

Rotated Guiding of Astronomical Telescopes

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Abstract: Most astronomical telescopes use some form of *guiding* to provide precise tracking of “fixed” objects. Recently, with the advent of so-called internal guide sensors and imager rotators, the measurement of guide errors for the guiding servo loop has become difficult to understand. This has become even more complex with the introduction of adaptive optic units whose drive errors are applied as bumps in the RA and Dec axes and not polar guiding corrections. This paper presents techniques by which a software program can control the MaxIm DL guide system during German Mount meridian flipping and imager rotation such that it is not necessary to recalibrate the guider. The paper focuses on correction vector rotations and the MaxIm DL controls which affect its response to same when sending corrections to the mount. Details of guiding servo operation and tuning are *not* covered.

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1 Introduction

Virtually all guiders are star-trackers mounted to the main optical assembly. A “guide star” is placed on a guide sensor for measurement input. The guiding servo attempts to keep that star at exactly the same guide sensor location by adjusting the telescope mount’s direction as it follows the apparent motion of the star. The goal is to minimize tracking errors and produce a still image on the main imaging sensor.

Tracking errors are measured by displacements of the guide star from its intended position on the guide sensor. Displacements are measured by finding the *centroid* of the guide star in sensor XY coordinates and comparing it to the intended XY position. The resulting XY deviations form an *error vector* which is then used by the guiding servo to generate “small” movements in mount position to effectively drive the guide star back toward its intended position on the guide sensor. Tracking velocity errors could also be corrected by the guiding loop (a second-order tracking loop) but this is not done in typical low-cost amateur class guiding systems.

The guide star XY deviations (error vector) must be transformed from guide sensor XY coordinates into appropriately scaled position corrections (a *correction vector*) in the mount’s coordinate system, typically equatorial Right Ascension and Declination. The magnitude of the correction vector determines the guiding servo loop gain, and thus its dynamics in responding to mount tracking errors. Sampling and correction rates also affect servo loop dynamics. The typical guiding servo is highly non-linear due to non-linearities in mount response to corrections, non-linear sources of mount errors (e.g., PE and stiction), discrete-time sampling and correction, and quantization of XY guiding error measurements.

This paper focuses on the transformation of the error vector from guide sensor XY coordinates into mount

coordinate errors. Specifically, it deals only with the *direction* or *angle* of the error and correction vectors and not the magnitude. Thus, this paper does *not* deal with guiding servo dynamics. Instead, it deals with the effects of optics, instrument rotators, and German Equatorial Mount (GEM) flipping on the directions of the XY error signals, and how to manage these effects via the MaxIm DL controls provided for same.

2 Guide System Configurations

The three most common configurations used for guiding are:

2.1 External Guide Scope

The guide sensor is mounted on a separate “guide scope” that is permanently fixed to the main imaging optics. The guide sensor has a relatively large field of view, resulting in a guide star being available most of the time regardless of the direction in which the telescope is pointed. This is the easiest type of guiding system to use, and it allows the most freedom in “composition” of the target within the main imaging frame. The disadvantage of this configuration is that it can be difficult to control differential flexure between the main and guiding optical paths, resulting in imprecise measurement of guiding errors.

2.2 Internal Guider

This configuration is patented by Santa Barbara Instrument Group (SBIG). The guide sensor is mounted adjacent to the main imaging sensor within the imager body¹. This

¹ Actually, the guide sensor is mounted at a 90 degree angle to the main imager. A small mirror is used to deflect guiding light from the main light path to the guide sensor.

configuration eliminates the issue of differential flexure that affects external guide scopes. However, the guiding field of view is relatively small. Furthermore, the guiding sensor is mounted behind any filter that may be in use, so the filter reduces intensity of the guide star, particularly when doing narrowband imaging. These issues lead to difficulty in finding a suitable guide star. Even if a suitable guide star is available, a tradeoff must be made between desired position of the imaging target on the main sensor and the position of the guide star on the guiding sensor. But most of the time, a suitable guide star is not available at all.

