Full Frame Guiding & Focusing

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Astro-photography challenges

A target must stay still for successful long exposures. Accurate tracking and optimal focus are critical. A ½ arc” tracking error maybe visible under good seeing conditions.

Common problems:
- Polar miss-alignment
- Mount mechanic and periodic error(s)
- Flexure(s)
- Focus shifts with temperature, location, ...

Require auto-guiding and periodic refocusing
Common tracking errors

- **Periodic errors (PE):**
  PEC helps but not necessary enough. Active guiding is likely.

- **Polar alignment error:**
  Drift & field rotation.
  10 arc’ error, \( f=2 \text{ m}, t=5’, \text{fov}=1°, @+35° \text{ elev.} \)
  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: \( \sim 130\mu\text{m}/°\text{C} \) (0.005”/°C).
  \(\text{CFZ} = +/-134 \mu\text{m} @ F/10 \rightarrow \text{focusing every °C or less.}\)
  Human hair Ø\( \sim 100\mu\text{m}.\)
  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
FWHM (Full Width at Half Maximum), correlated to PSF:

From space, diffraction limited (Airy disk) \( FWHM = 2 \times 10^5 \left( \frac{\lambda}{D} \right) \text{ arc"} \)

\( D = 0.3 \text{m}, \lambda = 550 \text{nm}, \Rightarrow 0.39 \text{ arc"} \) (Rayleigh’s limit)

From Earth, seeing limited (Gaussian like) \( FWHM = 2 \times 10^5 \left( \frac{\lambda}{r_0} \right) \text{ arc"} \)

average \( r_0 \approx 50 \text{mm} \)

\( FWHM = 2 \times 10^5 \left( \frac{550 \text{nm}}{50 \text{mm}} \right) = 2.3 \text{ arc"} \)

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: **RMS tracking error < 1/4 FWHMseeing**

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

<table>
<thead>
<tr>
<th>Seeing FWHM</th>
<th>Excellent 0.5 arc&quot;</th>
<th>Good 1.0 arc&quot;</th>
<th>Average 2.0 arc&quot;</th>
<th>Poor 3.0 arc&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS error</td>
<td>0.13 arc&quot;</td>
<td>0.25 arc&quot;</td>
<td>0.50 arc&quot;</td>
<td>0.75 arc&quot;</td>
</tr>
</tbody>
</table>

Example: Seeing 2 arc", scope focal = 2m, Pixel = 8 microns

FWHM seeing = 6.64 μm or 0.83 pixel
RMS tracking error < 1.68 μm or 0.21 pixel

1 μm ⇔ 4/100,000"

How much focus error is too much?

Rule of thumb: **Focus error < 0.1 λ**

Wavelength error: 0 λ, 0.1 λ, 0.3 λ
Focus error: +/- 0 μm, +/- 44 μm, +/- 134 μm

Focus error for 0.3 λ: CFZ = +/- 2.44 \( \times F^2 \times λ \) (Rayleigh's limit)
Focus error for 0.1 λ: \( FE_{0.1} = +/- 0.8 \times F^2 \times λ \) or ~1/3 CFZ

<table>
<thead>
<tr>
<th>F/# λ = 550 nm</th>
<th>F/3</th>
<th>F/6</th>
<th>F/8</th>
<th>F/10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus error 0.1 λ</td>
<td>+/- 4 μm</td>
<td>+/- 16 μm</td>
<td>+/- 28 μm</td>
<td>+/- 44 μm</td>
</tr>
<tr>
<td>CFZ error 0.3 λ</td>
<td>+/- 12 μm</td>
<td>+/- 48 μm</td>
<td>+/- 86 μm</td>
<td>+/- 134 μm</td>
</tr>
</tbody>
</table>
**Full frame image registration**

**Goal:**
Retrieve dX, dY image registration values from the all frame.

**Digital Image Correlation**

Digital image correlation extracts image registration.  
*Below image correlation intensity 2D and 3D color plots:*
**Good SNR, one star, no seeing**

Raw image (guider).
SNR=20 dB (10x), one star, no seeing, dX=dY=30 pixels.

**Astronomical Image Correlation**

Normalized correlation image (colored 2D and 3D plots).
SNR=20 dB, one star, no seeing.
Correlation peak clearly visible but noisy.
Poor SNR, one star, no seeing

Raw image (guider).
SNR=0 dB (1x), one star, no seeing, dX=dY=30 pixels.

