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Photometer System

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Description

This paper describes construction and testing of a photometer for fast (roughly 1mS) photometry. The photometer was tested with both normal PIN and Avalanche diodes, both on the bench and with stars. The photometer outputs a varying DC signal, so there is a also an analog to digital converter to allow logging the data into a simple text file. The converter can also be used with a small gps sensor to provide UTC timing to 1 ms for the data.

Photometer Design

The goal was to design a simple, inexpensive photometer that could be built by an amateur, but that would yield good scientific data. The usual detector is a simple PIN diode, but the unit has also worked with a variety of photosensitive detectors including cheap phototransistors and small solar cells.

The photometer unit has gone through several iterations, with the current version shown in Fig. 1& 2 and the schematic shown at the end of the paper.

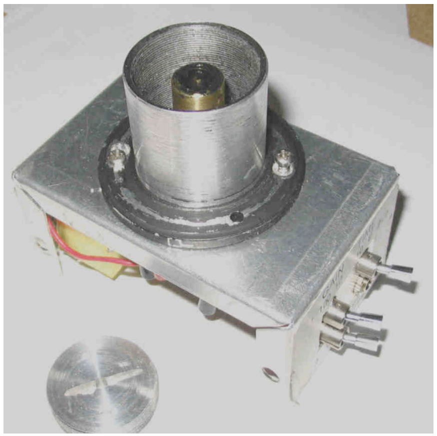


Fig 1 Photometer

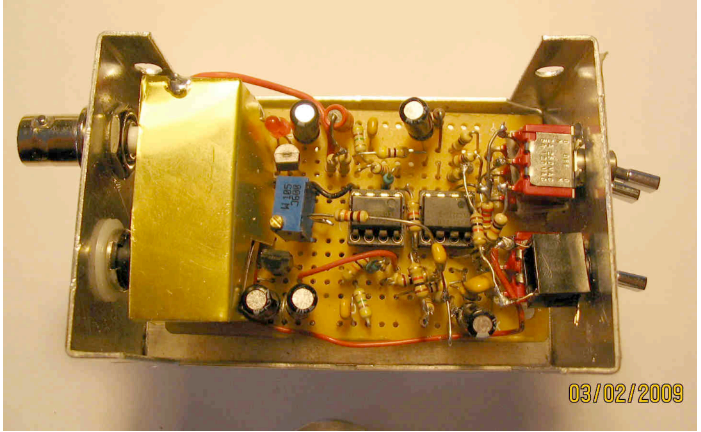


Fig 2 Photometer Circuit

The physical circuit is built into a simple minibox and is hand wired using printed circuit breadboard and common connectors.

The photodiode is mounted on a miniature 3 conductor plug, so it can be interchanged easily (Fig. 3). Because of the extreme sensitivity to electric fields, it is mounted in a nosepiece (similar to an eyepiece). The photodiode is encased in a brass cylinder, and an aluminum diaphragm is screwed into the end of the nosepiece. This design provides very good shielding, and allows use in a non-grounded system without susceptibility to external noise. The diode case can also be grounded unless the diode case is connected internally (as noted below, this design uses two amplifiers to balance noise, so neither side of the diode can be grounded).

Fig 3 Sensor

The circuit uses two input amplifiers A1 and A2 to increase the common mode rejection and to decrease the sensitivity to 60 cycle induced signals. They are wired in standard current amplifier form, with the feedback assuring that the voltage across the diode and relative to ground is virtually zero, thus reducing all leakage terms to a minimum. The output of the two amplifiers are combined into a difference amplifier A3 with a gain of x100. The signal at this point is approximately 100v/nA of photocurrent. The output of A3 feeds a voltage amplifier having selectable feedback resistors yielding gains of x1/x10/x100. A second switch selects the input resistor, yielding gains of x1/x2/x5. A third switch provides selected integration capacitors, yielding time constants of approximately 2mS/10mS/100mS. The inherent rise time of the amplifier system is set primarily by A1/A2 and is approximately 2mS. The 2mS time constant is always applied, and serves to reduce higher frequency noise present in the A1/A2 output.

