
<td>G</td>
<td>5,200-6,000</td>
<td>7.6</td>
</tr>
<tr>
<td>K</td>
<td>3,700-5,200</td>
<td>12.1</td>
</tr>
<tr>
<td>M</td>
<td>&lt;3,700</td>
<td>76.45</td>
</tr>
</tbody>
</table>

> 75% main sequence stars surface temperatures < 3700°K (class M)
Black Body & Quantum Efficiency

NIR guiding consideration:

Star spectrum x Optical transfer function x Sensor efficiency

Atmospheric extinction neglected

![Graph showing efficiency vs wavelength for a Sony ICX429AL chip and a star at T=3700 °K. The graph illustrates the cut-off of the ONAG and the efficiency changes with wavelength.]
ONAG® efficiency

Full spectrum (350 – 1000nm) v.s. ONAG NIR range (>750nm):

\[
\text{Efficiency} = \frac{\text{Energy}_{\text{Full}} - \text{Energy}_{\text{ONAG}}}{\text{Power}_{\text{Full}}} 
\]

>75% main sequence stars \( T < 3700^\circ K \)
>99% main sequence stars \( T < 6000^\circ K \)

Guide scope versus ONAG:

80mm (3.2”) guide scope versus C11

\[ \frac{3.15^2}{(11^2 \times 0.89)} = 0.09x, \text{ loss} = +2.6 \text{ mag} \]

ONAG: gain 1.5-2.6=-1.1 or 2.8x (worst case)

ONAG typical guide star magnitude:

Scope: C11 @ F/10
Guiding: ONAG® & SX-Lodestar - 1 second
Guide star typical magnitude: 9th

Guide star surface temperature \( T \) [°K] vs. Efficiency [%]

- Sony ICX429AL B/W chip
- +0.6 mag.
- +1 mag.
- +1.5 mag.
SharpLock leverages the ONAG technology for providing the only real time auto-focus in the market:

- Continually maintains critical focus without any interruptions in imaging operations. Scope remains on target.

- Uses the guide star images for focus directionality & quality assessments while auto-guiding.
Guide star profile

Guide star a best focus:

- Imager side
  - Visible light
- Scope side
- ONAG dichroic mirror
- NIR light
- Guider side
  - Guider port astigmatism
    - (exaggerated, not at scale)

- Star seen by imager
  - HFD = 6 pixels
- Star seen by guider
  - HFD = 6.2 pixels
Out of focus guide star

The star shape is function of focus position (in, out focus). *SharpLock* retrieves focus directionally from shape analysis.

- **Guiding camera**
  - -0.4 mm = intra-focal
  - 0.0 mm = best focus
  - +0.4 mm = extra-focal

- 400 µm from best focus at best focus + 400 µm from best focus


**SharpLock** Optical concept

- Imager camera focal plane
- Visible light path
- ONAG
- NIR light path
- Guider camera focal plane

**Guide star shapes versus best focus offsets**

- F 10 -200 μm -37%
- F 10 -100 μm -18%
- F 10 0 μm 0%
- F 10 +100 μm +18%
- F 10 +200 μm +37%

**Guide star relative roundness**

- Graph showing guide star relative roundness versus offset from best focus [micron]

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Relative Roundness

\[ RRDN = \frac{(1^{st} \text{ FWHM} - 2^{nd} \text{ FWHM})}{(1^{st} \text{ FWHM} + 2^{nd} \text{ FWHM})} \times 100 \% \]

- RRDN carries directionality information (signed).
- 1\text{st} & 2\text{nd} axes are defined during the SharpLock calibration.
- They are reference axes related to the guider camera frame.
Relationship between focuser position and guide star roundness

![Graph showing the relationship between guide star offset from best focus and relative roundness. The x-axis represents guide star offset from best focus in micrometers (µm), and the y-axis represents relative roundness in percent (%). The graph shows a typical transfer function with a linear relationship.]
- 10” RCT F/8, carbon fiber OTA + fans, absolute focuser.
- One hour temperature stabilization period.
- Target near the zenith (no mount pier flip, same side).

**Focus shift analysis with SharpLock**

**Focus changed up to 20 \( \mu m/\text{minute} \) (F/8 CFZ=+/-86\( \mu m \))!**
Periodic refocusing versus SharpLock side by side

CCDAP, same scopes, mounts, time & location. Credit Frank Colosimo
Periodic refocusing v.s. *SharpLock*

M82 - 27 March 2014

**Location:** Blue Mountain Vista Observatory, New Ringgold PA (USA)

**Scopes/Mounts:** Hyperion 12.5” F/8 (same model) / PME

**Imager #1:** SBIG STL-11000, 9x9μm, periodic focus (every filter or 30’)
24 frames (LRGB): 4h46’ ~ 12’ per frame (include periodic focus)

**Imager #2:** Apogee U8300, 11x11μm, ONAG + *SharpLock*
28 frames (LRGB): 4h22” ~ 9’ per frame (no interruption)

**Saving:** 2.6’ per frame, total for 28 frames = 1h13’ or 27%

Credit: Frank Colosimo

**Stacked FWHM in arc”**

- **L:** 2.3
- **R:** 2.5
- **G:** 2.5
- **B:** 2.6

Credit: Frank Colosimo

**Stacked FWHM in arc”**

- **L:** 2.4
- **R:** 2.2
- **G:** 2.2
- **B:** 2.4

Credit: Frank Colosimo
80mm F/6.25 refractor + OPTEC absolute focuser + ONAG XT:

- Imager port with an artificial star, guider port with a guiding camera.
- Flat mirror reflecting back the artificial star image toward the guider.
Thank you!

Clear skies!