Technical Bases for Modern Data Reduction on Photographic Plates

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Abstract

In a simplified way, the principles of CCDs and photographic plates as astronomical detectors are compared. Since there are large archives of photographic plates which will remain valuable sources of astronomical data, it is worthwhile to consider modern tools for digitization of photographic plates. One of the most accurate machines is the PDS microdensitometer, except that its photometric accuracy is limited by the originally employed analogue logarithmic amplifier, which leads to severe distortions at density gradients. A new, accurate amplifier/converter is described. It has successfully worked for several years at the PDS 2020 GM microdensitometers at Münster University and other machines; since September 2000 it has also been installed at the PDS 1010 microdensitometer of the Sofia Sky Archive Data Center (SSADC).

Introduction

Why do we still want do use the old–fashioned photographic plate? The photographic plate in astronomy is now more than 100 years old. CCDs are widely available for about 20 years. Still, most of the observations ever obtained in astronomy are stored on photographic plates. The Sofia Sky Archive Data Center (SSADC) counted until now 2 096 146 photographic plates obtained at 269 different telescopes and published them in a catalogue [1].

Large time bases are very important in astronomy, e.g. in astrometry. If an unexpected event occurs in the sky, we have the chance to look, what was there before this event; a prominent example is SN 1987A. Since large CCD–arrays are still rare and very expensive, for wide field work photography is still an alternative, although vanishing at an increasing rate.

To get good data from photographic plates, we need modern tools. It is very common to digitize a plate and reduce it with the help of computers. During the 70s and 80s, a lot of different scanning machines appeared in astronomy. An old, but very precise device is the PDS microdensitometer. One of these machines, a PDS 1010 microdensitometer, now is at the SSADC.

In this paper, I want to describe the machine and how to use the photographic plate in astronomy.

1 How does a CCD work?

Photographic plates and CCDs work very differently. Many young astronomers grew up with CCDs and never handled or processed a photographic plate. To understand the difference between CCDs and photographic plates, I start to explain schematically how a CCD works.

The CCD pixel works like a photon sensor with a "bucket". In the bucket we store electrons. When a photon hits the sensor, it creates an electron and a hole in the semiconductor crystal. The electron drifts to the bucket and falls into it. Each photon produces an electron. After the exposure of the CCD we just need to count the electrons in the bucket and then we know the number of photon events. In reality, the probability of getting an electron after a photon event is very nearly 100% in some wavelength range, but can be much less depending on the energy of the photon, also the properties of the chip, and the energy gap of the photon sensor. However, there is always a proportionality between the numbers of photons and electrons.

If one puts several photon sensors and buckets in one row, one gets a chain of buckets. To read out a row of a CCD, we measure the charge of the rightmost bucket and store it into a computer. Then, we fill the electrons of the next bucket to the left into its neighbour to the right. This has to be done in the complete row. Then again the charge in the rightmost bucket will be measured. In this way, we can read out a complete row pixel by pixel. In reality, of course, we can loose some electrons while transporting the charge. But in modern CCDs this effect is negligibly small.

If there are many rows in a CCD, the charge will be transported to the neighbouring row until the charge is in the row, which can be read out in the way described above.

2 How does a photographic plate work?

A photographic plate consists of crystals of silver halide (AgX). The halide (X) may be chlorine (Cl), bromine (Br) or iodine (I). In most cases AgBr is used, sometimes mixed with AgCl and/or AgI. These crystals may have very different shapes and sizes, depending on the properties of the photographic plate. The crystals are imbedded in gelatine. Everything together we call the emulsion. The crystals are randomly distributed throughout the emulsion. There are no pixels like in a CCD.

In Figure 1 we see silver halide crystals of an emulsion observed with a scanning electron microscope. It is an old Ilford emulsion (HP5) with many different sizes and shapes of crystals. In modern emulsions, like IIIaJ from Kodak (Fig. 2), the sizes and shapes of the crystals do not vary so much. This is more useful for work in astronomy.

If a photon with sufficient energy hits the crystal, the energy reduces an Ag^+ to a silver atom. We need an aggregate of at least 3 silver atoms to mark the whole crystal for development. The probability to get a crystal marked for development is about 0.1% to 3%, depending on the sensitivity of the emulsion.

