GETTING READY FOR EPSILON AURIGAE

by Bob Buchheim

During this year's SAS Symposium, Jeff Hopkins described the importance of making photometric observations of ε Aurigae starting soon, in order to prepare for the once-every-27-years eclipse that will begin in mid-2009 (first contact). There are very few observers monitoring this star out of eclipse, but if we don't adequately characterize its out-of-eclipse parameters, then we won't have a good baseline to compare the eclipsed parameters against. The next 2 years offer us the chance to characterize its pre-eclipse photometry (which hasn't been well-studied with modern instruments), and the upcoming eclipse may be the only one that most of us observe, since the next eclipse will begin in 2036.

The accepted comparison star (λ-Aur) is nearly 5 degrees away, so the typical procedure of differential photometry using a comp star in the same CCD field of view won't work for those of us with small FOV's. The need to move the FOV from target to comp star makes it doubly important to understand and minimize effects that can change between exposures.

For CCD photometrists, this is a difficult target because it's so *bright*: roughly V-mag 3.0. The target's brightness presents a confounding problem: in order to keep the stellar signal within the linear range of the image, we must use very short exposures or a very small aperture (or both). For example, with a V-band filter on my 11-inch SCT, the star will saturate the imager in an exposure of about 0.5 seconds. At such a short exposure, scintillation noise is terribly high. And if you use a small aperture, then scintillation noise will be much worse than it is with a large aperture. What to do?

Most noise sources we encounter in CCD photometry are additive. Scintillation is a multiplicative effect: if the star gets brighter, the scintillation effect increases proportionately (i.e. doubling the star's brightness doubles the scintillation noise, so that the signal-to-noise ratio doesn't improve). One common formula for atmospheric scintillation noise is:

$$\frac{\sigma}{S} = 0.09 \cdot \frac{X^{1.5}}{D^{2/3}\sqrt{2 \cdot t}} \cdot \exp\left(-h/h_0\right)$$

where:

X = air mass = sec θ (where θ is the zenith angle of the observation)
D = telescope aperture (cm)
t = exposure duration (sec)
h = observatory elevation (km)
h_0 = atmospheric scale height (typically about 8 km).

This formula shows why we want to find a way to use both a large aperture and a long exposure. As the exposure time is made longer, the relative magnitude of scintillation fluctuations will be reduced. The simplest way to allow longer exposure duration is to use a smaller aperture. Unfortunately, the equation shows that a smaller aperture increases the scintillation noise by almost the same factor that the longer exposure is reducing it – that is, merely reducing the aperture isn't going to provide a noticeable improvement in the scintillation noise.

This equation is based on the theory of atmospheric turbulence, in which "seeing" is caused by random temperature differences between small parcels of air. The temperature differences imply differences in refractive index; and blobs of higher or lower refractive index act like weak positive or negative lenses. Motion of the air carries these weak lenses past the telescope, giving rise to the time-varying intensity that we know as "twinkling" or scintillation. The scintillation amplitude drops as the exposure duration increases because the brightening- and dimming of the starlight is "averaged" over the exposure time. Take a long enough exposure, and this averaging is almost perfect (i.e. one exposure will show the same integrated amplitude as the next). But, as I've pointed out, with a real sensor's linearity limit, we aren't free to use arbitrarily long exposure duration.

The scintillation is also reduced using a large telescope aperture. If your telescope aperture is large enough to encompass several of these parcels of air, some with high and some with low refractive index, then it “averages” the positive and negative lens effects. But of course using a large aperture will force us back to a short exposure.

One way out of this quandary is to use a three-hole aperture mask, as shown in Figure 1 below. The idea is that the sub-apertures are small (allowing long exposure duration for “time averaging” of the scintillation), and they are spaced widely (giving a useful “aperture averaging” effect).

