Autoguiding

James (Jim) R. McMillan
valueware@msn.com
Original: 6/21/2004
Updated: 2/10/2005, 11/17/2005

Autoguiding is often thought to be a black art that relies on luck and a bit of magic to get right. This is exactly where I started with my autoguiding experience. However, I was not willing to accept that answer, so I began a personal quest to understand exactly what was happening, and why. I started by making guiding logs of every imaging session. I plotted and analyzed literally hundreds of hours of guiding logs. As I gained a better understanding of what was happening, and perhaps most importantly, why it was happening, I was able to modify my setup as well as change my guiding parameters to achieve consistently better guiding results. I do not claim to be an expert – only someone who has spent considerable time on the subject.

This note is being written to document what I have learned and try to demystify the process of achieving consistently successful autoguiding results in the hopes that it might be helpful to others as they hone their autoguiding skills. Many have contributed to my growth in understanding and enjoyment of this hobby. This is an opportunity for me to give a bit back.

The format of this note builds sequentially from beginning to end. I provide a brief background and then develop a series of thoughts, getting deeper and deeper into some theory. Based on these thoughts and theories, I establish some "important findings" and "guiding principles." Then, I take these findings and principles and provide specific guiding recommendations. This note does not attempt to solve any mount mechanical issues other than to emphasize the importance of correcting them.

Background - Overview:

<u>What is it?</u> Simply stated, autoguiding tries to "fix" the position of the guide star such that the mount tracks the sky perfectly. The result is an image with tight round stars.

<u>What does that mean?</u> As the earth turns, the stars continuously move across the sky. The mount's RA axis is designed to rotate at this rate. When the RA axis is aligned exactly parallel with the earth's axis, the DEC axis will not require any movement to stay aligned on the guide star (refraction excepted).

To the extent that the mount is not perfectly aligned with the earth's axis and/or the mount is not mechanically perfect (both of which are always true), the need to make guiding corrections is inevitable.

<u>How does it work?</u> The essence of the guiding process works like this:

1) Take an image with the guide camera.

2) Determine the position of the guide star – e.g. the guide star’s centroid.
3) Take another guide image.
4) Determine the centroid of the guide star.
5) Move the mount as required to align the second guide star centroid with the first.
6) Repeat – always realigning to the first guide star centroid.

If it is as easy as that, why does it seem so difficult to get good guiding? My view is that there are specific fundamental flaws with this process that cause guiding to be so challenging. **This is the first important finding:**

1) **The mount may not physically react precisely the way it is commanded.**
2) **The entire process is reactive – the calculated guiding command is reacting to something that occurred in the past and will be applied sometime in the future. By the time the mount actually finishes its corrective move, the required guide correction is not likely to be the right amount any more.**
3) **The change in the guide star’s centroid may or may not represent the actual amount of guide correction that needs to be applied to the mount.**

Background – Getting Into the Theory:

Let’s explore each of these important findings and reach three overall guiding principles.

After some sort of process is applied to determine what correction is to be sent to the mount (much more on this later), the mount may not physically move as it is commanded. The most obvious example of this is DEC backlash. Virtually all geared mounts exhibit some amount of backlash when the load on the gears is reversed. The implication is that the mount may not immediately respond to a guide correction. Generally, this is not too much of a problem because the next guide cycle should detect the need to apply the same correction again. Eventually, the mount will respond. As long as this process does not take too long, the final image does not smear. However, sometimes the mount motor applies the correction to the gears (either RA or DEC), but the axis does not respond – e.g. there is something restricting the axis from moving (e.g. friction, momentum, stiction, dangling cords, etc.). In this case, the energy is being stored somewhere in the mount’s gear train and will eventually get released. When the axis finally does move, it will over-correct. This leads to oscillations.

The second issue is that the entire process is reactive. Guide cycles will rarely be shorter than 1 second, and will most likely be 2 or more seconds long. By the time the mount has completed responding to the corrections sent to it, it is highly unlikely that the result centers the guide star – e.g. it is no longer the right correction amount. This continuous delay between detected guide star centroid changes and the mount responding to those guide corrections is another source of guide errors.

Since the mount may not physically react precisely the way it is commanded and the fact that the entire process is reactive, it makes intuitive sense that the fewer the number of guiding corrections made, the better.

This is the first principle: strive to make the setup so that it needs the minimum number of guide corrections possible. This principle addresses the first and second fundamental flaws in the guiding process. I will discuss how to accomplish this later.

The third fundamental flaw, the fact that the change in the guide star's centroid may or may not represent the actual amount of guide correction that needs to be applied to the mount, is perhaps the most interesting issue to deal with. Consider what kinds of errors might be captured via comparing the centroids of two guide exposures:

