More Than You Ever Wanted to Know About Autoguiding

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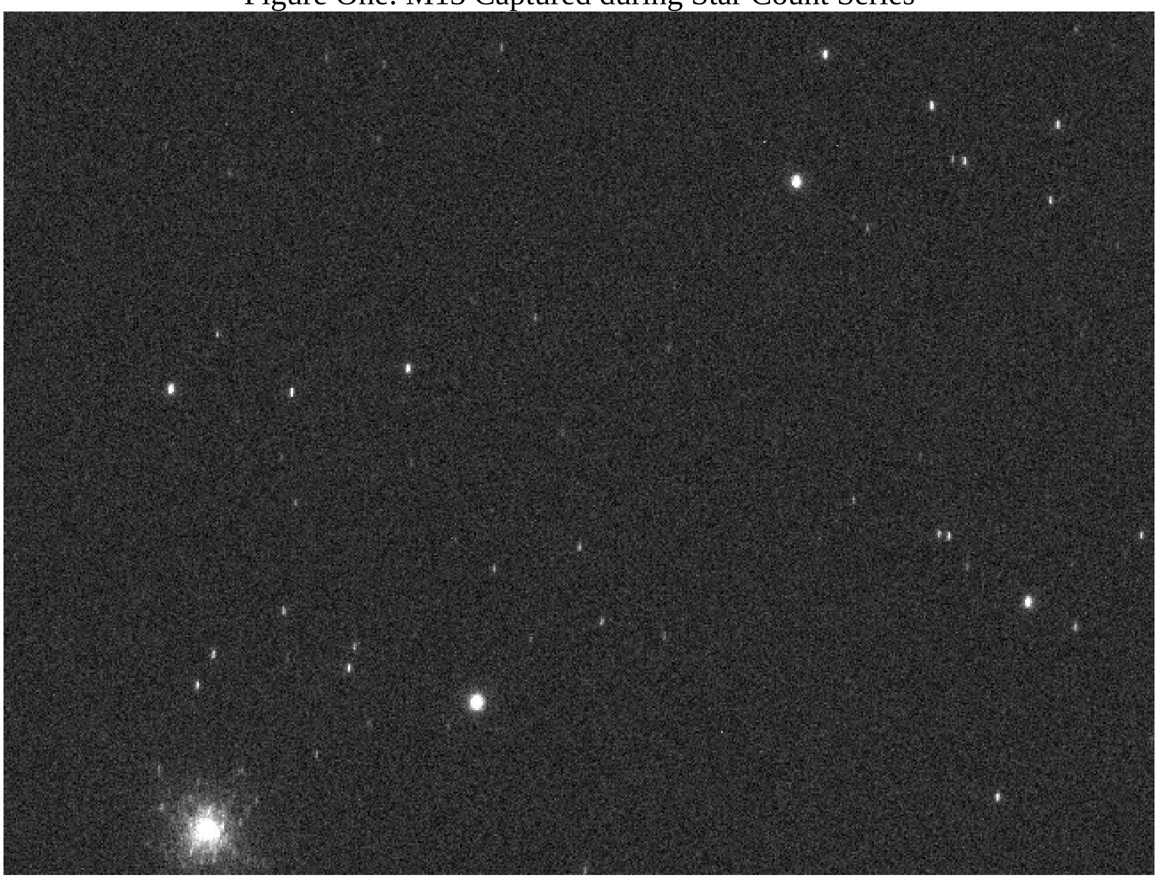
SBIG has been in the autoguiding business for 22 years and has learned a lot over that time. We have recently introduced our new ST-i guider coupled with a 100 mm F/2.8 lens and make the bold claim that this will perform quite well as a guider. In this paper I will outline the science behind this claim, and provide more background regarding the choice of the right focal length for the autoguider. Back in ST-4 days we stated that a focal length half that of the imaging scope's focal length was a good choice, but that was basically a guess that seemed to work. Now we have the data to clearly back up our choice!