2.3 Off-Axis Guider

The guide sensor is attached to the main imager body and receives its optical input from a “pick-off” mirror adjacent to the main imaging sensor. This configuration also has the advantage of eliminating the differential flexure problem. It also has an advantage over the internal guider since the pick-off mirror is usually positioned in front of the filter, eliminating the reduction in guide star intensity caused by the filter. Apart from that, however, it suffers from the other disadvantages of the internal guider as described in section 2.2.

3 Instrument Rotators

The usefulness of internal and off-axis guiders can be significantly improved by adding an instrument rotator. This allows the imaging package to be rotated about the main optical axis. By doing so, the chances of finding a suitable guide star are greatly improved because the guide star can be located anywhere in the annulus formed by rotation of the (offset) guide sensor about the main sensor.

An instrument rotator does not, however, solve the problem of needing to offset the imaging target from the desired position on the main imaging sensor in order to get the guide star positioned on the guiding sensor. Furthermore, selecting a guide star via rotation eliminates the freedom to choose the orientation of the imaging target on the main imaging sensor. Finally, imager rotation introduces additional complexity in planning an observing run, requiring the astronomer to manually “compose” the image in both position and rotation.

4 Adaptive Optics (AO) Devices

Santa Barbara Instrument Group (SBIG) has developed a special type of guider that has two nested servos. A tip-tilt mirror (or prism) deflects the incoming light on its way to both the main and (internal) guide imager chip.

The inner servo makes rapid measurements of the guide error and feeds corrections to the tip-tilt mirror. The objective is to remove the effects of “seeing”, the random variations in image positioning caused by air turbulence and differential refraction. As long as the tip-tilt mirror remains within its operating range, no other corrections are needed.

The outer loop is similar to a conventional guider in that it makes gross corrections by moving the mount in RA and Dec. If the tip-tilt mirror reaches one of its limits, the outer loop sends a “bump” to the mount, moving it such that the tip-tilt mirror can again operate within its range. Typically this happens when the mount’s mechanical tracking is not precise enough (e.g. periodic error, secular drift due to polar misalignment or drive speed errors). Since bumping is a gross correction, the bump system is usually rather crude. The tip-tilt mirror servo is responsible for the precise positioning of the image on the main sensor.

5 Issues Affecting Error Vector Direction

There are three issues that affect the direction (angle) of the error vector:

5.1 Reflections (mirrors) in the optical path

Each reflection in the optical path causes the *angle* of the error vector to be reversed.

5.2 Instrument rotators with internal/off-axis guiders

The angle of the error vector changes when the imager and its internal (or off-axis) guide sensor are rotated with respect to the telescope (equatorial) axes.

5.3 GEM flipping

German Equatorial mounts (GEMs) must “flip” at or near the celestial meridian. The orientation of the imager/guider package rotates 180 degrees (with respect to the sky) when the GEM flips. This causes a 180 degree rotation of the error vector from the guider. However, if a rotator is present, it is used to unrotate the imager package 180 degrees back to the original angle, in order to keep the same guide star on the guide sensor.

6 MaxIm DL Guider Calibration

MaxIm DL provides controls for *calibrating* the guide servo. After putting a guide star on the guide sensor, the user commands a calibration. The software moves the mount back and forth about each of its axes, effectively moving the guide star across the guide sensor, and measures the positions of the guide star at each step.

From this data, MaxIm calculates three values that it uses to transform the error vector into the correction vector:

- X Scale
- Y Scale
- Guide Angle

The guide angle is included so that the imager package can be mounted at varying rotation angles on the telescope, allowing the corrective inputs to the mount to be at the proper angle with respect to the equatorial coordinate system of the mount.

This takes into account of all of the previously mentioned sources of guide angle variation, resulting in a ready-to use system. For many types of mounts (e.g. fork mount), once the guider has been calibrated, there is no need for re-calibration unless the guide imager and/or scope are changed mechanically or optically. However, for a GEM, flipping alters the relationship between the error and correction vectors. And it should be clear that rotating the guider after calibration also changes this relationship. Both of these require either guider recalibration or corrective inputs to MaxIm.