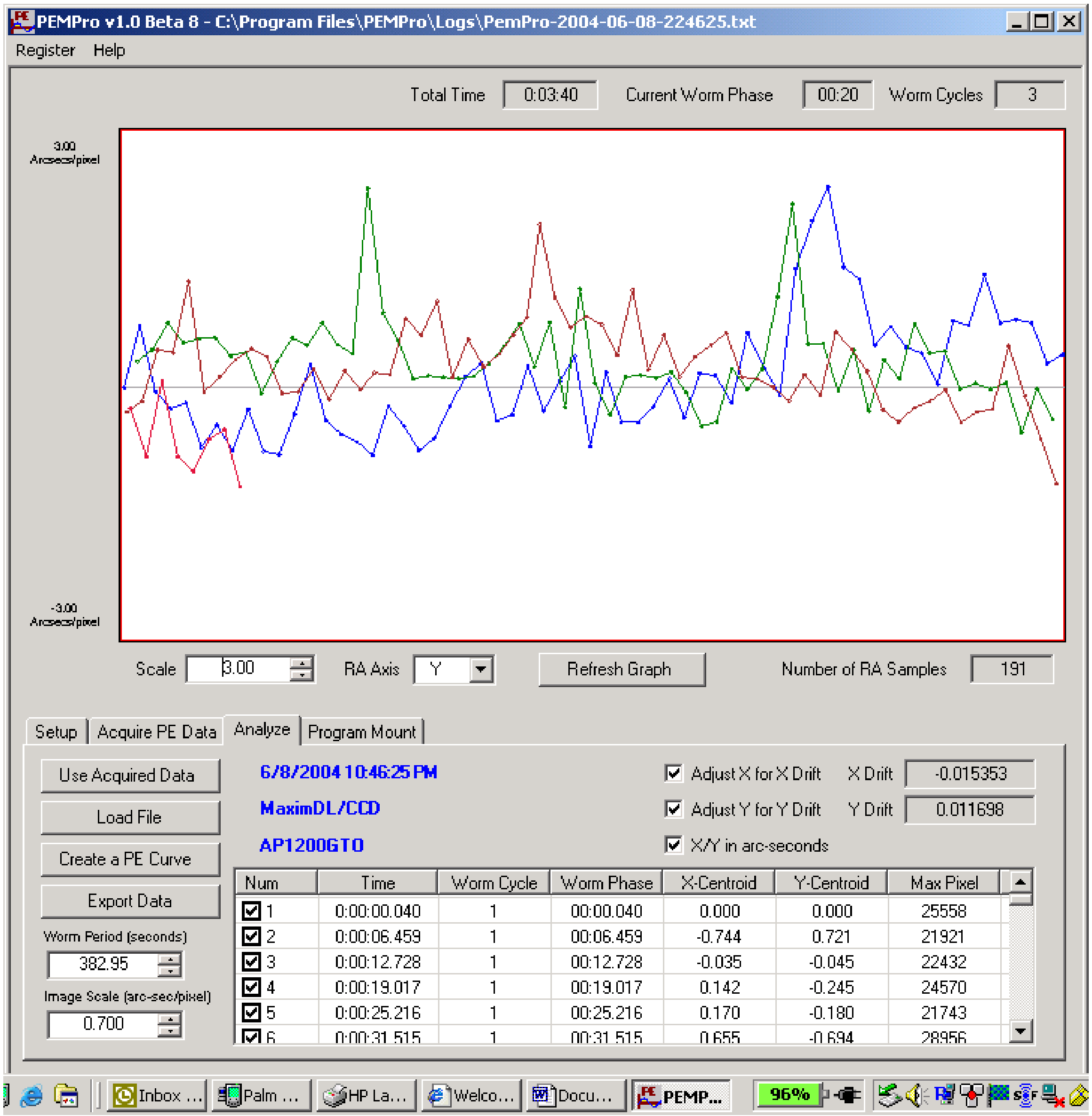
1) Any physical anomaly in the system – e.g. movement caused by dangling cords, mirror flop, camera/mount flexure, etc.
2) Drift (due to polar misalignment)
3) PE (Periodic Error)
4) Seeing-induced errors

I will ignore 1) for the moment as the first principle requires these issues to be minimized/eliminated before they become errors that need to be corrected by guiding.

<u>How big are these errors?</u> In any mount that is reasonably well polar aligned, the amount of drift will be small and in one direction only – on the order of 0.05 arcsec/second or less. For a 2-second guide cycle, DEC drift should be less than 0.1 arcsec, which is insignificant – perhaps even undetectable – for virtually all seeing conditions. However, at this rate over the course of a 5-minute exposure, DEC drift would amount to 15 arcsec, so guiding must correct for DEC drift.

A mount with a well-programmed PEC (Periodic Error Correction) might reduce PE to +/- 1 arcsec. Assuming this peak-to-trough might occur over 1 minute, it implies the maximum PE between guide exposures for a 2-second guide cycle is 0.067 arcsec, again insignificant. However, for any long exposure that extends over the mount's PE cycle, guiding must correct for it.

Seeing is quite variable and depends on many factors. It is probably safe to say that most of us image in less than ideal atmospheric conditions. Seeing will generally cause the star's position to oscillate around a point. Following is a graph that shows the shifting of the star's DEC position due to seeing at my location that normally achieves a FWHM of about 3 arcsec:



Each colored line represents one worm cycle of an AP1200GTO mount (6 minutes, 23 seconds). Each data point represents a 2-second guide cycle (1 second exposure, 1 second delay). The data has been corrected for any DEC drift (0.012 arcsec/second in this case). As the graph shows, seeing varied on this typical night as much as 2 arcsec between any two guide exposures – and it did it fairly often.

Summarizing the various types of errors the guider might detect for a 2-second guide cycle:

Drift	0.10 arcsec or less
PE	0.067 arcsec or less
Seeing	2.0 arcsec or less

The guiding implications of these numbers are most significant. **This is the second, and perhaps most significant important finding: the errors that need to be corrected (PE and drift) might be 20+ times smaller than the errors that should not be corrected (seeing) in any given guide cycle.**

If guiding corrections are made that follow the guide star's position as it oscillates with the seeing, the image will end up being smeared by the amplitude of the seeing oscillations, resulting in round, but bloated stars.

That is the second principle: do everything that can be done to not chase the seeing. I will discuss how best to do this later.

As a side comment, SBIG's AO7 unit addresses all three fundamental flaws of traditional guiding. Since the corrections are being applied to a small, low mass mirror instead of a high mass OTA/mount/camera setup, the corrections are most likely to be very accurate under almost all conditions. Further, if a sufficiently bright guide star is available, the AO7 can issue up to 30+ corrections per second. In other words, in addition to reacting very quickly, its corrections are fast enough such that it is ok to "chase the seeing." Indeed, that is what it is trying to do. This makes AO7 operations quite simple and relatively insensitive to its guide settings. However, if the guide star is not sufficiently bright such that guide cycles must be significantly slower, it is no longer acceptable to chase the seeing. My experience is that when guide cycles are about 0.25 seconds or longer, the AO7 guide parameters start reacting very similarly to conventional guiding. At this point, conventional guiding techniques are appropriate to employ with an AO7. Even when using long guide exposures (2+ seconds), it still has the advantage of consistently delivering highly accurate corrections (e.g. no chance of DEC backlash). The rest of this note also applies to AO7 use whenever approximately 0.25+ second guide exposures are used.