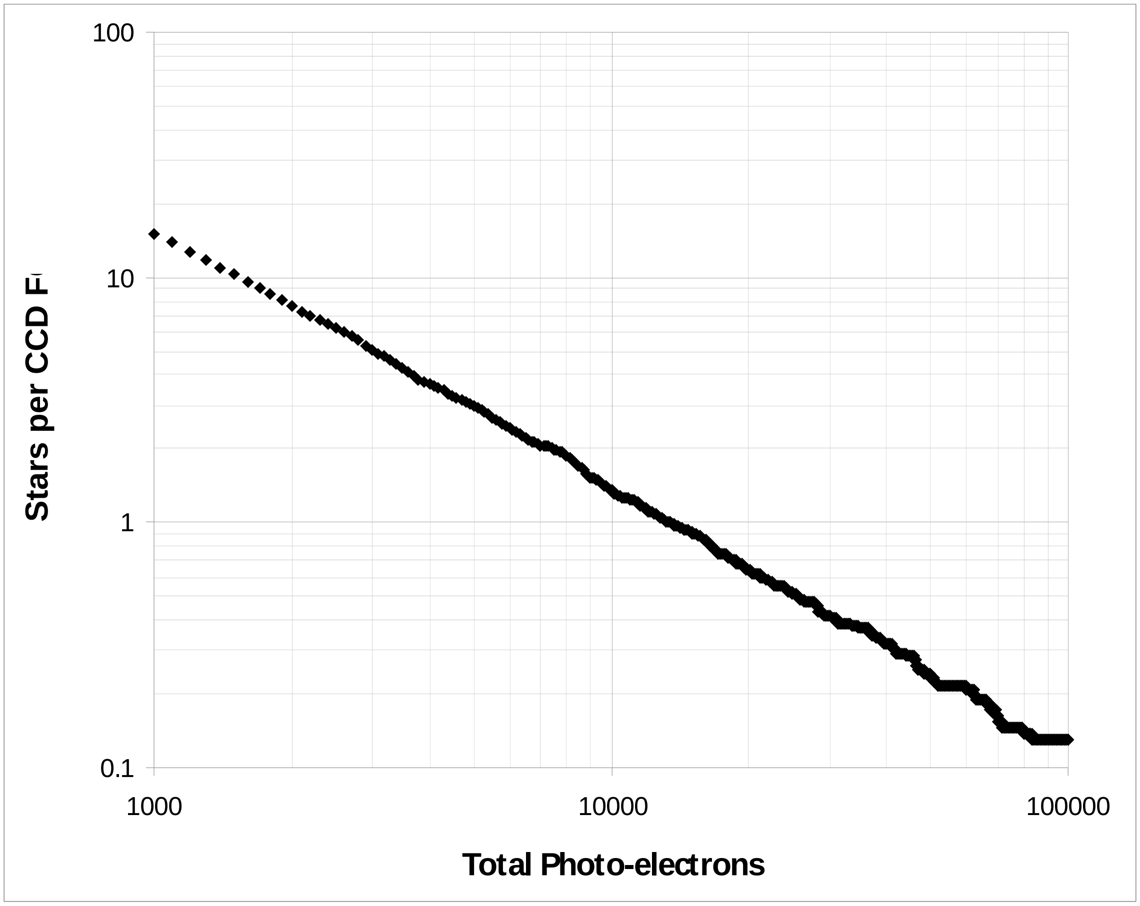
The first important question to answer is "How faint a star do you need to detect to be assured of having a guide star?" To answer this question, I set up an ST-i at the focus of a Borg 50 mm aperture 250 mm focal length achromat and captured a star field every 4 minutes for 8 hours one clear night, near the zenith. An example of one of these two-second exposures is shown in Figure One, where I happened to wing M13. Some drift is apparent since the system was mounted on a tripod while the sky drifted by.

Figure One: M13 Captured during Star Count Series



Note that M13 is starting to be resolved into stars with only a 2 second exposure! I then wrote a program to count all the stars in these images as a function of brightness and accumulate the data into that shown in Figure Two. What is shown is the average number of stars brighter than a certain number of total photoelectrons per star in one field of view (FOV).