7 MaxIm DL Guiding Controls

This paper presents techniques for avoiding guider recalibration, thus it covers the needed corrective inputs to MaxIm. Inputs can be applied via MaxIm's user interface or via its scripting interface. The controls provided are:

- X Scale
- Y Scale
- Guide Angle
- Pier Flip

The first three are just the values initially determined by calibration. The Pier Flip switch is just a convenience. The same effect can be achieved by changing the sign on the X scale, or by appropriately rotating the guide angle. Now let's look at the specifics.

8 GEM Meridian Flip

For convenience, let's assume that the guider has been calibrated with the telescope *looking* east (mount on the west side of the pier), the imager/guider aligned pole-up (zero position angle), and the Pier Flip switch off. When the telescope moves to the west side of the meridian and flips, two things happen:

- The sense of declination reverses. This can be corrected by negating the Y scale (Y is aligned with declination).
- The imager rolls upside down. This can be corrected by negating both the X and Y scales.

Taking both of these together, you can see that each reverses the Y sense, resulting in *no net change to sign of the Y scale.* All that's left is to negate the X scale or *toggle* Pier Flip. Older versions of MaxIm labeled this switch as Reverse X, and it is still called GuiderReverseX in the scripting interface. Now you know why. And now you know why negating the X scale is all that's needed to compensate for a GEM pier flip. No recalibration of the guider is needed.

This holds true even if the guider is calibrated at some angle with respect to equatorial and with any setting of Pier Flip. Each time the mount flips, you just need to *toggle* the Pier Flip switch. In order to keep your sanity, though, it's easier to adopt the convention of calibrating while looking

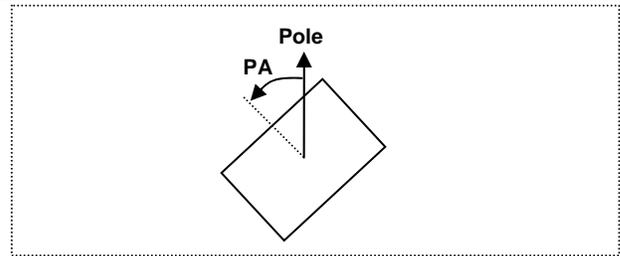
east with Pier Flip off. Then all you have to remember is that, when looking west, Pier Flip should be on.

9 Rotated Guiding

As described earlier, internal and off-axis guide sensors are severely limited without an instrument rotator. Thus, it is common to find these two on the imaging package. How can the guiding servo be adjusted to compensate for rotation without recalibrating?

First, it should be intuitively obvious that knowledge of the rotation angle with respect to the equatorial axes must be known independently of guider calibration. How this is achieved is beyond the scope of this paper; it is assumed that the exact rotation angle is known.

The most common representation of image rotation is Equatorial Position Angle (PA). This is the angle from pole-up, measured counter-clockwise.



Coincidentally (and conveniently) this is also the sense of the guiding angle in MaxIm (neglecting the effects of the things covered in section 5).

9.1 Guide Light Path Reflection

Again, rotators are almost always used with internal or off-axis guiders. Both of these add a reflection to the optical path to the guider. Most telescopes have zero or an even number of reflections (e.g. 2), so the total number of reflections in the optical path *to the guider* is odd.

This extra reflection causes the sense of rotation to be reversed, thus the guiding angle input to MaxIm is simply the negative of the rotator PA. To avoid the need to recalibrate the guider, adjust the guide angle to be equal to the negative of the new rotator PA whenever the rotation angle is changed.

9.2 GEM Meridian Flip with Rotator

The GEM flip situation differs from that described in section 8 because, after a flip, the imager is rotated 180° back to its original PA in order to keep the same guide star on the guide sensor. Thus the only difference after a flip is the reversal of the declination axis sense. This can be corrected by negating the sign on the Y scale after a flip. The scripting interface has a convenient property GuiderReverseY that effectively does the same thing.