Background Theory - Getting Really Deep:

I think it is useful to put guiding into a perspective using terms familiar to most imagers – e.g. Signal-To-Noise Ratio (S/N). I will use the S/N concept in 3 different ways. The first is the traditional way – what I call "Guide Star S/N ratio." The guide star needs to be sufficiently bright so that the centroiding algorithm is accurate. Achieving a high Guide Star S/N ratio is a function of star brightness and exposure time. My experience is that MaxIm is able to guide on stars with exposure times that result in guiding images that are too noisy. The result is the detected centroid is not always accurate. When in doubt, increase the exposure time or choose a brighter guide star. (Note: Guide Star S/N ratio is a specific setup parameter used by ACP to determine the length of the guide exposure as part of automated operations. This functionality was added, in part, because of this analysis and has made ACP's guiding process extremely reliable.)

The second use of S/N is not a traditional definition at all. However, I believe it is an extremely useful way to understand guiding issues and is the basis for much of the rest of this note. I define "Guiding S/N ratio" this way:

Signal = detected centroid changes that need to be corrected (PE/drift)
Noise = detected centroid changes that should not be corrected (seeing)

This is the third important thought: given the numbers developed above regarding the types and sizes of errors detected, the Guiding S/N ratio for an individual guide exposure is likely to be very poor. Worse yet, it is not known which guide exposures have high Guiding S/N and which ones have low Guiding S/N.

The next logical question is, <u>can this situation be improved – e.g. can the Guiding S/N ratio be improved?</u> As with any ratio, there are only a few choices: increase the numerator, decrease the denominator, or do both. Consider the Guiding Signal. It can be increased in 2 ways:

1) Increase the amount of error per guide cycle. Unfortunately, this is completely contrary to the first principle to minimize the number/amount of required guide corrections and is clearly not desirable.
2) Increase the amount of time per guide cycle. This will increase the size of detected errors that need to be corrected per guide cycle. However, there will be a law of diminishing returns with respect to overall guiding accuracy because if the time between corrections is too long, the image will smear.

Consider reducing the Guiding Noise. There are 2 logical ways to reduce it:

1) Improve the centroiding algorithms such that they can differentiate between seeing errors and other types of errors. In other words, filter out the affects of seeing from the guide star centroid calculations. Unfortunately, this idea is not currently employed in any of the guiding software. However, there is much evidence that this could be accomplished relatively simply by using multiple guide stars instead of just one. The effects of seeing are significantly different over a relatively small FOV. Therefore, the average of the centroids of a few guide stars would remove most of the effects of seeing. New guide cameras download speeds are now fast enough for this process to be practical. While the suggestion has been made to the appropriate people, it is not clear that this capability will be forthcoming. However, given its importance to the guiding process, I am hopeful this functionality will become available soon.
2) Increase the guide exposure. The idea is that a longer guide exposure will reduce the seeing variation per guide cycle. Again, there is a law of diminishing returns with this strategy. The amplitude of seeing variations is surprisingly large even when exposure time increases dramatically. To have a significant affect on Guiding S/N, guide exposures need to be on the order of 10+ seconds before seeing variations (e.g. guide noise) begins to average out below PE/drift (e.g. guide signal).

The fourth important thought: increasing the guide exposure will improve Guiding S/N, but there is a law of diminishing returns.

<u>What about other physical anomalies?</u> While it is critical to eliminate them, it is not very likely that they will be stopped completely. These physical anomalies could generate almost any size error, both large and small. Large errors could take many guide cycles to correct, almost certainly smearing the image. Another issue is that sometimes these errors need to be corrected and sometimes they do not. Consider something physically shifting in the imaging setup – e.g. mirror flop. Once it occurs, the error will remain until it has been corrected. Therefore, it needs to be corrected by guiding. However, in the case of wind buffeting, the error will only be there momentarily. So, that type of error should not be corrected.

This discussion leads to the third principle: err on the side of using longer guide exposures versus shorter ones. Guiding S/N for most setups is likely to be quite low for many, if not most of the guide exposures. Increasing the guide exposure length will improve it. The trade-off is the ability to correct for large, fast occurring guide errors caused by physical anomalies versus not making corrections as often and improving the Guiding S/N ratio.

There are a few interesting statements that can be drawn from this discussion and represent the fifth important thought:

1) **With very steady seeing, Guiding S/N ratio will be relatively high which allows a shorter guide exposure.**
2) **If the setup is susceptible to physical anomalies and/or PE and drift are excessive, it implies a relatively high Guiding S/N ratio and allows a shorter guide exposure. Indeed, short guide exposures may be needed to keep the error amount per guide cycle sufficiently small so that guiding corrections can keep up with the errors.** I would not suggest this is a good guiding strategy though. Said another way, do not go out and buy a bad mount just to improve the Guiding S/N ratio.
3) **If the mount is very good with low PE and excellent polar alignment, it implies a low Guiding S/N ratio and will probably benefit from using longer guiding exposures to improve the Guiding S/N ratio.**

Most setups probably represent a combination of these basic factors that affect Guiding S/N ratio. For instance, a great mount in excellent seeing conditions should successfully guide with either shorter or longer guide exposures. Either way, the Guiding S/N ratio is reasonably high. However, a poor mount used under poor sky conditions will likely struggle. Guiding S/N can be improved by lengthening the guide exposure, but the errors per guide cycle must be kept below an acceptable level. Even a great mount used under poor seeing conditions will guide poorly if not set up to minimize seeing-chasing.

In and of themselves, these conclusions are not particularly revolutionary. It is intuitively obvious that great mounts in great seeing conditions are easy to get to guide well. Conversely, poor mounts in poor seeing conditions are almost impossible to get to guide well. But, I think it is useful to understand why these obvious statements are true. By appreciating the issues that are limiting guiding success, each item can be addressed one at a time to improve overall guiding results.

