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 body. This 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.

2.2.1 Image Orientation

The internal guide sensor is mounted at right angles to the main sensor to save space. A 45 degree mirror deflects incoming light to the sensor. Normally this would result in the guide sensor image being flipped (upside down); however the system electronically flips the image to compensate. Therefore, the image on the guide sensor is in the same orientation as that of the main sensor, as though it were mounted co-planar with the main sensor. Star motion on the guide sensor follows star motion on the main sensor in both axes.

2.3 Off-Axis Guider

A mechanically separate guide sensor is attached to the main imager body and receives its optical input from a 45 degree "pick-off" mirror adjacent to the main imaging sensor. This configuration also has the advantage of eliminating the differential flexure problem. It has an additional advantage over the internal guider since the pick-off mirror is 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.

2.3.1 Image Orientation

Since the guide light is reflected by the pickoff mirror, the guide sensor image is flipped (upside down) with respect to the main sensor. Unlike the internal guide sensor, the circuitry normally does not flip the image back over as it does for the internal guider (see 2.2.1). This requires adjustment of guiding/bumping polarities as described in subsequent sections.

Since the off-axis configuration uses a mechanically separate guide sensor ("guide head"), there is the possibility of mounting this assembly at any rotation angle. In order to avoid needlessly complicating guiding calculations, <u>the guide sensor must be mounted such that its image is flipped (upside down) with respect to the main imager</u>. To test this, assure that star motion resulting from small changes in the X direction of both imagers result in parallel motion in the same direction on both sensors.

3 Instrument Rotators

The usefulness of internal and off-axis guiders can be greatly 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 Guider Image Orientation

The guide sensor image may vary in orientation with respect to the main sensor. See sections 2.2.1 and 2.3.1.

5.4 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. See section 8.

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

Virtually all German equatorial mounts have their motion the same as a simple/fork mount when they are on the *east* side of the pier, looking west. For convenience, let's assume that the guider has been calibrated with the telescope *looking* west (mount on the east side of the pier)[1], the imager/guider aligned pole-up (zero position angle), and the Pier Flip switch off. When the telescope moves to the opposite 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 west with Pier Flip off[1]. Then all you have to remember is that, when looking east, Pier Flip should be on.

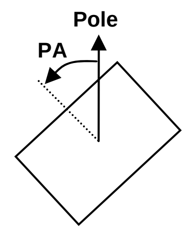
9 Rotated Guiding

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.

[1] Unfortunately, the opposite convention was adopted in the early days of ACP. Changing it now would cause confusion. ACP requires calibration with the telescope looking *east* (mount on west side) with PierFlip *off*.

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 GEM Meridian Flip with Rotator

The GEM flip situation differs from that described in section 8 because, after a flip, the imager is rotated 180º 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. Also assumed is an external guidescope or an internal guider, neither of which add reflections (as would an off-axis guider, see section 2.3.1). 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 guider[2] and forget it.

10.2 German Equatorial Mount, All Guider Types, No Rotator

1. Calibrate the guider[2] once with the scope pointing west of the meridian (mount on east side of the pier) and PierFlip/GuiderReverseX *off*.
2. When the scope is looking east (mount on west), turn PierFlip/GuiderReverseX *on*.

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

1. Calibrate the guider[2] once *at any rotation angle* with the scope pointing *west* of the meridian (mount on the east side of the pier) and PierFlip/GuiderReverseX *off*.
2. When the rotation angle is changed, set the guide angle equal to PA for an internal guider and to the negative of the PA for an off-axis guider.

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

1. Calibrate the guider[2] once *at any rotation angle* with the scope pointing west of the meridian (mount on the east side of the pier) 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 PA for an internal guider and equal to the negative of the PA for an off-axis guider.
4. When the scope is pointing east of the meridian (mount on the west side of the pier), 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 east.