The zero offset control is necessary not only to balance the circuit to provide zero output when there is no light entering the sensor, but to allow easy offset of background light from the sky, nearby stars, moonlight, etc.

Roughly, at gain setting of x100, an output of 1v corresponds to about 10^-13 A at the input.

The amplifiers are inexpensive low input current amplifiers (about $2 ea), having a bias current of about 1 pA (10^-12 A). The only exotic item are the 1 Gohm resistors used in the feedback, but these are available from Mouser and other electronic suppliers. As can be seen in the figure, shielding is necessary in the minibox, due to the voltage inverter being used to convert +12v to -12v for the amplifiers. This converter could be moved to the ADC/GPS box to provide more circuit space and to eliminate the need for shielding. Otherwise, there are no particular special "tricks" needed for this circuit other than the usual careful attention to ground paths.

During testing of the avalanche diode, the circuit was modified to allow application of approximately 150V to the diode and the zero offset was modifed, as shown on the schematic.

Testing

The initial testing employed a pulsed LED shining onto the sensor. While this method worked well for measuring the response time of the photometer (about 2mS with the 1Gohm resistors), testing the linearity of the photometer by reducing current in the LED showed that the LED itself was apparently non-linear, ie., the output light was not proportional to the current. Therefor, a constant incandescent source was constructed (Fig. 4) having a 1 mm spot, that could be moved in a tube from an inch to approximately 48 inches from the sensor. Thus, the linearity of the system could be checked using the 1/R^2 relationship--which in fact was verified.

Test Results

As noted, the amplifier system had a response time of about 2mS, and showed no non-linearity or pathological behaviors. Although most tests were done using the Hamamatsu 1 mm^2 detector, the other detectors all worked almost as well with respect to sensitivity and noise. Reducing the feedback resistor would speed up the response time, but at a commensurate reduction in the low light sensitivity.

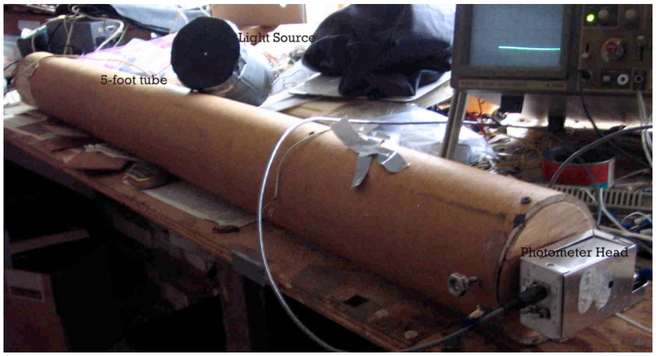


Fig 4 Test Rig

The major limitation on the sensitivity is the inherent noise of the amplifier and sensor diode. This noise current has general characteristic as shown in Fig. 5, and a specification of XxfA/Hz^1/2 but is specified at 1KHz. Thus, the "low frequency" noise is 10-100 times worse than that specified for the higher frequencies. This noise current behaves just as does the signal. The wider the bandwidth of the signal data, the more the noise (very narrow bandwidth has relatively lower noise).

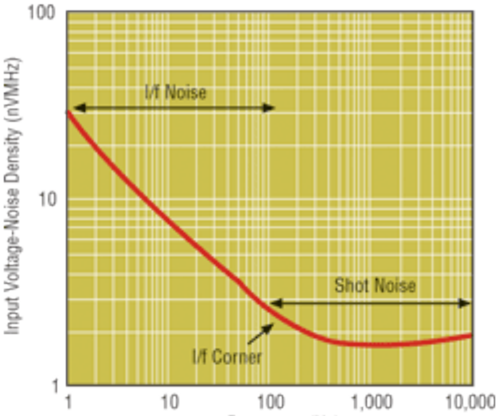


Fig 5 Noise Spectrum

Thus, how and whether one filters the signal (or later applies some form of high or low frequency averaging) depends on the signal regime one is after. If watching for very slow signals (eg, slower than 0.1 sec), then one would smooth the signal to eliminate those signal components faster than 0.1 sec. However, if one is seeking only high frequencies (eg, faster than 5 mS), then one would apply a filter to eliminate low frequencies. While the circuit has high frequency filters built in, either high or low frequency filters can be applied to digital data in a spreadsheet.