Guiding Recommendations – Almost Ready to Apply the Theory:

It is worthwhile to review the guiding process again – steps 2 through 5:

2) Determine the position of the guide star – e.g. the guide star's centroid.
3) Take another guide image.
4) Determine the centroid of the guide star.
5) Move the mount as required to align the second guide star centroid with the first.

Now, put this process into Guiding S/N perspective. In an ideal world, the full correction should be sent to the mount for all cycles with high Guiding S/N and all of the cycles with low Guiding S/N should be ignored. However, Guiding S/N ratio in any given guide exposure is unknown – but likely to be poor. Said the more conventional way, it is most likely that seeing dominates what the guider detects in terms of centroid changes. Said in perhaps the most negative way (and the way I think of it), the quality of the data we are forced to use is extremely poor because its accuracy with respect to making desired guide corrections is unknown. Sending this raw correction amount to the mount with no manipulation will almost always result in oscillations, causing smeared and/or bloated stars.

The sixth important thought and perhaps the most important one to understand: there is no way to determine whether the detected corrections are based on high Guiding Signal or high Guiding Noise. Therefore, corrections will be indiscriminately detected for both. Until the software changes (e.g. multiple star guiding), there is no way around it. Fortunately, between steps 4) and 5), the opportunity exists to effect how much of the detected change in the guide star position is actually sent to the mount. Done properly, the effects of correcting the noise can be minimized.

One Last Step Into Theory:

It is useful to take the Guiding S/N ratio thought process one step further to determine how best to modify the raw guiding commands. The third use of S/N is to include the mount. I define "Mount Guiding S/N ratio" as:

Mount Guide Signal = mount moves (arcsec) made that need to be made
Mount Guide Noise = mount moves (arcsec) made that should not be made

The seventh important thought: to achieve the best guiding results, the objective is to maximize Mount Guiding S/N ratio. Again, to accomplish this the numerator can be increased, the denominator decreased, or do both. For a given physical setup, once the guide exposure length is set, the numerator is fixed. Therefore, the denominator must be reduced to improve Mount Guiding S/N. Said another way, the objective is to minimize the number of bad corrections made and/or minimize the effect of making bad corrections.

Guiding Recommendations – Applying the Theory To the Practicalities of Guiding:

Clearly, there are a number of challenges to achieving consistent guiding results. I believe there are **three basic guiding recommendations that need to be followed:**

1) **Fix all the physical problems possible.**
    a. **Minimize any physical anomalies with the setup that could cause tracking problems. Examples are: loose/dangling cables, poor mechanical connections between any components (mount/OTA/guide scope/cameras), poor mount mechanics, wind buffeting, etc.**
2) **Minimize the need for making guide corrections to the extent possible.**
    a. **Polar align the mount. The better the alignment, the fewer the number of guide corrections required due to polar misalignment.**
    b. **Minimize the mount's periodic error (PE) via PEC (Periodic Error Correction) training. The lower the PE, the fewer the number of guide corrections required due to PE.**
3) **Maximize Mount Guiding S/N ratio.**

How To Achieve the Best Mount Guiding S/N Ratio:

Once the physical setup has been optimized, the best Mount Guiding S/N ratio possible must be achieved. To do this, the software's guiding parameters must be set up to minimize the number of guide corrections issued due to noise and/or minimize their effects. **Specific Guiding Recommendations:**

1) **Insure Guide Star S/N ratio is sufficient so the centroiding calculation is consistently accurate.**
2) **Optimize Guiding S/N ratio first. This has been discussed at length previously. Summarizing: choose a guide exposure that is long enough to maximize Guiding S/N ratio while being short enough to send needed corrections often enough.**
3) **Minimize Mount Guiding Noise – e.g. reduce the Mount Guiding Noise denominator. The objective is to arrive at guide parameter settings that minimize the number of bad corrections made and/or minimize the effects of making bad corrections.**

I use MaxIm DL, so I will discuss that specifically. However, most guiding software includes similar guide setup parameters. The guide setup parameters in MaxIm to reduce the Mount Guiding Noise denominator are:

1) Aggressiveness – how much of the detected move is applied (10 = 100%, 0 = 0%).
2) Maximum Move – the largest detected move that can be applied.
3) Minimum Move – the smallest detected move that will be applied.

Both Maximum and Minimum Move are in seconds – e.g. 0.100 represents a 100-millisecond pulse sent to the mount. At 1x sidereal guide speed, that represents a 1.5 arcsec move.

<u>How to use the guiding parameters?</u> It is useful to think in terms of probabilities – e.g. what is the probability that the calculated guiding correction is correct? It is probably not very high since the Guiding S/N ratio for any given guide cycle is likely to be low. What is the implication if we send the full guiding command?

1) If the Guiding S/N ratio for that exposure happens to be high, the sent guide correction will be correct – albeit reactive. Assuming the mount responds correctly, this is the best situation possible.
2) If the Guiding S/N ratio for that exposure is low, there are 2 possibilities:
    a. The issued guiding correction is too much. This occurs when the noise is substantially higher than the required correction (which is most of the time). In this case, the over-correction in one direction will require another correction in the opposite direction on the next guide cycle. However, the next guide cycle will also probably have a low Guiding S/N ratio, which will create unpredictable results. More than likely, this will create another over-correction in the opposite direction. The result is oscillation. This is particularly true when the seeing variations are large and PE and/or drift is small.
    b. The issued guiding correction is not sufficient. This occurs when the desired correction is offset by the noise. Again, it will require further guide cycles with unknown, but probably poor Guiding S/N ratios to issue the required correction. More than likely, it will start the oscillation process on the third guide cycle instead of the second.

Aggressiveness Setting:

Consider the implication of reducing the Aggressiveness setting. In other words, what happens if only a portion of the required correction, say 50%, is sent to the mount?

1) If the Guiding S/N ratio for that exposure is high, the sent guide correction will be insufficient – e.g. under-correct. In this case, it will require another correction to be issued in the same direction on the next guide cycle. However, the Guiding S/N ratio for the next guide correction is unknown. If it is high, there will still be

an under-correction – albeit smaller than the last one – to be made up on the next guide cycle(s).