Image Correlation, no processing

Normalized correlation image (colored 2D and 3D plots).
SNR=0 dB, one star, no seeing.
Correlation peak no visible, signal is beneath the noise floor.
Image Correlation, with advanced statistical processing

Normalized correlation image (colored 2D and 3D plots).
SNR=0 dB, one star, no seeing (same raw images).
Correlation peak clearly visible, sub-pixel localization.

Good SNR, 10 stars, various magnitude, no seeing

Raw images (guider).
SNR 1.6 to 20 dB, 10 stars, no seeing, dX=dY=30 pixels.
Image Correlation, full field, with advanced statistical processing

Normalized correlation image (colored 2D and 3D plots). SNR 1.6 to 20 dB, 10 stars (diff. mag. -2.3 to 0). Correlation peak clearly visible, sub-pixel localization.

Poor/bad SNR, 10 stars, various magnitudes, no seeing

Raw image and correlation images, advanced processing. SNR -32 to 0 dB, 10 stars, diff. mag. -4 to 0, no seeing. Correlation peak clearly visible, sub-pixel localization.
Astronomical seeing is the blurring of astronomical objects caused by Earth’s atmosphere turbulence and related optical refractive index variations (air density fluctuations).

- It impacts the intensity (scintillation) and the shape (phase) of the incoming wave front.
- This presentation will ignore scintillation.

The angle for which the wavefront error remains almost the same (~\(\lambda/6\)) is known as the isoplanatic angle:

\[
\theta_0 \approx 0.31 \frac{r_0}{h}
\]

\(h \sim 5\text{km}, \ \theta_0\) is usually few arc-second across (@550nm):

- \(r_0 = 50\text{mm} \rightarrow \sim 0.6''\)
- \(r_0 = 200\text{mm} \rightarrow \sim 2.6''\)

\(\theta_0\) increases as \(\lambda^{6/5}\)
Effect of the isoplanatic angle on AO

AO operation is usually only effective in a very narrow FOV.

<table>
<thead>
<tr>
<th>Guide star offset [&quot;]</th>
<th>FWHM [&quot;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>5.5</td>
<td>0.3</td>
</tr>
<tr>
<td>13</td>
<td>0.45 - 0.59</td>
</tr>
<tr>
<td>23</td>
<td>0.51 - 0.68</td>
</tr>
</tbody>
</table>

Credit R. Dekany, Caltec

Fair SNR, one star under seeing limited condition

Raw image & registration scatter plot (100 samples). SNR=6 dB (2x), one star, seeing (wander) 2 pixel rms. Green dot: correlation, blue cross: traditional centroid.
Poor SNR, one star under seeing limited condition

Raw image & registration scatter plot (100 samples). SNR=0 dB (1x), one star, seeing (wander) 2 pixel rms. **Green dot:** image correlation.

Fair SNR, 4 stars, same mag. under seeing limited condition

Raw image & registration scatter plot (100 samples). SNR=6 dB (2x), 4 stars (same mag.), seeing 2 pixel rms. **Green dot:** image correlation, **blue cross:** constellation centroid, **red diamond:** one star centroid (brightest, in red).
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Fair/poor SNR, 40 stars, various mag. under seeing limited condition

Raw image & registration scatter plot (100 samples).
SNR -30 to 6 dB, 40 stars (diff. mag. -4.5 to 0), seeing 2 pixel rms.

**Green dot:** correlation, **red diamond:** one star centroid

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**Full frame auto-guiding no registration error**

Comet against a star field. dX=dY=0 pixel.
(*Crosshairs centered to an arbitrary star for visualization only*)
Comet against a star field. $dX = -13$ $dY = -12$ pixels. 
(Crosshairs centered to an arbitrary star for visualization only)

Comet against a star field. $dX = dY = 0$ pixel. 
(Crosshairs centered to an arbitrary star for visualization only)
A guide star profile with an ONAG

Guide star a best focus:

Out of focus guide star with an ONAG

The star shape is function of focus position (in, out focus). This allow retrieving focus directionally from shape analysis. The same concept is applied to the all guider frame.
Full frame auto-focus at best focus

At best focus.
*(Stars elongated due to comet motion during exposure)*

Intra focal.
*(Stars elongated due to comet motion during exposure)*
Full frame auto-focus
extra focal image

Extra focal.
*(Stars elongated due to comet motion during exposure)*

Thank you!

*Clear skies!*