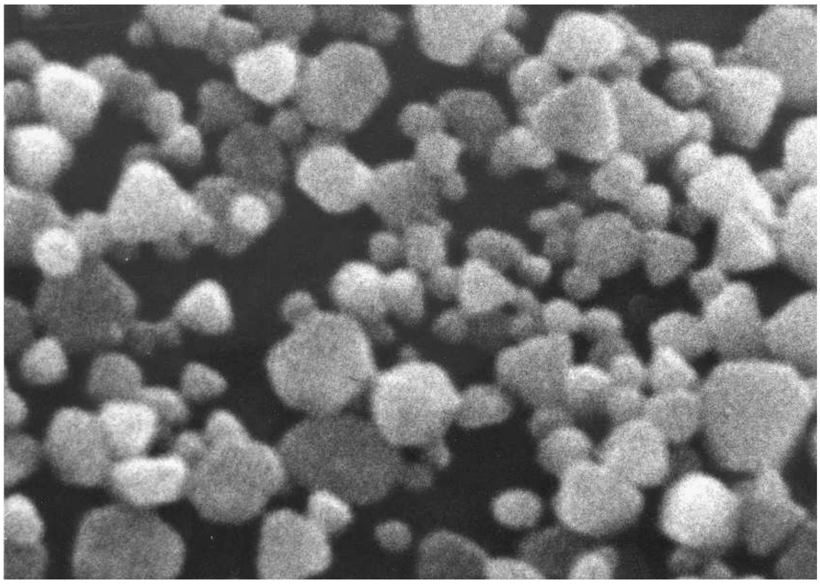

Figure 1: Undeveloped crystals of an Ilford HP5 emulsion. These have very different sizes and shapes. The enlargement is about 5300 times.

After the exposure, there are only a few silver atoms in the emulsion, too few to constitute a recognizable image. To get a visible image, we have to amplify the number of silver atoms. With some chemicals we can reduce all the silver in a crystal. These particular chemicals reduce only exposed crystals. They use the silver aggregate created by the exposure to lock onto the crystal.

After developing, we have both developed and undeveloped crystals in the emulsion. To get an image, which is stable over years, we have to remove the undeveloped crystals. For this purpose we use the fixing bath, which is able to transform the silver halides into a water soluble complex, which is then washed out. In the end, several of the original crystals in a very small region have been transformed into one black Ag–grain. The size of a silver grain can be influenced by the size and shape of the silver halide in the emulsion, by the kind of developer and by the development time.

A single grain does not contain much information about the image. We know only, that there were at least three photon events at that position. A single crystal is only digital, 1=exposed or 0=unexposed. To get the information of the number of photons in an area, we have to count the number of silver grains in that area. The resulting value we for now call grayness. Later, we will introduce the photographic density as a more useful quantity.

The integration area should be large compared to the size of a single silver grain, in order to overcome the noise introduced by the random distribution of the sizes and positions of the grains. Thus, the resolution of the photographic emulsion is limited by the noise due to the graininess. Nevertheless, the effective resolution of some astronomical emulsions (like Kodak IIIa–J) is several times larger than that of a typical CCD.

Another very big difference to the CCD is the response of the whole process

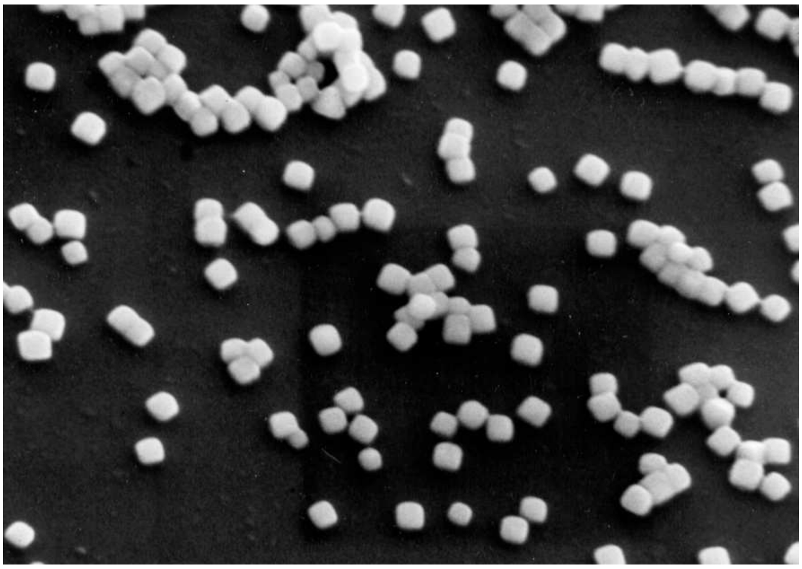

Figure 2: Undeveloped crystals of a Kodak IIIa–J emulsion. These are designed cubic and have nearly the same size. The enlargement is about 5300 times.