2) If the next Guiding S/N ratio is low, it will probably start an iterative process by oscillating as above. However in this case, the size of any oscillations is reduced by 50%. In other words, the size of the Mount Guiding Noise has been reduced by 50%, thereby improving the Mount Guiding S/N ratio by a factor of 2. This is a very significant and desirable result.

Reducing the size of potential guiding oscillations is extremely important. **Specific Guide Parameter Recommendation: set the Aggressiveness relatively low to significantly reduce the potential for oscillation caused by low Guiding S/N.** Under-correcting is not a significant problem as long as each guide cycle is not so long that most required guide moves can be accomplished within a few guide cycles.

Maximum Move Setting:

This command is also used to reduce the potential for oscillation. Most, and hopefully all, large changes in the guide star centroid are the result of low Guiding S/N ratios – e.g. seeing is dominating PE and/or drift. Therefore, if all large moves are limited, the Mount Guiding Noise is effectively reduced for any guide cycles where large guide star centroid changes are detected. **Specific Guide Parameter Recommendation: set the Maximum Move parameter as low as possible for the physical setup.** Where this might cause a problem is when very large errors occur that need to be corrected – e.g. the Guiding S/N ratio is high because a large physical anomaly has occurred and the error must be corrected. In this case, it may take a number of guide cycles to make the correction, resulting in a smeared image. This is the most compelling reason to minimize any physical anomalies that might require large corrections. Said another way, the better the mount and physical setup, the lower this parameter can be set.

Minimum Move Setting:

Likewise, even small changes in the guide star centroid are likely to result from seeing variations versus PE and/or drift. Therefore, if these moves are ignored, Mount Guiding S/N ratio is increased. **Specific Guide Parameter Recommendation: ignore corrections that are much smaller than the seeing variation.** This supports the first principle to minimize the number of guiding corrections made. Used in conjunction with a relatively low aggressiveness setting, this is a very effective way to minimize oscillations caused by chasing the seeing. Obviously, setting this parameter too high will cause guiding to ignore corrections that need to be made.

The other consideration with this command is to determine how small an error the mount is likely to be able to physically respond to accurately and consistently. Setting this any lower than this level will cause guiding to be inconsistent.

Setting the Minimum Move parameter correctly will dramatically improve guiding by minimizing unneeded corrections that are likely to cause oscillations. This is particularly important for the DEC axis where backlash might be a problem. Finding the right setting will probably require some experimentation.

DEC Compensation Setting:

The object of DEC Compensation is to maintain the same amount of RA movement relative to the sky regardless of where the mount is pointing in DEC. For a given amount of guide correction issued in seconds to the RA axis at DEC = 0, it represents an increasingly smaller amount of movement relative to the sky as DEC is increased by moving towards the pole. Indeed, when pointing exactly towards the pole, the mount will remain pointed in exactly the same place regardless of the amount of RA axis movement applied. Physically, what happens by turning DEC Compensation on is that it increases the length of time a guide correction is applied in RA by the formula COS(DEC). In other words, a guide correction of 0.05 second issued at DEC = 0 will be doubled at DEC = 60.

Now put DEC Compensation into the context of Guiding S/N, then Mount Guiding S/N. PE is a function of a predictable physical anomaly in the mount. The PE variation in terms of microns of movement in the mount's RA axis is fixed at any point in the worm cycle. Therefore, the guiding correction required (in seconds) to offset PE is also fixed. This is true regardless of where the mount is pointing. Said another way, PE is a function of the physical characteristics of the mount. It has nothing to do with the sky.

However, the impact of PE in terms of the movement of a guide star centroid does change depending on where the mount is pointing. The effect of PE gets smaller and smaller as the pole is approached. However, the effect of seeing stays the same. Therefore, Guiding S/N ratio gets lower and lower as the pole is approached.

In terms of Mount Guiding S/N, Mount Guiding Signal decreases as the pole is approached because Guiding S/N (PE) decreases as measured against the sky. To keep Mount Guiding S/N the same, Mount Guiding Noise must also decrease. This is accomplished automatically by making no adjustments to the amount of movement in the RA axis as DEC changes. In other words, the mount's ability to respond to seeing noise in RA naturally decreases as you approach the pole.

Consider what happens when DEC Compensation is on. As the pole is approached, each RA axis correction is increased by that amount necessary to insure all detected centroid changes move the mount sufficiently to correct them. In other words, it is insuring that the mount moves so that it can correct the noise – e.g. chase the seeing. The likely outcome is oscillations in RA.

In theoretical terms, if Guiding S/N ratios are relatively high, then turning on DEC Compensation may not cause significant problems, particularly if the Maximum Move setting is a limiting factor. Conversely, with relatively low Guiding S/N ratios, DEC Compensation will probably cause RA oscillations. Said another way, good mounts in poor seeing conditions will probably guide better with DEC Compensation turned off while poor mounts in good seeing may not be affected nearly as much by this setting.

Recalibrating the guider for different targets as DEC changes is exactly the same as turning on DEC Compensation**. Specific Guiding Parameter Recommendation: calibrate the guider on a star at DEC = 0 and do not recalibrate regardless of the target. Disable DEC compensation completely.**

I recognize this is probably my most controversial recommendation. Fortunately, this phenomenon is relatively easy to detect. Calibrate your guider at DEC = 0. Guide at DEC = 0 and at DEC = 60 with DEC compensation both on and off. By analyzing the guiding logs, it should be clear whether turning on DEC compensation helps or hurts guiding results. Look for any RA oscillations. If RA oscillations increase, DEC Compensation is the cause. Implement what works best for the specific setup.

FYI – In MaxIm, DEC Compensation is turned on anytime there is a non-zero value in the DEC field under the guiding tab. This is true regardless of whether DEC Compensation is checked or not. In ACP, unless DEC Compensation is explicitly turned off in the setup parameters, DEC Compensation is turned on regardless of the settings in MaxIm.