What other factors affect how faint a star one can measure? Obviously, a larger telescope will gather more light. But in addition, one must consider how the sensor is used.

A typical scope such as a C11 at f/6.3 has about 1 a-s per 9u pixel of a typical CCD chip. Thus, if the seeing is about 3 a-s, and if the image is well focused on the detector, the starlight will occupy perhaps a 6x6 set of pixels, or about .05x.05 mm of the chip. However, the silicon sensor I used is 1 mm square, so the image only occupies about 1/400 of the chip area. Thus, if the sky background is 400x fainter than the star, the contribution to the sensor current from the sky background will roughly equal that from the star. The background signal will introduce an offset in the detected signal that is difficult to distinguish from the star (the user must move the star off the detector without moving another star onto it). The background signal will also contribute to scintillation and shot noise.

It is obviously desirable to have a sensor that is very small, eg., .05x.05mm. However, then the challenge is to "find the star"--how does the user center the star on this tiny sensor? It is hard enough to do so on a 1mm sensor that subtends perhaps 1 a-m--doing this on a 10-20a-s chip would be very hard. And once the star is on the sensor, how does one keep it there as the telescope drive moves, atmospheric refraction occurs, etc? Again, it is hard enough to do so (with most amateur equipment) on a 1 a-m sensor!

So, there is a compromise between sensor size and sensitivity for a given scope. It turns out that for the reference system (C11), a 1mm sensor is not a bad choice. The background light can certainly cause a bothersome offset; however, the noise associated with a faint star is dominated by the amplifier noise and scintillation, not by the background light. For this system, I found a lower limit of about 9.5 mag star using approximately 10mS averaging. Depending on the target and the precision and speed involved, one could go fainter, or not so faint.

How could this limit be reduced (other than by a bigger telescope)?

One way would be to use a chopper that would chop the light beam at, say, 1 KHz. Then one would build a simpler AC amplifier, tuned to approximately 1 KHz. One can extract the dc component of the signal by using a phase comparison to the chopper. Because the noise level of the amplifier is lower at high frequencies, there is thus a reduction of noise in the answer. And, of course, one can tune the amplifier and smooth even the high frequency noise to gain even more signal to noise ratio.

Chopping the light source at a high rate (>100 Hz) requires a very significant effort. However, the payoff in lowered noise is very attractive.

Another method is to employ a more sensitive detector, ie., one that creates more signal current for a given light level. Most pin diodes have rather similar sensitivity. However, the "avalanche" diode offers multiplications of up to x100. Many of these are expensive ($100), but even worse, they require a large bias voltage (around 200v) which complicates the system. The large bias voltage produces a large leakage current, of order

1 nA. This introduces its own noise, and introduces a dc offset that must be balanced out to high precision (the signal currents are in the 10pA range). Even worse, the avalanche multiplication depends not only on the applied voltage (not too bad), but very strongly on the temperature. Thus, either the detector has to be temperature controlled, or the temperature must be measured and the bias voltage programmed correctly to compensate, so as to hold the multiplication fairly constant.

These are all major complexities. I did set up and try this, with very disappointing results. While it did "work", for this application, I could see little benefit. This was primarily because the noise from the diode is of order 1000x that of the original amplifier. That is, we gain perhaps x100 in signal, but the noise is worse by x1000--we have lost ground (so far as faint objects are concerned). Avalanche diodes have their uses, but this appears not to be a good application for them.