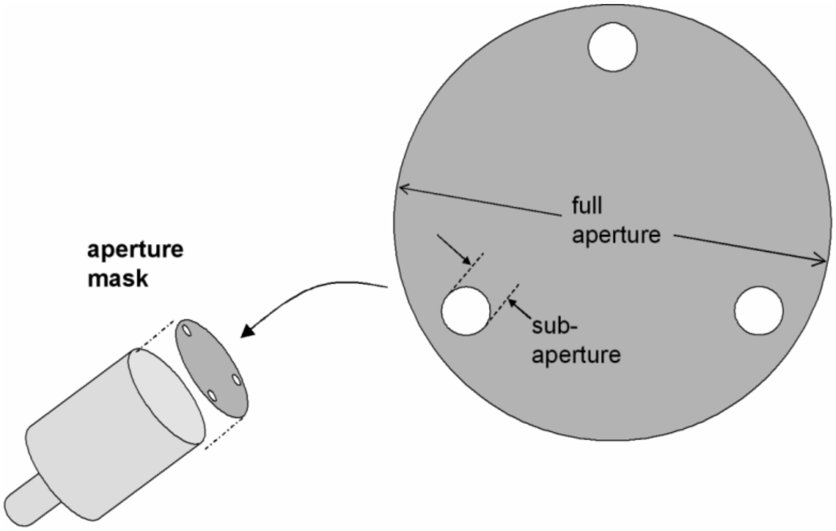


Figure 1: Aperture mask comprising three "sub apertures"

In order to test whether this idea will work, I did some experiments using η-Boo as the target star (it’s a little brighter than ε-Aur).

For my experiments, I used my 11-inch SCT. The sub-apertures were cut from a black cardboard aperture mask. Three sub-apertures arranged in a triangle comprised the sub-aperture array, with the centers of the sub-apertures approximately 3.5 inch (radius) from the center of the telescope aperture. Sub-aperture diameters tried were: 3”, 1.5” and 0.75”. As it turned out, the smallest seemed to be the best choice, permitting me to use nice long exposures (30 - 60 second) without saturating the imager.

The results of this experiment validate its principle. For each sub-aperture size, I made 10 images at each exposure duration, measured the instrumental magnitude of the star in each image (using MPO Canopus), and converted the IM to “intensity” signal by the formula

$$S = t \cdot 10^{\left(\frac{-IM}{2.5}\right)}$$

As I reduced the size of the sub-apertures, I was able to use longer exposures, as desired. When the scintillation amplitude (σ/S) is plotted versus exposure duration, as in Figure 2, the data points lie along the expected $t^{-1/2}$ trend line. This indicates that even though the sub-apertures are small, their separation provides the benefit of aperture averaging. That’s good news!