<u>The importance of a good PEC.</u> In developing the Guiding S/N ratio discussion, I used an example of a mount with a well-behaved PE. In other words, PE is relatively small and occurs relatively evenly over time. Consider the case where PE is large (10+ arcsec) and the variation occurs quickly (within 10 seconds or less) once or twice over the course of the worm cycle. It implies that for many guide cycles, PE is small, but for a few guide cycles, it is very large. This is a reasonable representation of many mounts, and in particular, the LX200. Put in Guiding S/N ratio perspective, for much of the time Guiding S/N is low. However, for a few guide cycles, Guiding S/N is high because the required correction (Guiding Signal) is very high, perhaps even larger than the seeing variations (Guiding Noise).

Again, the problem is there is no way to determine which guide cycles have high Guiding S/N and which ones have low Guiding S/N. If the guiding parameters are set up to deal with the typical Guiding S/N situation – e.g. when it is low, it is doubtful that the guiding corrections will be timely and sufficient enough to correct for large, fast PE. The result is smearing in RA. If the guiding parameters are set up to deal with large, fast PE – e.g. when Guiding S/N is high, chasing the seeing when Guiding S/N is low is almost guaranteed. The result may produce round stars, but they will be bloated.

Increasing the Maximum Move command may help the situation to some extent, but the results will probably still not be satisfactory. The best solution is to reduce PE via PEC. Or, repeating, implement the first principle to make the setup so that the number of needed guide corrections is minimized.

A Word About Guider Calibration:

Much has been written about this subject and I won't go into significant detail here. The MaxIm manual provides a wealth of information. The key things to watch for are:

1) Make sure the guide star moves a significant amount of the available FOV. The MaxIm manual recommends a minimum of 5 pixels. More is better.
2) Have your PEC trained before calibrating the guider. The issue is guider RA calibration can be significantly affected by PE. If the calibration is done when the RA axis is moving faster than sidereal due to PE, the guider will under-correct in RA. Similarly, if the RA axis is moving slower than sidereal, the guider will over-correct in PE.
3) Insure DEC backlash settings have been properly determined. If there is still significant backlash when calibrating, the guider will over-correct in DEC.
4) If you choose to use DEC Compensation, calibrate at DEC close to 0 and insure the proper DEC value is input into the DEC field. If this is not done correctly, the math used by DEC Compensation will be wrong and create unpredictable results.

<u>What do good guiding results look like?</u> To improve guiding results, it is most important to save tracking logs and analyze them.

Final important thoughts: **The characteristics of good guiding logs are:**

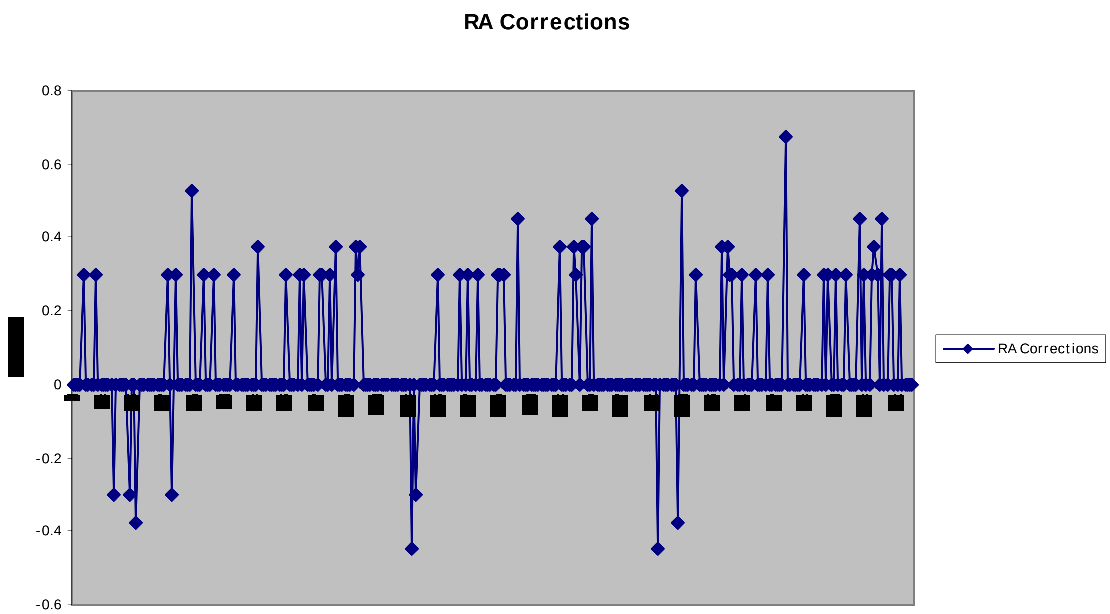
1) **Not making guide corrections that are well within the limitations of the seeing.** The result is that there will be a fair number of guide cycles where it does not require sending any corrections at all to the mount. This implies the Mount Guiding S/N ratio is set correctly.
2) **Minimal oscillation – e.g. it only takes one or two corrections in the same direction before returning to the state where no corrections need to be made.** This implies the mount Guiding S/N ratio is set correctly.
3) **If there are corrections each in the opposite direction for a series of consecutive guide cycles, there are too many oscillations.** In other words, the Mount Guiding S/N ratio is too low, most likely caused by chasing the seeing. Try increasing the Guiding S/N ratio by increasing the guide exposure. Or, try decreasing the Mount Guiding Noise by decreasing the Aggressiveness setting, increasing the Minimum Move setting, or decreasing the Maximum Move setting.
4) **In DEC, there should only be occasional corrections in one direction to compensate for any drift.** DEC backlash issues exacerbate any oscillation problems. If there are many DEC oscillations, the Mount Guiding S/N ratio is too low. This is most likely caused by chasing the seeing. Try increasing the Guiding S/N ratio by increasing the guide exposure. Or, try decreasing the Mount Guiding Noise by decreasing the Aggressiveness setting, increasing the Minimum Move setting, or decreasing the Maximum Move setting.
5) If it takes a number of corrections in the same direction before returning to the state where it does not need to make any corrections, it implies a relatively high Guiding S/N ratio but a relatively low Mount Guiding S/N ratio. In other words,

