Use of On-axis Guiding to Reduce the Effects of Polar Misalignment on Field Rotation

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The transit method for exoplanet detection is a popular technique used by amateur astronomers for confirming and characterizing exoplanet candidates. This method relies on accurate and precise differential aperture photometry - i.e., looking for a drop in the flux of the exoplanet's host star relative to the flux of an ensemble of non-variable comparison stars. Most amateur astronomer setups can detect at least a 1% drop in flux, if one occurs.

When using CCD and CMOS sensors, it is very important that the host star, as well as the comparison stars, remain at their same sensor locations (photosites) as long as possible. Although flat field calibration is used to attempt to correct (inevitable) photosite to photosite variations across the sensor, there is a limit to the level of correction that this strategy could eventually achieve.

Movement of a star field during an observing session occurs primarily for three reasons: Polar misalignment, periodic errors caused by the mount's worm and ring gear interaction, and mount tracking errors. Movement can also be introduced by external factors such as wind gusts, cable snags, local vibration, atmospheric refraction, etc.

Auto-guiding, along with good polar alignment, low periodic error, a stable mount platform, and a mount with good tracking precision, all go a long way toward keeping the imaging camera field-of-view (FOV), therefore the stars of interest, somewhat stationary over the sky region of interest. Sometimes, an active optics (AO) unit, consisting of a tip/tilt clear window, supplements an auto-guiding system to correct for rapid mount errors. Since most auto-guiding systems rely on one guide star, only one point of the FOV, namely the guide star itself, is actually actively guided. This means that mount (and/or any AO) corrections address only the FOV translations in the horizontal and vertical detector axes, and not any rotational aspect.

Since any mount polar misalignment translates to an inevitable field rotation (FR), which increases in magnitude when moving further away from the guide star, it is important to understand the consequence of such an error, as well as the impact of the guide star's location in the FOV of interest. This is especially true for exoplanet differential photometry. Since it is not unusual to track a potential transit for many hours, FR accumulation could eventually become quite significant.

Hook (Hook, 1989) analyzed this FR aspect in the context of a single star auto-guiding in his 1989 paper, which provides the fundamental and basic mathematics used in this document.

In his paper, Hook assumed, rather arbitrarily, 30 microns of FR, see Equation C in Hook, 1989. He also explicitly used the scope focal length ***F*** and the angular distance **Δ** between the guide star and the point of interest in the scope FOV for which we are interested in the FR.

From his work we can derive (see Figure 1 below) an explicit FR value $\boldsymbol{\rho}$ (in micro-meters or microns $[\mu m]$) while we introduce the distance $\boldsymbol{d}$ (in millimeter $[mm]$) from the FOV point-of-interest to the guide star location instead of using the scope focal length F and angular distance **Δ**. This is true, since for small angles, $\boldsymbol{d} \cong \Delta F$ (Δ in radian).

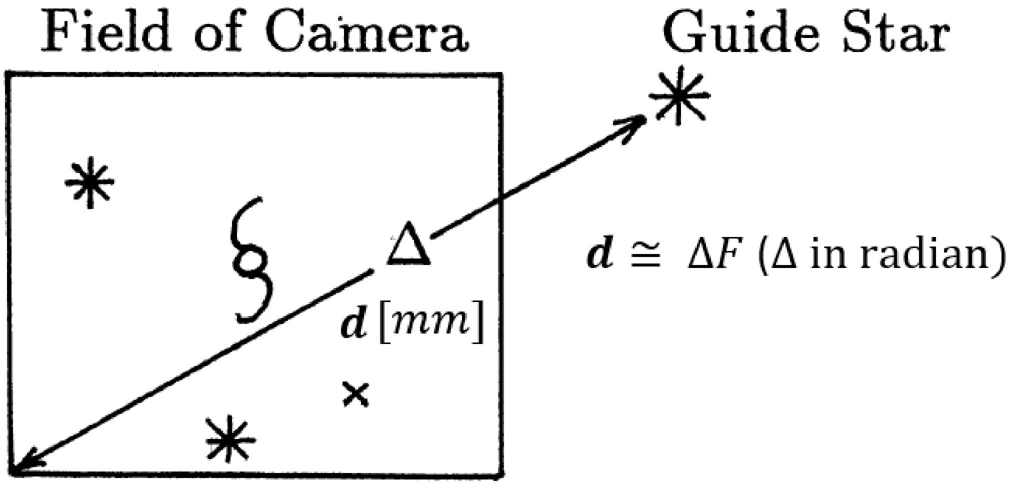

Figure 1: The imager FOV and position of the guide star with the introduction of the distance $\boldsymbol{d}$*.*
Elaborated from the original Figure 3 in Hook's paper.