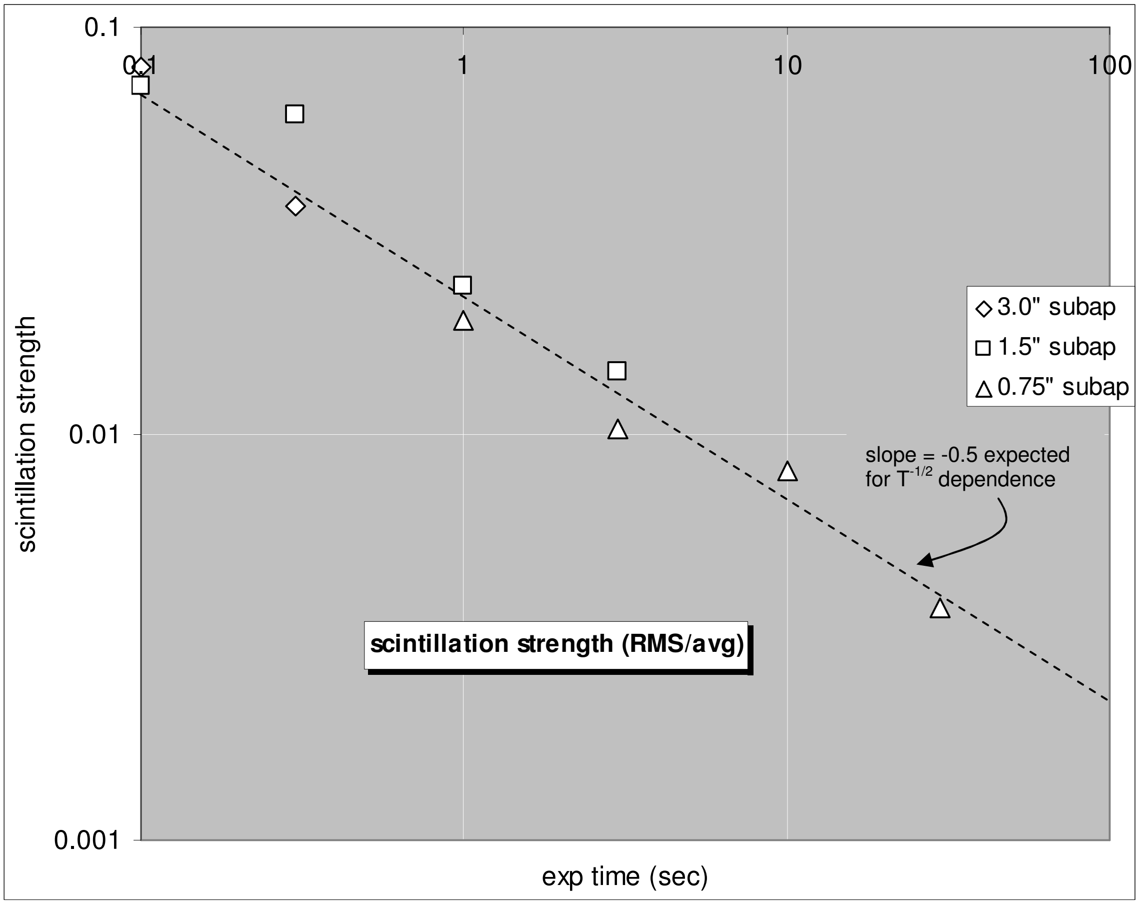
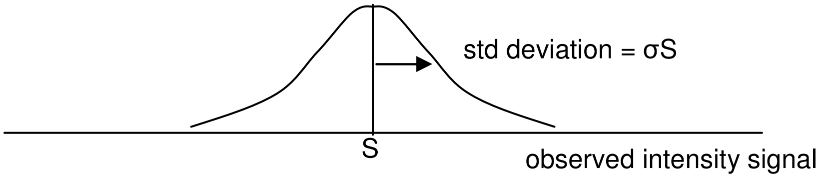


Figure 2: Scintillation strength vs. sub aperture size

How low must scintillation be driven, in order to get good photometric accuracy? The exact math is beyond my education, but here's a heuristic explanation that gets pretty close. Suppose that the average signal (in ADUs) is S. For a given level of scintillation, the observed signal will be a random variable whose standard deviation is σS. That is, on 68% of the images, the observed signal will range between (S-σS) and (S+σS):



The "1-sigma" variation in observed intensity is a change from intensity = S to intensity = S+σS = S(1+σ). This variation in terms of magnitudes is

$$\Delta m = -2.5 \log\left[\frac{S}{S + \sigma S}\right]$$

Some reasonably straightforward algebra reduces this to

$$\Delta m = +2.5 \log[1 + (\sigma / S)]$$

and since (σ/S) <<1, we can use the approximation

$\ln(1+ \alpha) \approx \alpha - (1/2)\alpha^2 - (1/3)\alpha^3 + \ldots$

and keep only the first term. We also have to recognize the difference between natural logarithms (ln) and base-10 logarithms (log):

$\log_{10}(Z) = \ln(Z)/\ln(10)$

and remember that it is the base-10 logarithms that are used in the definition of magnitudes.

Since ln(10)= 2.3, the scintillation noise, in magnitudes, is approximately

$$\Delta m = (2.5 / 2.3) \cdot [\sigma / S] = 1.09 \cdot \frac{\sigma}{S}$$

Since the “sub-aperture” mask approach allowed me to get down to $\sigma/S \approx 0.004$ (see the graph above) the scintillation noise will contribute less than a hundredth of a magnitude to the error budget. Very good!

The image point spread function is significantly bloated by the diffraction of the small sub-apertures: I had to use a photometric measurement aperture of about 45 arc-seconds diameter in order to capture all of the light from the stars’ images with the smallest sub-aperture. This brings in a fair amount of “background skylight”, but I judge that as unimportant considering the brightness of the target and comp stars, and the relative faintness of nearby field stars.

I won’t be able to use this approach on ε Aurigae until September, but I wanted to let you all know about these results so that you can try it on your own CCD photometry setups, to get ready for the observing season.