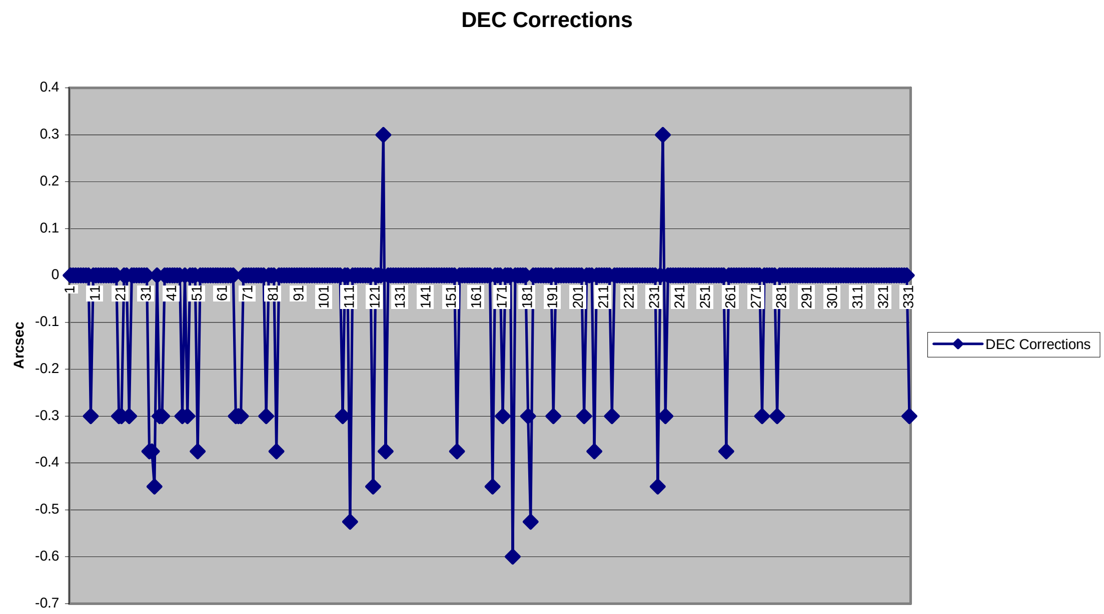
the number of guide cycles where a correction is made can be increased (e.g. lower the Minimum Move parameter) or the amount of correction issued per guide cycle can be increased (e.g. increase the Aggressiveness/Maximum Move setting).

6) If it occasionally requires corrections that are very large, these are most likely caused by some physical anomaly with the setup and the cause should be eliminated. It is extremely difficult to achieve good guiding results under these conditions because most of the guiding settings are designed to minimize chasing the seeing – e.g. not making big undesired movements relative to the small desired movements. When a big movement is required, there is no way to deal with it other than by letting it take a number of guide cycles to accomplish. The result is probably a smeared image. (Also, see PEC discussion above.)

Examples of Guide Log Graphs:

These two graphs represent all RA and DEC corrections made during a 10-minute exposure (guide exposure = 1 second). These are about as good as can be hoped for: almost no oscillation, almost no seeing-chasing, no large physical anomalies, and the majority of guide cycles did not require a guide correction at all.





My Guide Settings:

My guide settings are the result of my physical setup and typical seeing conditions. They may or may not be appropriate for others since their situation is unlikely to be identical to mine. However, I am including the details of my normal setup in this note for completeness.

Mount: AP1200GTO
OTA: LX200 10” F10 extensively modified to minimize mirror shift/flop; focal length = 2575 mm
Imaging Camera: ST8E
Image Scale: 0.7 arcsec/pixel
Guide Scope: Orion 80 mm short tube; operating at focal length = 213 mm
Guiding Camera: ST237A
Guide Image Scale: 7.12 arcsec/pixel
Seeing: rarely allows FWHM less than 2.5 arcsec; usually around 3.0 arcsec

MaxIm Guiding Parameters:

Aggressiveness: 5
Maximum Move: 0.1 seconds (minimum allowed by MaxIm)
Minimum Move: 0.040 seconds
DEC Compensation: off
DEC Backlash Compensation: 0.60 seconds (specific to my mount)
Guide Exposure: never less than 1.0 second. Given my short focal length guide scope, I rarely need to increase it above 1.0 second to achieve a sufficient Guide Star S/N ratio. Most times, I find 2.0-second exposures provide the best compromise between averaging

