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**Editors:
Brian D. Warner
Jerry Foote
David A. Kenyon
Dale Mais**

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Fast Photometry

John Menke
22500 Old Hundred Rd
Barnesville, MD 20838
John@menkescientific.com

Abstract

Fast photometry is measuring changes in brightness in the range of several seconds down to a few milliseconds or faster. Increasingly, asteroid and lunar occultation measurements are carried out using camcorders or video cameras. These can be very inexpensive, and allow event timing to about .02 sec. GPS timing signals, good to a microsecond or better, can be combined with video or photometers to allow UTC timing to as good as the sensing device allows. Beyond video cameras that are usually limited to event timing, there is also a role for amateurs to explore true high speed photometry. I will describe use of several inexpensive devices that allow an amateur to conduct fast photometry. I include observing results from this equipment as used in occultation and scintillation studies, and will discuss some of the possible areas of amateur work.

1. Introduction

So what is fast photometry? Fast photometry is the process of measuring brightness that varies at a "high" rate. "Slow" photometry is measuring at a rate slow enough for conventional methods (formerly film, now CCD cameras) to give good results. Normally, we want to measure to some specified precision within a specified time. Measuring a 1% change in brightness of a faint star in a millisecond is a very different problem from taking a minute to measure a 10% change of a bright star. We will fairly arbitrarily say that "fast photometry" means measuring intensity changes occurring faster than about 1 minute. In this paper, I report measurements at 1ms, but some fast photometry is done at the microsecond rate.

What kind of equipment and techniques are feasible for amateurs to use to do fast photometry? And what are some of the phenomena that require these techniques? And what do the data really look like?

2. Equipment

2.1. Telescope

Most astronomy phenomena require a telescope to gather enough light to measure. As we shall discuss, in the fast photometry regime, you may be surprised to discover that chief problem may not be that the objects are too faint. Rather, even for bright objects, the atmospheric scintillation sets a limit on the precision of a brightness measurement that may be made at a particular speed. As usual, the bigger the scope, the more light there is to use (almost always a good thing) AND the more scintillation will be averaged. The work reported here has been done with a

C11 on an AP mount (but I look forward to my fast Newtonian 18in. f3.5).

2.2. CCD Cameras

Most CCD cameras these days operate with shutters that will operate in 0.1 sec or faster. While the full frame download time may be 1-10 sec or longer, one can often operate with partial or sub-frames and achieve download times down to 1 sec or even a bit faster. Thus, a CCD camera may operate at close to 1Hz. Note, however, that using a subframe will probably prevent you from having a suitable comparison star in the field--you are then in almost the same boat as a person with a standard one-channel photometer.

2.3. Photometer

A photometer uses a photosensitive device (silicon diode, photomultiplier, etc.) to convert light to an electric current that can be measured. A silicon diode is similar to a single pixel in a CCD, but whereas the CCD accumulates charge for a delayed readout, the photometer detector reads out continuously. There is always a tradeoff of speed vs. sensitivity: the widely used Optec photometers using silicon diodes achieve fairly high sensitivity by foregoing operation faster than about 1 sec response. However, it is entirely feasible to build a homemade fast photometer. My own, shown in Fig. 1, cost about \$50 in parts, and uses a 1mm square silicon photodiode (see References). I designed it more for speed than sensitivity, achieving about 2 ms rise time with an internal noise roughly equal to a mag 9.5 star in a C11. The output

of the photometer is digitized and sent over a serial link to a PC for recording and analysis. I used this instrument for many of the data in this paper.



Figure 1. Fast photometer Equipment

To reduce background light from nearby stars and skyglow, one normally operates the photometer with a diaphragm to limit the field of view (I used about 1 a-min). The smaller the field, the more challenging is the tracking. Most photometers do not let you see whether the image is landing on the sensor--i.e., you only see the resulting intensity whether the change is due to a tracking error or a cloud passing by. Thus, an excellent mount is a big plus in photometry (conversely, a big advantage of using CCD or video is that there is less need for accurate telescope pointing and tracking).