This leads to the Equation <1>, below, expressing the relationship between a given FR $\boldsymbol{\rho}$ centered at the guide star, the distance $\boldsymbol{d}$ from the guide star, the target declination (DEC) $\boldsymbol{\delta}$ (in degrees [°]), and the total polar alignment error $\boldsymbol{\theta}$ (in arc-minutes [′]), as well as the total exposure time $\boldsymbol{t}$ (in minutes $[min]$):

<1>
$$\boldsymbol{\rho} \cong \frac{\mathbf{13}\times\mathbf{10}^{-\mathbf{4}}\times\boldsymbol{d}\times\boldsymbol{\theta}\times\boldsymbol{t}}{\boldsymbol{cos}(\boldsymbol{\delta})}$$

For instance, consider the following FR calculation for a star at the edge of an APS-C chip of 28mm in diagonal. Assume the following for this calculation:

1. the guide star is off axis at a distance of 24mm from the center of the FOV of interest;
2. it is positioned such that it is on a straight line through the center of the FOV to the star on the chip's edge;
3. there is one arc-minute of polar alignment error;
4. imaging is over a 1 hour time period;
5. the target's declination is $50°$.

$$\boldsymbol{d = 28/2 + 24 = 38mm}$$

$$\boldsymbol{\rho \cong 13 \times 10^{-4} \left(\frac{38 \times 1 \times 60}{cos(50)}\right) \cong 4.7\ um}$$

Note, this is somewhat of a worst case scenario since the guide star is as far as possible from the chip's corner.

Since the FR is proportional to the mount polar alignment error, a 10' error leads now to a field rotation value of $47\ \mu m$. Assuming a pixel size of 6 μm this means about 8 pixels of drift per hour at the edge of the sensor. This is likely to impact differential photometry accuracy.

Although polar alignment error could be minimized, atmospheric refraction typically limits the minimum error value of what one could practically achieve to a few arc-minutes.

As an alternative to traditional off-axis guiding, if the guide star is placed at, or near, the optical axis, the related FR becomes much smaller. For example, by taking the above example and assuming a guide star is now at the center of the APS-C chip, we have the following value for FR at the corner of the sensor after one hour:

$$\boldsymbol{d = 24/2 = 12mm}$$

$$\boldsymbol{\rho \cong 13 \times 10^{-4} \left(\frac{12 \times 1 \times 60}{cos(50)}\right) \cong 1.4\ um}$$

This leads to a decrease of the FR by a factor about 3 times under the same conditions.
Thus, the use of an on-axis guider (ONAG) provides an option to significantly reduce FR.

Figure 2 below shows, for one arc-second polar alignment error, the FR (at the corner of the chip) in μm, for an APS-C chip (28mm in diagonal), with a guide star at the center of the chip using an ONAG, as a function of the observing time (in hours) and for various target declination values (DEC in degrees). Negative DEC values are not shown in this Figure 2 since they lead to identical FR values - the sign of the angle is irrelevant for the COS function here.

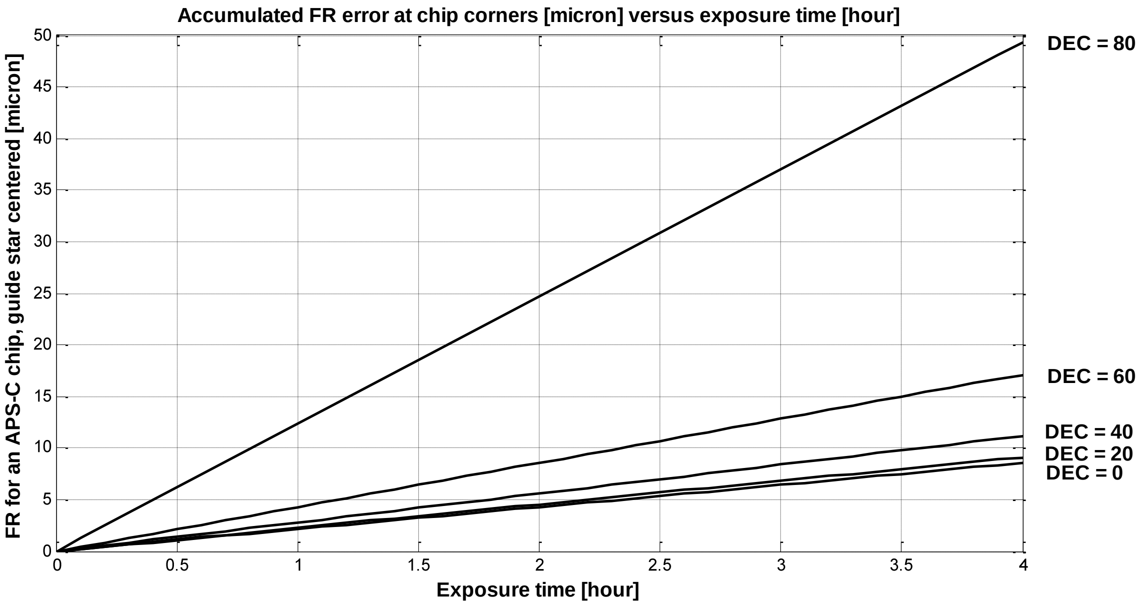

Figure 2: Accumulated FR errors, for 1’ polar alignment error, at chip corners [in microns] versus observing time [hours]

From Figure 2, we can clearly see the significant impact of the target’s declination (DEC) and how it leads to a dramatic increase of FR values when close to any of the celestial poles. This is a direct consequence of the COS function in the denominator of Equation <1>.

Acknowledgement:

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Reference:

1 - Hook 1989. Hook, R.N., “***Polar axis alignment requirements of astronomical photography***”, Journal of the British Astronomical Association, vol. 99, no. 1, p. 19-22, February. 1989.