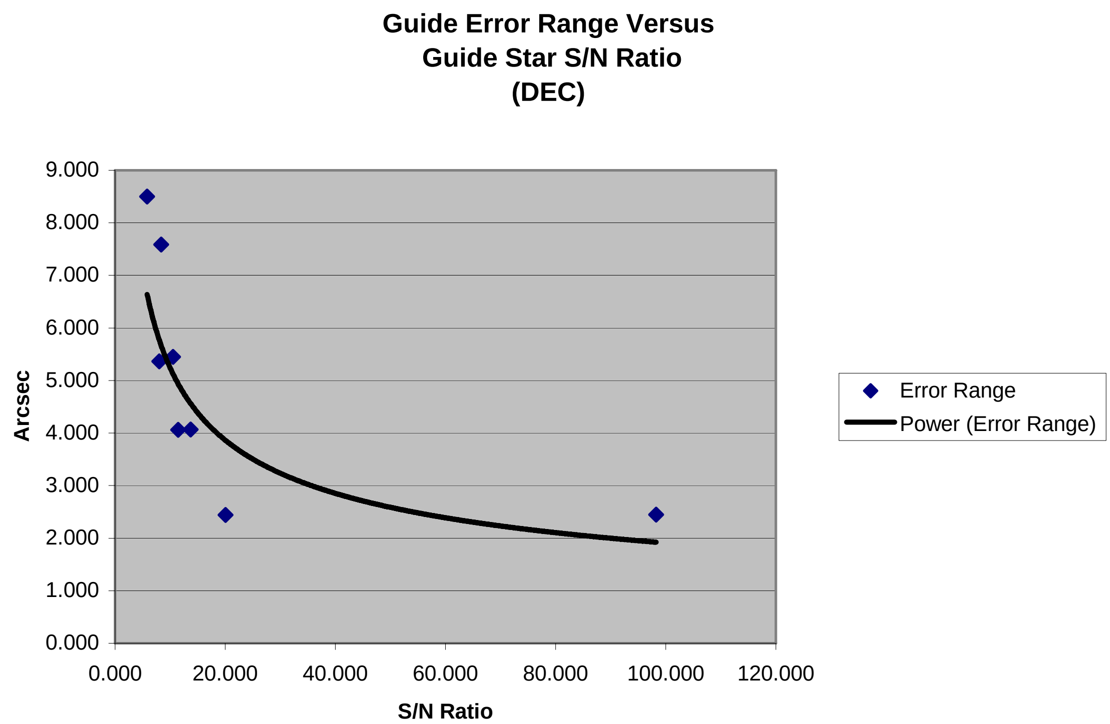
out some of the effects of seeing (reducing Guide Noise) and making corrections fast enough – particularly since my Aggressiveness and Guide Speed is low.
Guide Speed: 0.5x sidereal. This speed was arrived at because of the Minimum Move setting. My mount does not seem to be particularly consistent executing commands any shorter than about 0.030 sec. I have conversed with other AP1200GTO owners and they seem to have similar results. If the Minimum Move is set to 0.030 seconds, at 1x sidereal guide rate, it implies all corrections less than +/- 0.45 arcsec are ignored. Even though my seeing is not all that good, that just seemed too large to me. So, I reduced the guide rate to 0.5x sidereal and set the Minimum Move to 0.040 seconds. At these settings, all errors below +/- 0.3 arcsec are ignored, which seems just about right. The negative implication is that the DEC backlash setting has to be doubled – e.g. it takes twice as long to unwind DEC backlash at 0.5x sidereal versus 1.0x sidereal guide rate. But, if polar alignment is good and the other guide settings are working effectively, DEC corrections should only be in one direction anyway. Therefore, the negative impact is minimal.

Post Script – Guide Star S/N Ratio:

I recently had the opportunity to test a user-developed MaxIm multiple guide star plug-in. I will not go into significant detail with respect to the results except to say that it works – and works well. The benefits of using this approach begin as you add the second guide star and increase as more stars are added. There are two basic reasons for this: 1) it reduces the effects of seeing, and 2) it improves the Guide Star S/N ratio. However, in both of these cases there were surprises, at least for me.

Regarding seeing, at least in my location, the effects are not just rapid, random oscillations around a point, but can also consist of rather large movements where one oscillation may last for many seconds at a time. For the sake of this discussion, I will call the rapid oscillations “fast seeing” and the multi-second oscillations “slow seeing.” My suspicions are that slow seeing is caused by multiple heat/cold sources typical of suburbia that create a number of columns of air at varying temperatures (think chimneys, ponds, grassy areas, rooftops, parking lots, trees, etc.). The effects of fast seeing are quite different over a very small FOV while the effects of slow seeing are similar over a relatively large FOV. Therefore, using multiple guide stars with a FOV of about 30 arcmin virtually eliminates the effects of fast seeing but is much less effective in eliminating the effects of slow seeing.

Perhaps most interesting to me is the effect Guide Star S/N ratio has on the accuracy of the centroiding algorithm. While it is understood that Guide Star S/N ratio is an important component of this calculation, I did not appreciate how critical a component it actually is. When using multiple guide stars, you have the opportunity to compare the Guide Star S/N ratio of each guide star to the range of values computed for their centroids. This comparison is valid because these values (Guide Star S/N ratio and centroid) are computed for each star at the exact same time (e.g. same seeing conditions) over a number of guide cycles. As expected, the higher the Guide Star S/N ratio, the lower the range of computed values for their centroids. What is surprising is how high the Guide Star S/N ratio needs to be for the calculation to be reliable.



MaxIm will happily guide with a Guide Star S/N ratio of 3.0 or perhaps even a bit less. However, as this chart demonstrates, the centroiding error range increases geometrically when the Guide Star S/N ratio is below 20. Reading from the chart, for a bright guide star (Guide Star S/N ratio > 20), the error range is only 2.5 arcsec – consistent with my normal seeing conditions. However, for a dim guide star (Guide Star S/N ratio < 8), the error range is over three times larger. Using multiple guide stars, particularly when they are relatively dim, improves the Guide Star S/N ratio very significantly. While you cannot see it from this chart, the centroiding error range is reduced by 100% just by adding a second dim guide star to the centroid calculation. Another clear lesson here is that darks should be used for all guide exposures to maximize the Guide Star S/N ratio potential for a given star brightness.

My initial premise was that the types of errors a guider might detect in a 2-second guide cycle (excluding physical anomalies) are:

Drift	0.10 arcsec or less
PE	0.067 arcsec or less
Seeing	2.0 arcsec or less

There is clearly a fourth error type that needs to be added to the list. Centroiding Error could be as large as (or even larger than) the seeing error if using a guide star with a low Guide Star S/N ratio. Said another way, unless using a bright guide star (e.g. Guide Star S/N ratio > 20) the centroiding error will be significant.

Fortunately, this new finding has a minimal impact on my guiding recommendations since they are already designed to deal with the fact that we are forced to use bad data (or at best, unknown quality data) as the basis for making guiding corrections. All this finding really does is add another source of bad data under certain circumstances.

The positive aspect of this finding is that if your guide settings are already effective in dealing with the effects of seeing, they should also be effective in dealing with the effects of inaccurate centroiding as well. Said another way, you should be able to guide successfully even when forced to use a dim guide star.