2.4. Video Camera

For some work, a camcorder can be used either aimed at the target or even through a telescope. But one can also use an inexpensive video camera and feed the image from a telescope into a camcorder for recording, or directly into a computer for recording and analysis frame by frame. In any case, the best time resolution is 1/60 sec (17ms) with 8 bit digitization. Video can eat even hard-drive storage very fast (a mere one hour of video can be tens of 25GB).

2.5. Human Eye

The human eye's best feature is that it is pretty sensitive, portable, and has no wires or batteries. But it does weigh a lot (especially as it gets older), and is only good to about 0.2 sec time resolution. The eye is especially useful for transient, one time events. For

example, the eye can be used with a telescope to observe asteroid occultations, and can easily discriminate one star from many.

2.6. Timing

Many events require only approximate timing (>1 sec), but some events or experiments require very accurate timing. There are pros and cons of using WWV, telephone, and computer time based on the Internet. Internet/PC-based timing sources frequently are off by as much as one second. While the display on a GPS is frequently wrong by many seconds, GPS modules are available that output a UTC pulse every second with an accuracy of a microsecond or better. One entrepreneur has developed a device for imprinting this time on raw video for use in asteroid occultation work (see References). I built a related device for time stamping digital data from the photometer, or for use in visual occultation work (cost about \$50 plus another \$75 for the GPS module, and good to about 1ms).

3. Phenomena

There is a huge range of phenomena to observe in the "fast photometry" category, only a few of which have been explored widely by amateurs. In a few areas, amateurs can contribute to the science (e.g., asteroid occultations), while in others, at least at this time, the benefit is in learning how to do the measurements. However, if more people worked this area, it is likely that we would learn how amateurs might contribute to new areas in the science.

Here is a sampling of some of the interesting high-speed photometry measurements (some of which I have done or am planning).

3.1. Lunar Occultations, Grazing and Total

These are fun to watch, and highly organized. David Dunham and others have developed a wonderful network of observers, with extensive website support on suitable targets, recommended methods, a convenient place to send data to be analyzed and combined. A good website to start from is <http://iota.jhuapl.edu/exped.htm> and follow links from there. Equipment may be portable, telescopes in the 4-12 inch range, and observation is usually visual or with video.

3.2. Asteroid Occultations

Because asteroid occultations give direct information on the size and shape of the objects, this field is now being aggressively developed, again by Dunham and friends. Like grazing lunar events, the

event is usually studied by a series of observers spread out over the relatively narrow (20-100 mile) predicted track. Watching a star wink out when crossed by an asteroid would be cool: I've been wiped out by weather 7/7 of my recent attempts. Observation methods are similar to lunar occultations.

3.3. Pulsars

Pulsars rotate at rates from 1ms to about 1 second. But they are usually faint (though the Crab is at 8.5mag), and may be embedded in nebulosity. The photocurves cannot generally be detected directly, but require substantial effort to pull out of the background noise. Note that the Crab at 33ms is well inside the range of atmosphere scintillation effects, and also happens to be 1/2 the 60Hz rate, a potential source of interference.

3.4. Planetary Occultations

Detecting the Saturn ring gaps and ring structure, Uranus rings, inferring atmospheric structure and similar studies can be done as a planet passes in front of a star. The big problem is that the light of the planet tends to overwhelm the fainter star. Some relatively rare events should be observable with amateur equipment, but predictable events are not likely to produce science opportunities for amateurs. But wouldn't it be fun to record the central flash from atmospheric focusing of light a billion miles away!

3.5. Solar variations

The five-minute oscillations in the sun, and variations thereon, are potential experiments. Obviously, getting enough light is not the problem--the tiny size of the effect is the problem.