Figure Two: Average Number of Stars on FOV as a function of Total Photoelectrons



An important point to glean from this data is that the number of stars seen is linear with the brightness – if you have 10 times more sensitivity, you will find 10 times more stars. What this means is that, when it comes to finding a star on the chip, what's important is the F-number of the telescope, not the aperture, and not the focal length. An F/4 system will see four times more stars than an F/8.

Now that we have this data, what is the probability of actually having a guide star? We can predict this from Poisson statistics, which estimates the probability of an event based on its average rate. I will leave out the details here, but what one can calculate is that if the average rate is 3 stars per FOV, then there is a 95% probability of having at least one (which is all you need to guide). If the average rate is 4.6 stars per FOV the probability of at least one is 99%. An examination of the table reveals that at F/5 we need to guide on stars of at least 5000 total electrons to reach 95% probability of having a guide star, and 3300 electrons to reach 99% probability. Now we need to address the question of focal length.

Question Two is "How accurately can you guide on a Dim Star"? This one is a bit tricky to answer. To experimentally determine this I put a very short focal length lens on the ST-i, a 6 mm C-mount camera lens, and put the assembly on a tripod viewing the sky near the pole. I then took a number of short exposures while the earth rotated, and plotted the centroid position of each star as a function of time, for stars of different brightness. What I found is a slope to the data, since the star is drifting with time, and a root mean square (RMS) "chatter" about the slope. An example of this is shown in Figure Three, for both X and Y pixel directions, where the overall slope (15 and 8 pixels for X and Y respectively) has been removed. The "chatter" is a measure of the tracking accuracy.