to the infalling light. In a first approximation, the grayness is proportional to the logarithm of the number of the photons. In a later section the response function of the photographic emulsion will be discussed in detail.

3 Digitizing photographic plates

3.1 Principle

The photographic plate is put on a stage and illuminated from one side. On the other side, a detector measures the light, which passes through the plate. The ratio of the intensities of the transmitted light I to the irradiated light I_0 is called transmission$T = \frac{I}{I_0}$. In order to register the transmission as a function of position the stage with the plate is moved with respect to the light source allowing a systematical scanning of the plate.

If a photomultiplier tube is used as a detector, which translates a stream of photons into a proportional electrical current, a dynamic range of typically 1:100 000 is obtained. This will create some problems while digitizing the transmission. Even very precise analogue–to–digital converters (ADCs) with 16 bits have only 65 536 digitizing steps. The minimum step is 0.000 015 in transmission. 90% of the digitizing steps of an ADC are in the range of transmission 1 to 0.1, about 9% are in the range 0.1 to 0.01 and there are only a few digitizing steps in the range 0.000 1 to 0.000 01. However, as we will see later, there is still useful information on a photographic plate at these low transmissions.

We have to compress the values in the higher transmission range and expand them in the lower transmission range. For this, a well suited function is the logarithm. We define the density D as: $D = -\lg T = \lg \frac{I_0}{I}$. After this

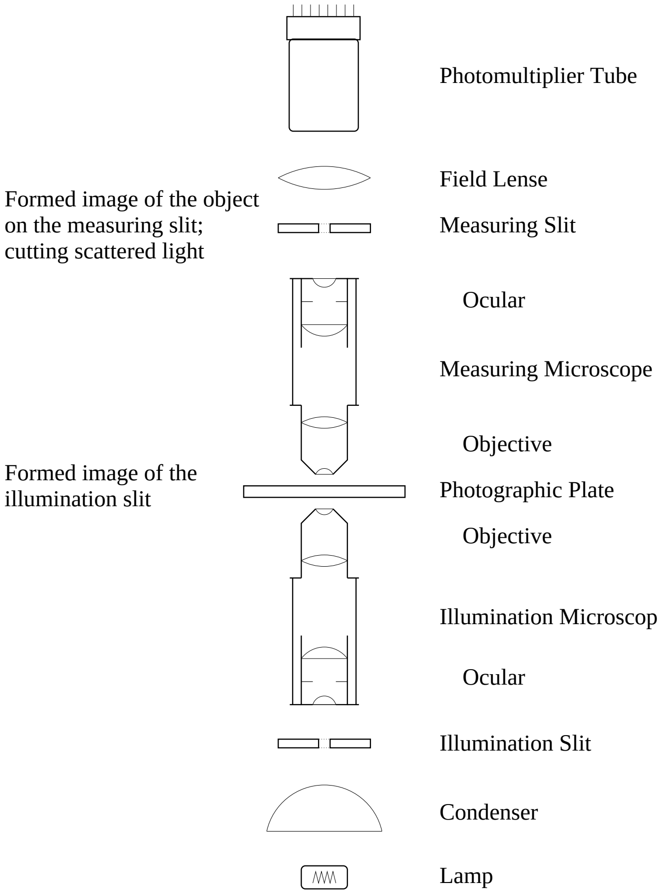

Figure 3: Simplified diagram of the optics of a PDS microdensitometer

transformation, 20% of the digitizing steps occur in the transmission range 1 to 0.1 and also 20% in the range 0.000 1 to 0.000 01. Thus, we also can resolve details in very dense regions, e.g. in images of star clusters and galaxy cores.