3.6. Cataclysmic and Irregular Variables

Professionals and amateurs follow these objects, usually looking for relatively slow variations (egg, 60 sec). Because the observations are often of long duration, the data requirements are high.

3.7. Gamma Ray Bursters

Amateurs are doing great work on GRBs, with time resolutions usually in the one-minute range. Most GRBs are faint, so it will be very difficult to have enough signal to do true fast photometry.

3.8. Atmospheric Studies

Stars are a wonderful probe for our own atmosphere: we can use them to learn more about all those

interesting motions of the air that we like to complain about. I will describe work I have done in this area.

3.9. Other Fast Variations in Starlight

There are recurrent claims for observing very transient stellar phenomena, e.g., "XYZ star tripled in brightness for three seconds". Most of us have been "sure" we have seen such events...out of the corners of our eyes. On the other hand, extensive studies have verified very little of this. Unless we know of a good candidate, we are likely never to make a positive observation (at least, one that will stand up to scrutiny).

But some of us have always wondered about why more stars don't produce fast photometric signals. It does seem hard to believe that binaries can be rotating so close and so fast without violent disturbances of the atmosphere that can be observed. While the signals might be small, we know we can take lots of data and then spend computer time searching for signals. While there seem to be few such targets suitable for amateurs, as an example I will report on one of my own investigations in this area.

This list is NOT all inclusive. There are many objects that show fast intensity changes. However, most of the interesting ones are under constant investigation by professionals, where to add to the science requires professional level equipment and expertise. However, there are many bright people out there, and it is very likely that someone in this room will identify some new fast photometry area for pro-am research. And beside, it is a very interesting field!

4. Fun with Photometry

As I mentioned, I have built a 2msec photometer that I have used for several study areas and will describe these to help demonstrate some of what can be done by amateurs. I make no claim to originality in this work, and I am not an expert. But each of us sometime started with our first photocurve, so here goes.

5. Scintillation Studies

We all know that the atmosphere is not uniform, and that there are small regions called cells in the 6 inch size range, having non-uniform temperatures, some 2-10 miles up. The temperature variations cause variations in refractive index that affect seeing. We all know this, but few of us have connected the dots to understand scintillation. The basic mechanism is shown in Figure 2 and summarized below.

- Scintillation is an atmospheric phenomenon. Therefore, it must affect stars of all brightness equally. Bright stars scintillate as much

as faint ones. Of course, faint stars introduce additional noise sources including the shot noise from the sporadic arrival of small numbers of photons, and the risk of being submerged in other noise sources, whether in the detector element, electronics, or extraneous light sources.

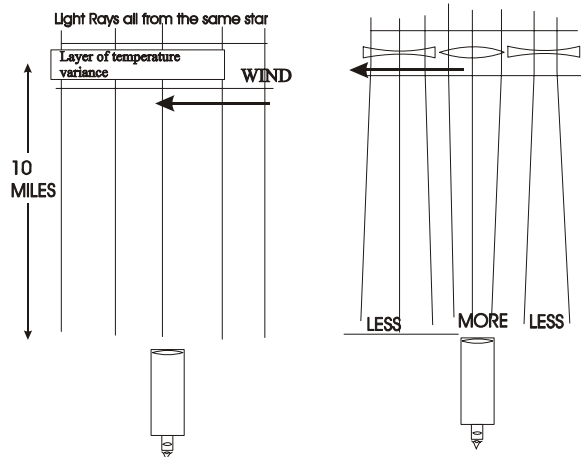


Figure 2. Cause of Scintillation

- The cells have an effective size of about 6 in., and move with the wind at perhaps 100 km/hr (100 ft/sec).
- The distortions in the wavefronts by the over and under focusing caused by the cells produces bright and dim patches of similar sizes at the objective of the scope. This patch of light is moving at 100ft/sec and crosses an amateur scope in about 10 ms.
- As the cell(s) cross the scope objective, more or less light is received and the apparent object brightness varies: this is scintillation
- One can average received brightness over time to measure the "true" average
- Or, one can average over space, i.e., have a bigger scope receiving a larger number of bright and faint cells that all merge at the focal point for a more accurate average intensity
- Or one can take several telescopes, each with photometers, and add the electrical signals together to produce the same improved average (one does not need adaptive optics)

How real is all this? Here are some data that show the effects.