10 Summary (Conventional Guiding)

The following procedures assume a main optical system with an even number (zero is even) of reflections, e.g., refractor, Schmidt-Cassegrain, Ritchie-Chretien, etc. They also assume that internal and off-axis guiding configurations add a single reflection in the path to the guide sensor. Finally, it is assumed that a GEM flip with a rotator includes unrotation of the imager package to keep the PA constant across the flip. These are the most common configurations.

10.1 Simple Equatorial Mount, All Guider Types, No Rotator

Calibrate the guider² and forget it.

10.2 German Equatorial Mount, All Guider Types, No Rotator

1. Calibrate the guider once with the scope pointing east of the meridian and PierFlip/GuiderReverseX *off*.
2. When the scope is looking west, turn PierFlip/GuiderReverseX *on*.

10.3 Simple Equatorial Mount, Internal or Off-Axis Guider, With Rotator

1. Calibrate the guider once *at any rotation angle* with the scope pointing east of the meridian and PierFlip/GuiderReverseX *off*.
2. When the rotation angle is changed, set the guide angle equal to the negative of the PA.

10.4 German Equatorial Mount, Internal or Off-Axis Guider, With Rotator

1. Calibrate the guider once *at any rotation angle* with the scope pointing east of the meridian and PierFlip/GuiderReverseX *off*.
2. Note the sign of the Y scale.
3. When the rotation angle is changed, set the guide angle equal to the negative of the PA.
4. When the scope is looking west, set the Y scale to the negative of the value noted in (2) above. Alternatively, if you are using the scripting interface, just turn the GuiderReverseY switch on when the scope is looking west.

² Be sure to enter the declination at which the guider is being calibrated *before* calibrating (not related to the issues discussed here, but a very common user failure).

11 Adaptive Optics (AO) Guiders³

MaxIm DL's AO *drive* control system has no concepts of guiding angle. Instead a simple set of three switches, Reverse X, Reverse Y, and Swap Axes, are used to adjust the bumping directions for varying imager PA. These switches are separate in MaxIm's user interface (in the Drive tab of the AO control window). In MaxIm's scripting interface, the GuiderReverseX, GuiderReverseY, and AOSwapMotorAxes properties provide these controls.

11.1 Without a Rotator

For a simple equatorial mount and no rotator, one drive calibration is all that's needed for all-sky operation. With a GEM and no rotator, the rules are the same as described in section 10.2, except that in the UI you use the AO Reverse X switch instead of the Pier Flip switch. The GuiderReverseX switch is still used for scripting.

11.2 With a Rotator

When using an AO with a rotator, it is necessary to effectively duplicate the three polarity switch settings that would result from doing an AO *drive* calibration at the current rotation/PA, and if the mount is a GEM, at the current side of the meridian.

11.2.1 Background

AO drive calibration is similar to that for conventional guider calibration. Assuming a guide star is on the guide sensor, the software moves the mount slightly in each axis and notes the XY displacements on the guide sensor. From this data, the software calculates the three switch settings *only*. No scaling of magnitude or angle is calculated, bumps are constant in each mount axis. Clearly, this has limitations, but then bumping does not need to be precise; it only needs to move the scope enough to bring the tip-tilt mirror back into its active range.

Recall that a bump is generated in response to the tip-tilt mirror reaching an edge of its range. The bump must move the mount enough in the right direction to bring the tip-tilt mirror into its active range. Ideally the bump will be just enough to bring the mirror back to the center of its range.

Consider the case where the imager/guider PA is 0, such that X and Y correspond to RA and Dec, respectively. For example, let's say that the mount polar alignment is off a bit such that there is a secular drift in declination error. As time goes on, the tip-tilt mirror will drift towards one of its Y limits, finally reaching it. At this point a bump will be sent to the mount's declination axis to make up for the error that the mirror is correcting for.