11 Adaptive Optics (AO) Guiders[3]

MaxIm DL's AO *drive* control system has no concepts of guiding angle and no scaling on mount inputs. Bumping is done with a (configurable) fixed-duration pulse to the appropriate mount axis and in the appropriate direction. 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 visible 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 *Drive* Reverse X switch instead of the Pier Flip switch. The GuiderReverseX switch is still used for scripting.

[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).

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

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[4]. 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.

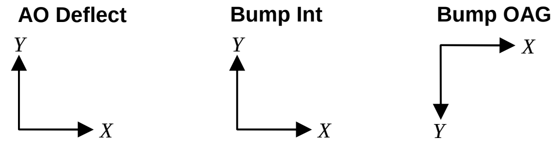
Recall that a bump is generated in response to the tip-tilt mirror reaching an edge of its range. The bump must move the mount enough in the right direction to being the tip-tilt mirror into its active range. Ideally the bump will be just enough to bring the mirror back to the center of its range.

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

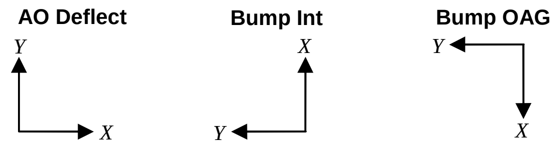
We will now analyze each of these cardinal angle cases for an internal guider (no guide image flip) and an off-axis guider, without, and then with, a GEM flip. Note that in the first four diagrams below, the internal guider bump axes are simply rotated counterclockwise (the correct sense for PA) by 90 degrees for each step. The off-axis guider bump axes are flipped about the horizontal with respect to those for the internal guider, reflecting the fact that the off-axis guider's image is flipped about its sensor's horizontal axis.

11.2.2 PA = 0 (Simple or GEM on East side of pier)



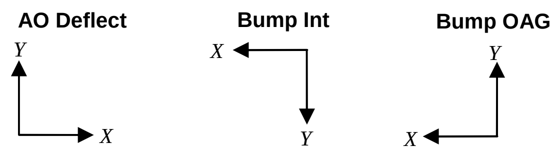
Reverse X	**OFF**	**OFF**
Reverse Y	**OFF**	**ON**
Swap Axes	**OFF**	**OFF**

11.2.3 PA = 90 (Simple or GEM on East side of pier)



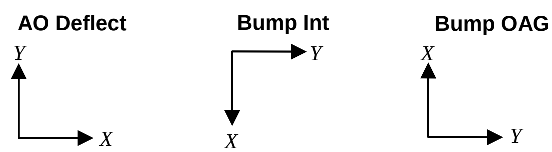
Reverse X	**OFF**	**ON**
Reverse Y	**ON**	**ON**
Swap Axes	**ON**	**ON**

11.2.4 PA = 180 (Simple or GEM on East side of pier)



Reverse X	**ON**	**ON**
Reverse Y	**ON**	**OFF**
Swap Axes	**OFF**	**OFF**

11.2.5 PA = 270 (Simple or GEM on East side of pier)



Reverse X	**ON**	**OFF**
Reverse Y	**OFF**	**OFF**
Swap Axes	**ON**	**ON**

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.

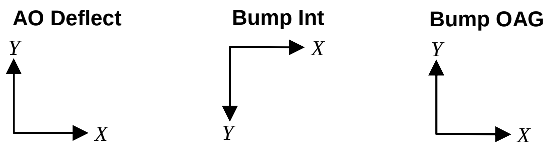
Thus, at non-cardinal PAs, a bump will affect the centering on both the tip and tilt mirror axes. The worst case is at PAs of 45, 135, 225, and 315 degrees, where a bump on one axis will cause equal centering changes about both mirror axes.

[4] The magnitude of *all* bumps is controllable by configuring the time duration of the bump signal to the mount.