Figure 3 shows three data sets using three apertures on a C11 to simulate different scope sizes. You can see that the bigger the scope, the more scintilla-

tion cells are averaged, the slower the time variation becomes, and the lower its amplitude. Using these data, one can see that detecting a 10% drop in five milliseconds is simply not feasible with a C11-no matter how bright the star!

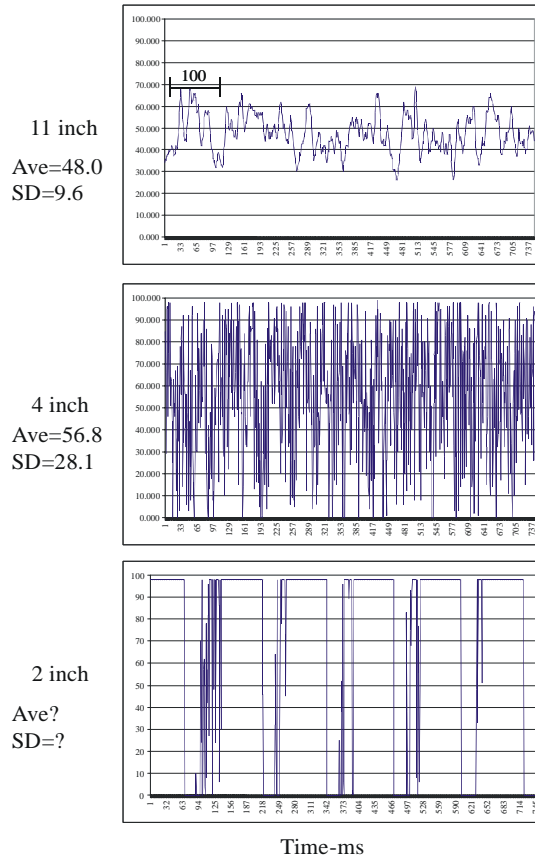


Figure 3. Scintillation with different Scope Sizes

As one examines the trace for the 11 inch scope, one can see that the time structure tends to occur in the 5-20 ms range. That is, there are few 1ms excursions, and there are few times when there is not a major change in 50 ms. One can even see suspicions of pieces of sine waves in the trace!

More quantitatively, one can do a Fourier transformation on the intensity time data to determine the amplitudes of the different frequencies of waves that make up the raw data. Excel will do this on up to 32,000 points, but 20 min of data at 1000 samples per second is a million points. Using Google, I found an inexpensive package that would do this called ScopeDSP (see References) that produced most of the graphs shown here.

In Figure 4, I show an example of Fourier spectra. The top graph shows the Fourier transformation of 20 min. of data similar to that shown in Figure 3(top). The frequencies run from close to zero to 500Hz. After this run, I then shifted the scope off the star, and obtained data leading to the middle spectrum of the background and instrumental noise--note that it is lower at all frequencies. The bottom graph shows the difference, which represents the star minus background, i.e., the spectrum of the scintillation noise. Most of the energy is below 100Hz, which is about how "fast" the cells move across the aperture, but there is substantial apparent energy in the higher frequency bands as well.