Figure Three: Centroid Position of Drifting Star

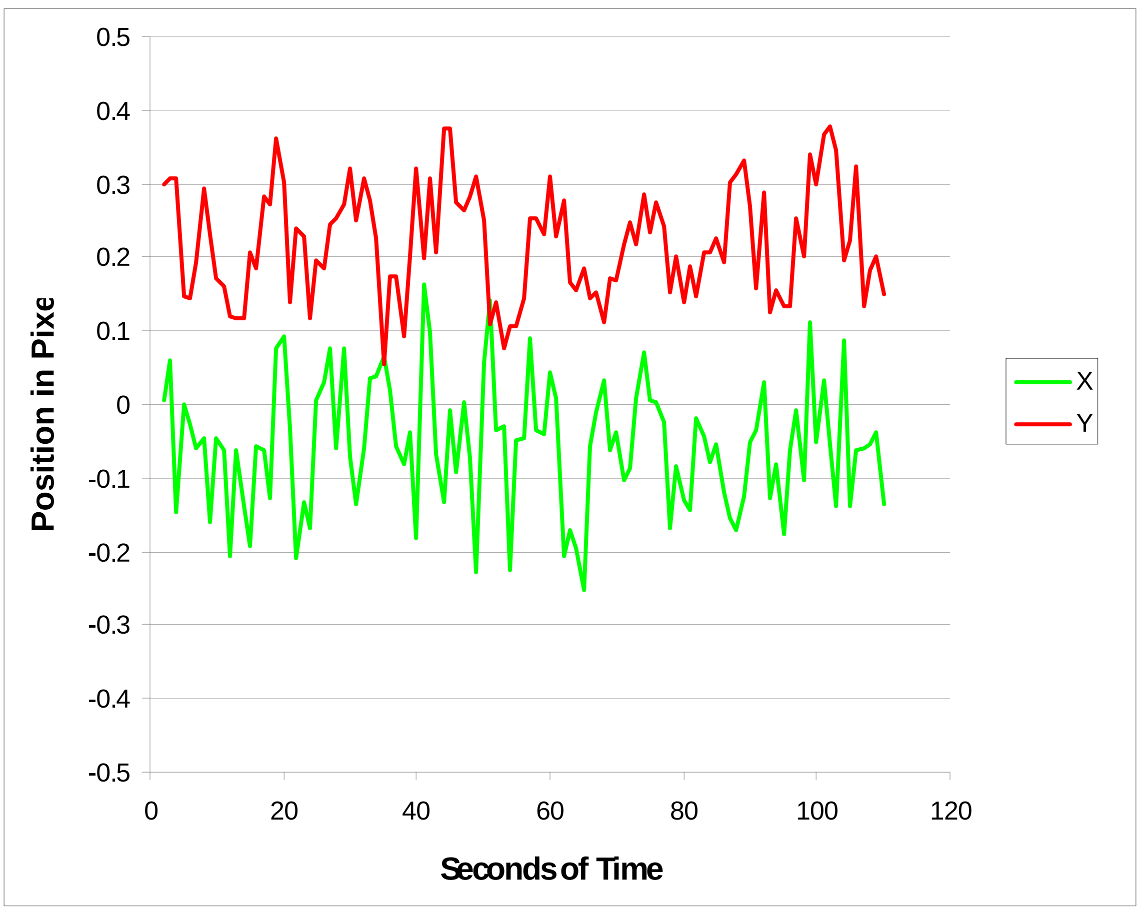
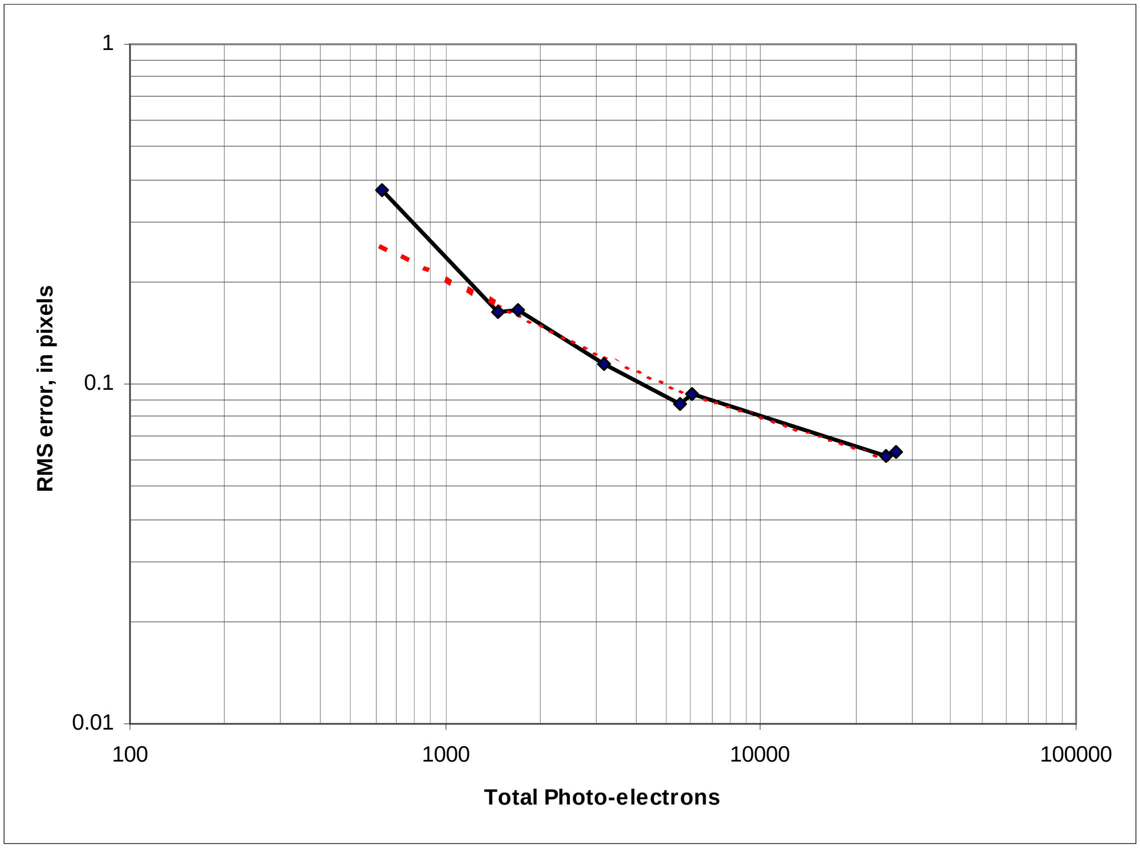


Figure Four plots the chatter as a function of star brightness, along with a fitted curve (dashed – in red). What we find is that for dim stars the measurement noise causes some position uncertainty, which improves as the square root of the total electrons as brighter stars are used. There is also a "floor" to how good the RMS error can be since, even for bright stars, pixel non-uniformities will cause some centroid error. The data indicates the floor is around 0.045 pixels rms. This floor is not an issue for guiding, since the star is held to its initial position.