Bumping directly moves the mount about its equatorial axes. Therefore, the only times when a bump will correct the mirror in only one axis (X or Y) is when the imager package is at one of the cardinal rotation angles (0, 90, 180,

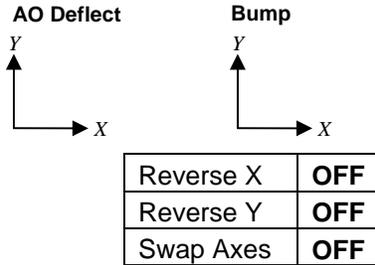
³ You may want to review the description of AO devices in section 4.

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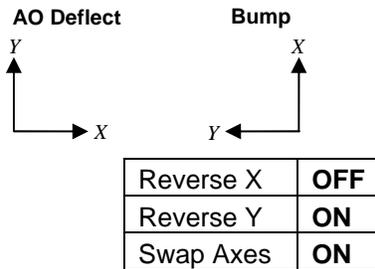
270). At any other imager PA, the bump will affect the centering of the mirror about *both* of its axes.

We will now analyze each of these cardinal angle cases ignoring GEM flipping. Maxim's AO drive control switches assume (reasonably) that the guide light path has an odd number of reflections.

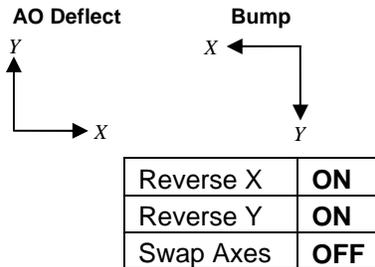
11.2.2 PA = 0 (Simple or GEM on East)



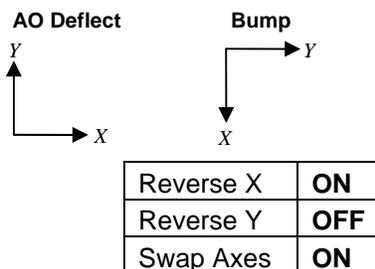
11.2.3 PA = 90 (Simple or GEM on East)



11.2.4 PA = 180 (Simple or GEM on East)



11.2.5 PA = 270 (Simple or GEM on East)



11.2.6 Intermediate Angles

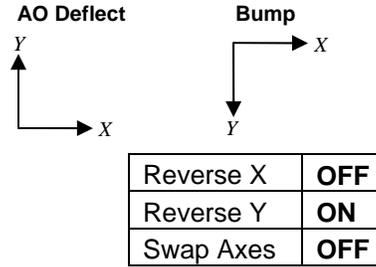
For simplicity, MaxIm bumps with the settings for the nearest cardinal angle as described above. For example, any PA between 315 and 45 degrees, the settings for 0 degrees are used.

Thus, at non-cardinal PAs, a bump will affect the centering on both the tip and tilt mirror axes. The worst case is at PAs of 45, 135, 225, and 315 degrees, where a bump on one axis will cause equal centering changes about both mirror axes.

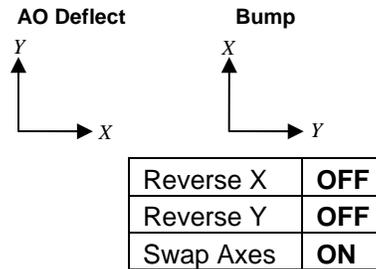
11.2.7 GEM on West side of pier

With a rotator, the PA is the same, but the declination axis reverses its sense compared to a simple/fork mount or a GEM on the East side of the pier..

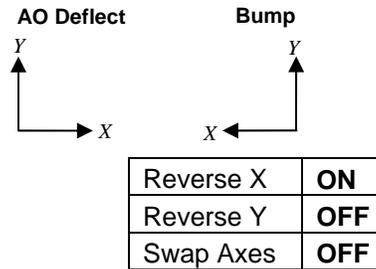
11.2.8 PA = 0 (GEM on West)



11.2.9 PA = 90 (GEM on West)



11.2.10 PA = 180 (GEM on West)



11.2.11 PA = 270 (GEM on West)