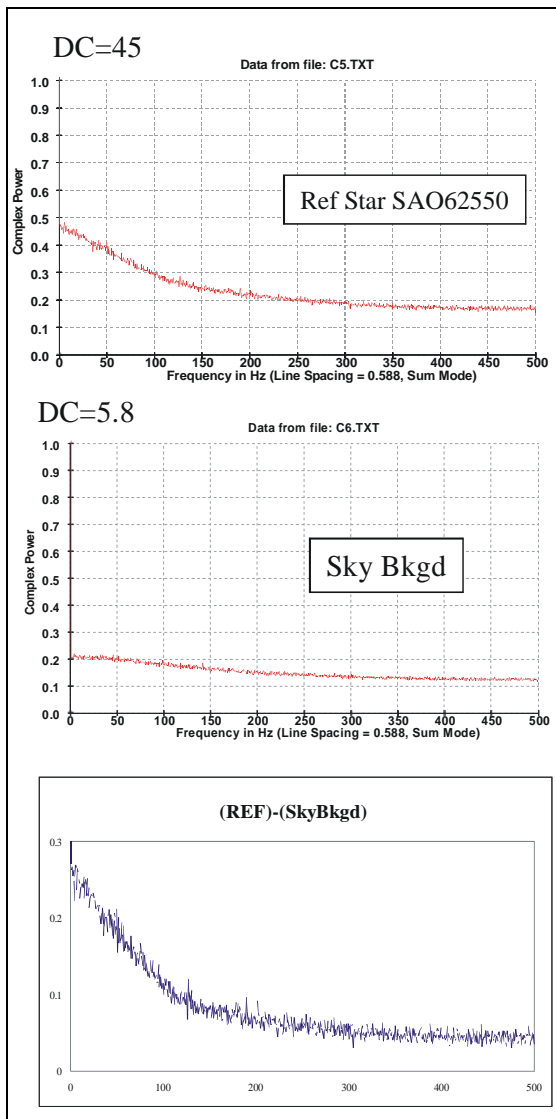


Figure 4. Scintillation Spectrum

6. Eclipsing Binary Study

Years ago, one of our dome customers (my wife and I used to run Technical Innovations with HomeDome and ProDome) mentioned that he was searching for fast signals from stars. He was using a photometer and a tuned amplifier, slowly scanning the amplifier frequency while observing. I didn't have a photometer at that time, so I built a system that would use a video camera signal and measure the brightness of stars in the image in real time (reported as a poster at SAS2000). Thus, the data storage needed was only one digital value every 17ms, or less than 1 MB (not GB) per hour. With this, I could record hours of data, then do a Fourier analysis to calculate what frequency sine waves were buried in the signal. After much debate with the customer, he agreed that mine was the more efficient process.

Although I did some work with the video photometer several years ago, I decided to try again with my new fast photometer. I chose for my current target AW UMa, a close eclipsing binary (surely something must happen there!). Why did I pick this one? It is bright (6.9mag) so I have good signal, it is very high (75deg) in the sky (reduces scintillation), and it has an almost identical (brightness and spectrum) star only 30 a-min away for use as a reference.

At this writing, I have had three good nights (for Maryland) intermixing a total of 8 runs on AW and 4 on the Reference star. Most runs were about ten minutes long, with the mount easily keeping the star in the 1a-min diaphragm during the run. At 1000 samples/sec, there are about 0.5 million data points in each run. While doing these runs with the photometer, I also used a second scope and camera to measure the photocurve of AW, so that I could be sure to sample all the phases with the photometer. In the course of this measurement, I stumbled onto TU UMa, a 9mag RR Lyra type (pulsating star) that seems to show irregularities in the lightcurve - a worthy target, but a bit too faint until I get my 18inch scope into operation!

The resulting twelve Fourier spectra all look similar to Figure 4(top). There was no sign of any narrow (spike) or broad (hump) band frequency in the curves (except an occasional 60Hz spike). Although they appear similar, might there be more subtle systematic differences between AW and the Reference star spectra that show up in relatively narrow frequency bands?