Figure Four: RMS Tracking Error as a function of Total Photo-Electrons



Question Three is “How good does the guiding need to be for round star images”? I have determined over the years that blur adds in an RMS sense, which not everyone realizes. What this means is that if you have 5 pixels of blur due to seeing, and the star moves three pixels during the exposure (or between corrections), the final blur will be the square root of 5^2 +3^2, or 5.83 pixels in length. Perpendicular to the movement the star is 5 pixels in diameter, so the final image is only 20% out of round, which is at the edge of acceptability for most users. I know some of you will dispute this point about RMS summing, and think that 5+3 = 8, but you can easily verify my result. Set your polar alignment a little off so the star drifts, and measure the star profiles as a function of the total drift during an exposure.

I have seen many images over the years, and taken a lot of images myself, and the average good night at my site shows seeing around 3 arcseconds, measured as the full width at half maximum (FWHM) for the star image. This may be fairly typical of most backyard setups. (By the way, do not trust your measurement unless the FWHM is greater than three pixels, otherwise pixel effects perturb the result.) So, based on this, 1 arcsecond RMS guiding is good enough for the majority of users, particularly with focal lengths under two meters (66 inches) such as a short focus refractor. For users with big scopes on mountaintops I would drop this to 0.33 arcseconds RMS to be completely safe.

Putting it all together: we see from Figure Two that at F/5 we need 5000 electrons to have a 95% chance of having a guide star on the CCD. According to Figure Four, this will give us guiding to an accuracy of 0.089 pixels RMS. For this amount of chatter to equal 1 arcsecond rms, we need a focal length of 136 mm. For a faster F/number the star will be brighter and the focal length can be reduced. For convenience, I have tabulated the necessary F/numbers for accurate guiding in Tables One and Two below.

Table One: F/numbers Required for 1 Arcsecond RMS Tracking

Focal length (mm)	RMS Tracking Required (pixels)	F/number Required 95%	F/number Required 99%
100	0.066	3.7	3.0
150	0.098	5.6	4.5
200	0.131	7.3	6.0
250	0.164	9.2	7.5
300	0.197	11.2	9.1