11.2.7 GEM on West side of pier

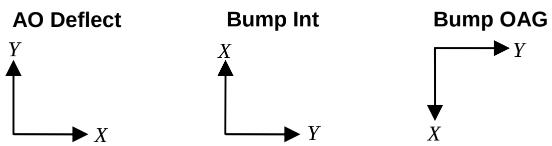
With a rotator, the PA is the same, but the declination axis reverses its sense compared to a simple/fork mount or a GEM on the East side of the pier. Note that the polarity switch settings are the same as those in the preceding four diagrams except that the Reverse Y switch is opposite that of the corresponding case above.

11.2.8 PA = 0 (GEM on West side of pier)



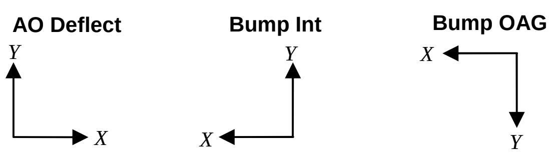
Reverse X	**OFF**	**OFF**
Reverse Y	**ON**	**OFF**
Swap Axes	**OFF**	**OFF**

11.2.9 PA = 90 (GEM on West side of pier)



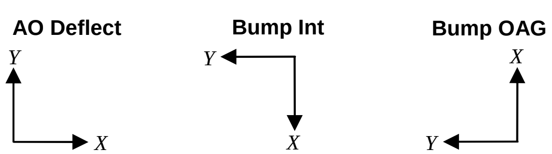
Reverse X	**OFF**	**ON**
Reverse Y	**OFF**	**OFF**
Swap Axes	**ON**	**ON**

11.2.10 PA = 180 (GEM on West side of pier)



Reverse X	**ON**	**ON**
Reverse Y	**OFF**	**ON**
Swap Axes	**OFF**	**OFF**

11.2.11 PA = 270 (GEM on West side of pier)



Reverse X	**ON**	**OFF**
Reverse Y	**ON**	**ON**
Swap Axes	**ON**	**ON**

Appendix A Demonstration Script

The following script (in Javascript) implements the switch settings for a rotated AO guider as described in section 11.2.

```
//
// Generate bump switch vector for the given position angle (PA)
// Vector of booleans for ReverseX, ReverseY, and SwapAxes (in that order)
//
function Rotate(PA)
{
    var r0 = [false,false,false];                               // Polarity switch vectors
    var r90 = [false,true,true];
    var r180 = [true,true,false];
    var r270 = [true,false,true];
    var svv = [r0, r90, r180, r270];                            // Vector of switch vectors

    var paq = Math.round(PA / 90.0);                            // PA in quadrants
    return(svv[paq]);                                           // Return switch vector for given PA

}

//
// Flip the bump vectors about the "horizontal" axis (after rotation)
//
function Flip(sv)
{
    if(!sv[2])
        sv[1] = !sv[1];
    else
        sv[0] = !sv[0];
    return sv;
}

//
// Reverse sense of Y for GEM *and* looking east
//
function RevY(sv)
{
    sv[1] = !sv[1];
    return sv;
}

WScript.Echo("PA W/E [Internal] [OAG] (W/E refers to pier side not look)");
WScript.Echo("----------------------------------------------------------");
for(a=0; a < 360; a += 90)
{
    WScript.Echo(a + " S/GE: [" + Rotate(a) + "] " + " [" + Flip(Rotate(a)) + "]");
    WScript.Echo(a + "   GW: [" + RevY(Rotate(a)) + "] " + " [" + RevY(Flip(Rotate(a))) + "]");
}
```

This script produces the following results on the console (aligned here for clarity). The polarity switch settings match those given in section 11.2.

```
PA W/E [Internal] [OAG] (W/E refers to pier side not look)
----------------------------------------------------------
0 S/GE:   [false,false,false]  [false,true,false]
0   GW:   [false,true,false]   [false,false,false]
90 S/GE:  [false,true,true]    [true,true,true]
90   GW:  [false,false,true]   [true,false,true]
180 S/GE: [true,true,false]    [true,false,false]
180   GW: [true,false,false]   [true,true,false]
270 S/GE: [true,false,true]    [false,false,true]
270   GW: [true,true,true]     [false,true,true]
```