To answer that question, I normalized each curve to its own average value over the range 45-450 Hz. For each curve, I then calculated the ratio of the average over a narrow frequency range (1-3Hz, 3-10Hz, etc) to that normalized value so that I could find the

relative strength of different frequency bands in each run, and then compare them. This result is in Figure 5. Each frequency band has a series of bars, and each bar is the relative strength of that frequency band, in the order I did the runs. The light bars are the AW, the dark are the Reference star.

One would hope to see in some frequency band that all the AW bars were higher (or lower) than the Reference bars: this would indicate some systematic difference between the stars. Alas, it is not so. In the lower three bands, we see that there were definite trends during the evenings in the effects of scintillation, i.e., slow variation in the energy in the scintillation bands 1-100Hz. In the higher frequency bands, there was less variation.

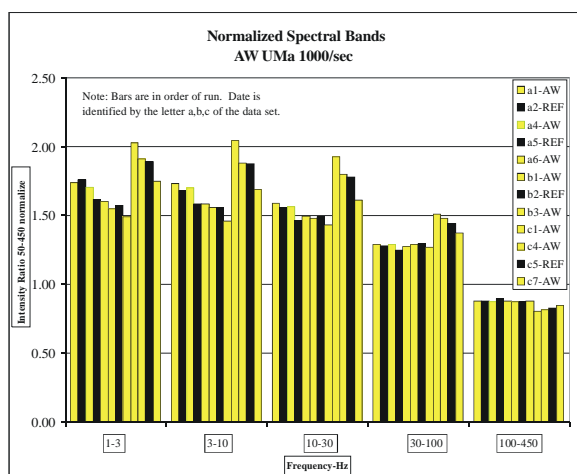


Figure 5. Spectral band strengths

Nowhere in the results are there systematic differences between the shapes of the AW and Reference star frequency spectra. Observing the low frequency bands, it is also clear that atmospheric scintillation changes can easily mask small signals unless there is a very nearby reference star that can be observed simultaneously with identical equipment (which I did not have).

Of course, using these measurements, we can only set a lower limit on a possible signal. From the variation in the data, and by injecting known signals into the data, we can estimate these limits. We could take more data using improved techniques to search for ever smaller effects. I believe there is at least one person in this room who regularly calls for "more data" whenever a question arises! But not for me this time: there are other things I want to do!

7. Conclusion and Future Options

It is clear from this initial effort that it is feasible for amateurs to use high speed photometry, and in

some areas, make contributions to astronomical science. The equipment is reasonable in cost, and at least some of the techniques are well within our capability. Relatively little has been done in this area, so there is an open opportunity to identify and develop new avenues of investigation.

With scintillation being the limiting condition for a large class of interesting measurements, one thinks about bigger scopes! While my new 18in. will make some measurements more feasible, it is not really big enough. One thinks about 36 inch and bigger. Maybe we need to look again at stretching aluminized Mylar on a frame and sucking a vacuum. Hmm. That would take care of the spatial averaging, but can we correct the aberrations well enough to get the light into a reasonable size detector with a reasonable size (egg., 1 a-min) diaphragm? And then can we steer it well enough? We might think that flexure would be a tough problem so even a guide scope may not be enough, but we would have plenty of light so we should be able to pick off light from the central cone for a guidance system. Hey, if someone wants to build it, I'll offer my field!

8. Acknowledgements

I would like to acknowledge my debt to our former customer David Wright for his stimulation in starting this work many years ago. I am also thankful for the book *High Speed Astronomical Photometry* by another Brian Warner (i.e., not our own MPO Brian Warner) which so clearly lays out much of the science. And of course, to IAPPP-West and now SAS for the wonderful venue to share these ideas with other astronomers.

9. References

Warner, B. (1988) *High Speed Astronomical Photography*. Cambridge University Press.

ScopeDSP software for Fourier transformation. Iowegian International Corporation. www.iowegian.com

KIWI OSD. This device imprints GPS time onto video. Available from PFD Systems at <http://www.pfdsystems.com/>.

Go to www.Menkescientific.com for information on the photometer and other devices mentioned.