Another method of noise reduction is to cool the detector and amplifier. This is easier said than done. The space limitations are hard to deal with, and both the detector and amplifier may require cooling. Use of a thermoelectric cooler generally implies substantial electric fields and currents. If these are close to the detector or amplifier, they must be highly regulated or noise will be induced in the photometer. To test whether this was worth pursuing, I built a thermo electric cooler that could cool the photometer amplifier and sensor by about 25F. Running from about 65F down to 38F and back up, the low frequency noise (ie, 60Hz and below) appeared to change not at all (certainly less than 30%). This is consistent with null results that I had obtained several years ago with dry ice while testing similar circuits. Based on this test, at least for flicker noise, temperature reduction does not appear to be a very effective solution.

Finally, it should be noted that one can often use filtering to suppress the noise. For example, in measuring slow (many seconds) changes in brightness, one can take the data and simply average it either electronically or in data manipulation. On the other hand, if observing at the high frequency end (eg, faster than 10ms), one can simply develop a rolling average (over say 100ms) and subtract that from the fast data, thus largely removing the low frequency variations.

Analog to Digital Converter and GPS Timer

The output of the photometer is a 0-5v signal. The user will likely want a visual indication of the amplitude, and will want to feed it into a computer for later analysis. It is also very desirable in may applications to mark the time of the data. The device described her is a simplified version of a device I called an occultometer, which was designed to allow 1 mS UTC marking of both electronic and manually generated data.

The ADC is shown in Fig 6 and the schematic is shown at the end of this paper. Construction is simple, and again, is done by hand wiring on a pc breadboard in a minibox.

The signal passes into the ADC unit through a DC amplifier that can be set for a gain with an internal control from x1-x20. The output is sent to a small 150uA meter for display, and to the PIC microcontroller for the actual analog to digital (ADC) conversion. Also connected to the controller is an optional gps "pod", as well as several setting switches. The output of the PIC is a digital RS232 signal stream that sends the measurement in clear text to a PC or other device (or an LCD screen).

The switches tell the PIC how often to report the measurement of the input signal. Choices are 1mS, 10mS, 100mS, 1S. In all settings, the PIC actually measures the signal at 1mS intervals, and for intervals of 10mS or longer the PIC will average the measurements, then report the averages at the interval selected. At the 1mS reporting rate, the PIC transmits at 56K a value from 00-98 (ie, 98 is full scale), while at the slower settings, the transmission is 000-254 at 9600 Baud (254 full scale).