Table Two: F/numbers Required for 0.33 Arcsecond RMS Tracking

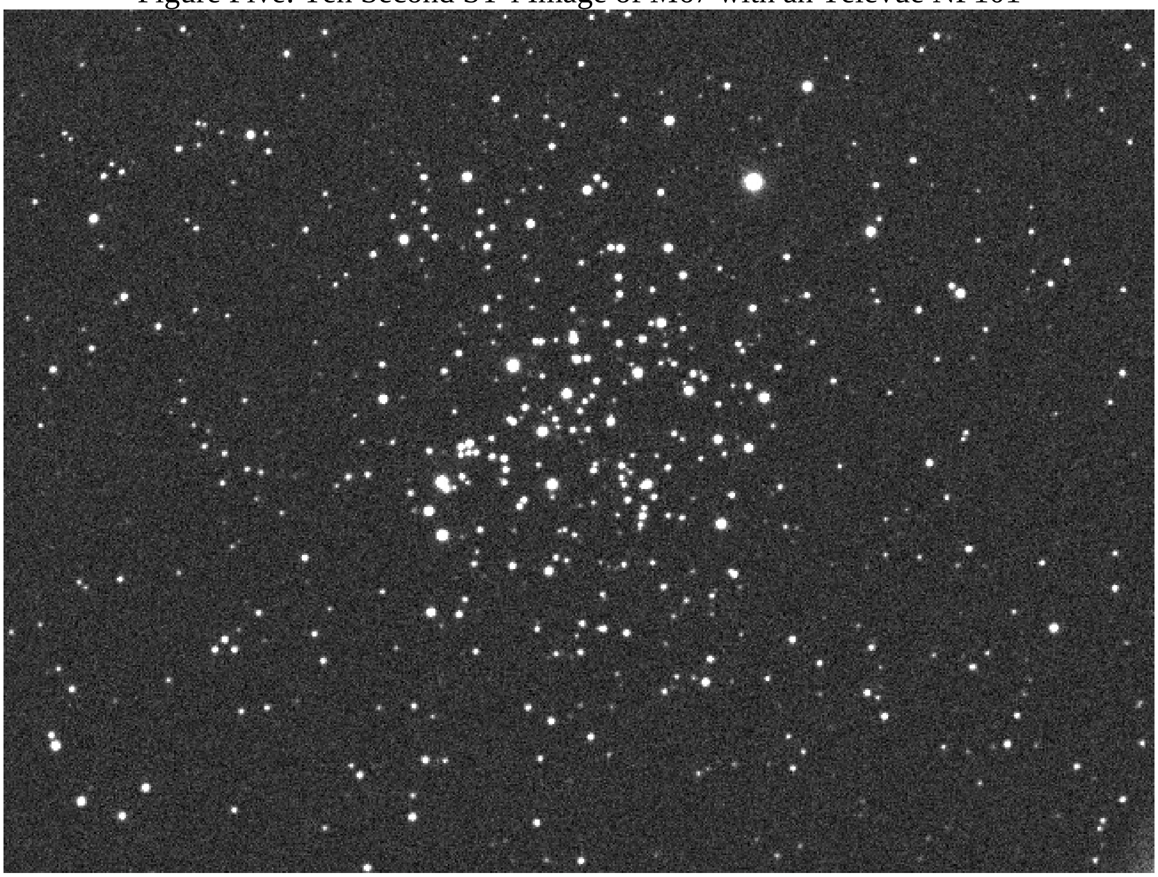
Focal length (mm)	RMS Tracking Required (pixels)	F/number Required 95%	F/number Required 99%
300	0.066	3.7	3.0
500	0.110	6.2	5.0
1000	0.220	12.3	10.0

Of course, there may still be some star fields where you get unlucky. The star count does vary quite a bit from the Milky Way to galaxy-rich areas. I used the average here as a good measure, but longer guide exposures of 3 to 6 seconds may be required at times.

From this data you can see that SBIG's new ST-i with the 100 mm F/2.8 lens should provide arcsecond guiding for 99% of the star fields viewed - anywhere in the sky. This means you can guide where you are, instead of having to struggle with guide scope alignment knobs in the dark, or tolerate flimsy tilt adjustments that are truly an insult to astrophotography. After all, it's an imaging accessory and you want to spend your evenings imaging, not wrestling with a guider that had price as its only positive attribute. Solid guide scope mounting is absolutely necessary to reduce differential deflection problems. Nor does buying a perfect mount solve all your problems. Mirror shifts, thermal shifts and gradients, and changing gravity loads mandate guiding with update rates of at least every 60 seconds or so. A “perfect” mount is not an option, in my experience.

Interesting Asides: As part of this process I measured the sensitivity of the ST-i in stellar magnitudes. Figure Five shows a 10 second image of M67 captured with a Televue NP101.

Figure Five: Ten Second ST-i Image of M67 with an Televue NP101



Based on this image, the sensitivity to starlight for the ST-i is approximately 932000 electrons per second per cm squared of aperture (varies somewhat with B-V value). This means the ST-i with our small, 35mm diameter, 100 mm FL, F/2.8 lens is guiding to one arcsecond accuracy or better on stars down to magnitude 7.5 in one second.

Also, for years and years SBIG has sold self-guided cameras with a similar tracking CCD. At the full imaging system focal length any star bright enough to reliably detect will provide sub-pixel tracking. The data of Figure Two indicates we should have a 99% probability of a star 2000 electrons or better at F/6.3 and a 1 second exposure, without rotating. This is why self-guiding works. Of course, for filtered or H-alpha imaging longer exposures or rotating the camera may be required.