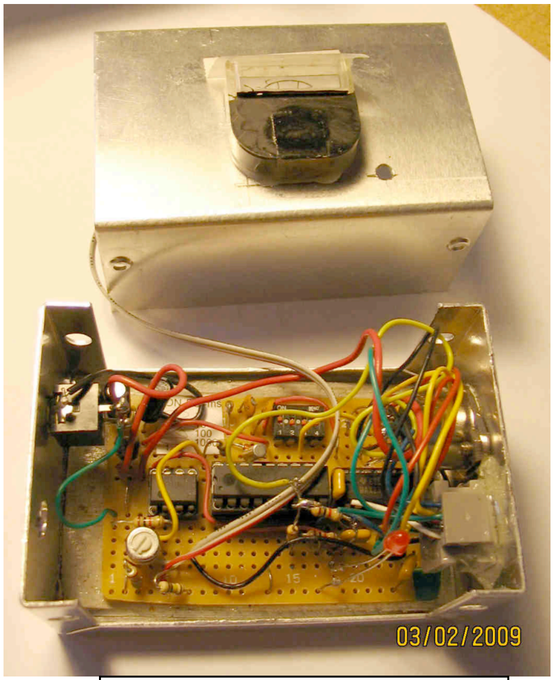


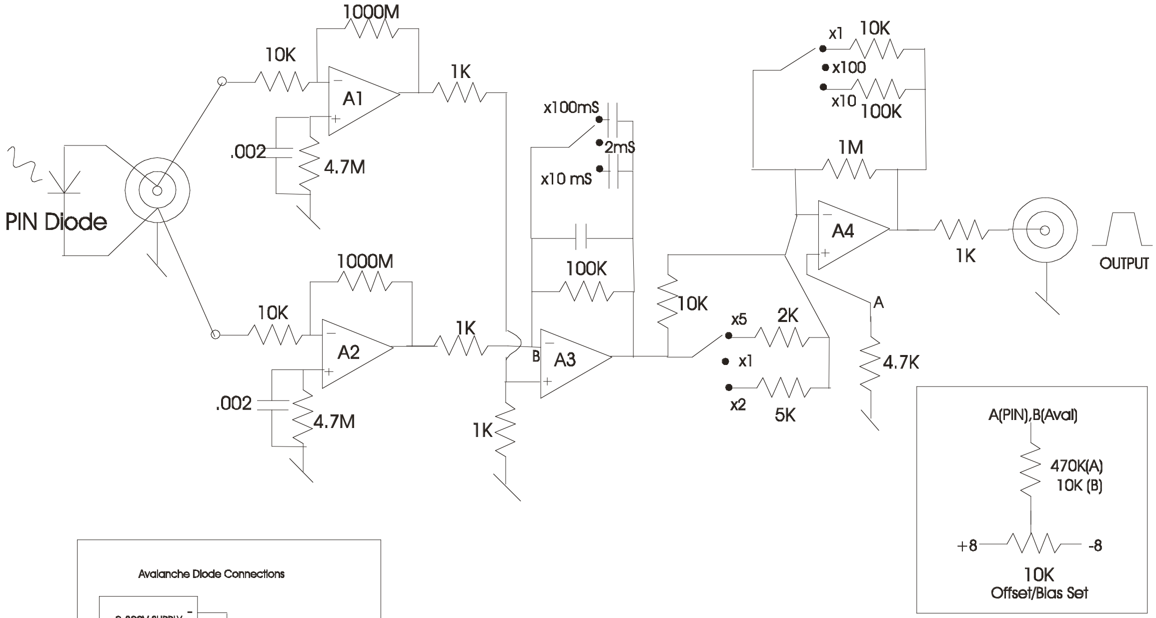
Fig 6 ADC/GPS Timer

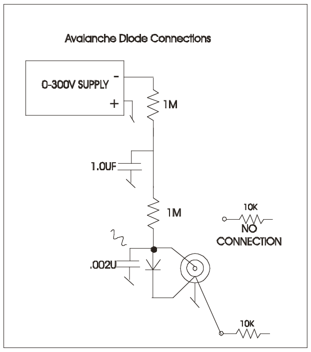
If the gps pod is attached when the ADC is powered up, the PIC will detect the gps, and will wait for the gps to acquire its satellites. When ready, the PIC will then transmit the date and time to the pc (at 9600) and will then begin measuring. At every UTC "second" signal, the transmitted measurement reading will be forced to be 99 or 255 so that the seconds after the start of the run can be counted. If the gps is not connected, or is unplugged later, the ADC will run at the selected rate, but the time will drift away from precisely correct (usually about 1:10000). If there is no gps, the seconds marks are not imposed on the data.

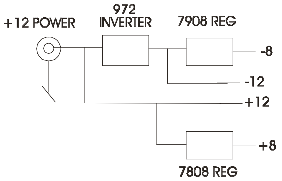
The data into the pc can be captured by any communication program. The data can be saved, then pasted into an excel spreadsheet or other analysis program for graphing fourier analysis, or other work.

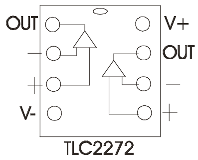
I also have provided a simple graphic utility that will capture the data as well as display it in real time.

Photometer1 Schematic









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ADC-GPS Converter Schematic