To measure the transmission or density of a photographic plate accurately, we need a well defined area over which to sum the number of silver grains. A PDS microdensitometer has two slits to define this area. One slit limits the area of the illumination; only that part of the plate is illuminated, where we want to measure the transmission/density. The other slit limits the field of the photomultiplier tube; it cuts scattered light. In Figure 3 we see a simplified diagram of the optics of a PDS microdensitometer.

3.2 Analogue logarithmic amplifiers

As we have learned from the previous section, first the logarithm of the output current from the photomultiplier tube should be obtained, and then the signal should be digitized.

The standard method to get the logarithm of an analogue signal is to use an operational amplifier and a diode in feedback (see Fig. 4). The output voltage of

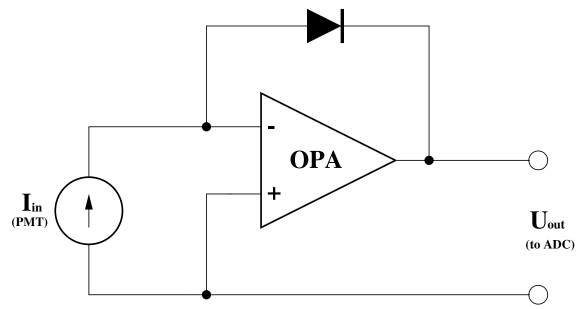

Figure 4: Schematic of an analogue logarithmic amplifier with a diode.

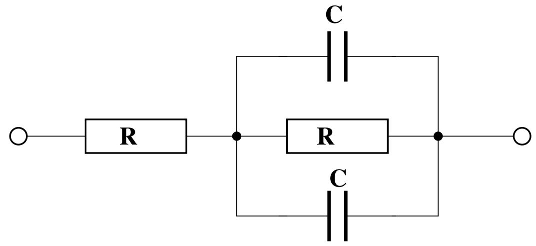

Figure 5: Equivalent circuit of a real diode.

this amplifier is proportional to the logarithm of the input current $U_{\rm out} \propto \lg I_{\rm in}$ (Now I means current).

This, however, is only valid in the static case. If this amplifier is used with dynamically changing input current, we have to take into account that a real diode has also capacitors and resistors (see Fig. 5), which constitute a lowpass filter, whose cutoff frequency depends on the input current: the lower the input current the lower the cutoff frequency.

Instead of the diode it is better to use a transistor. Then, it is possible to use the logarithmic amplifier over 9 decades. However, also with a transistor we have the same dynamical problem. We can minimize this effect, but not avoid it.

In Figure 6 we see the quasi–statically digitized signal while scanning over a sharp edge. A slit width of $50\,\mu$m in X was used with a stepsize (i.e. distance between subsequent pixels) of $1\,\mu$m. After each motion of the sharp edge, the amplifier was allowed to settle to the new input signal for several seconds before registering the density. The zero point of the position is set, when the sharp edge and the edge of the measuring slit coincide. This curve is taken as the reference response of the sharp edge.

In Figure 7 we see a scan over a sharp edge, moving it with a constant speed of 25 mm/s, which is about half the maximum speed of the microdensitometer at SSADC. All other parameters are the same as in Figure 6. Two scans were made. In one scan (b $\rightarrow$ d) the edge moved from bright to dark. This means, the detector was under full light and then gradually eclipsed by the edge. The second scan (d $\rightarrow$ b), the edge moved from dark to bright. As we can see,

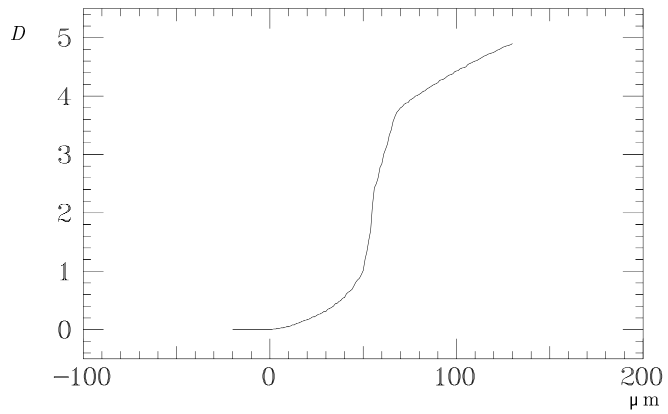

Figure 6: Scan over a sharp edge with the analogue logarithmic amplifier in the quasi–static mode.

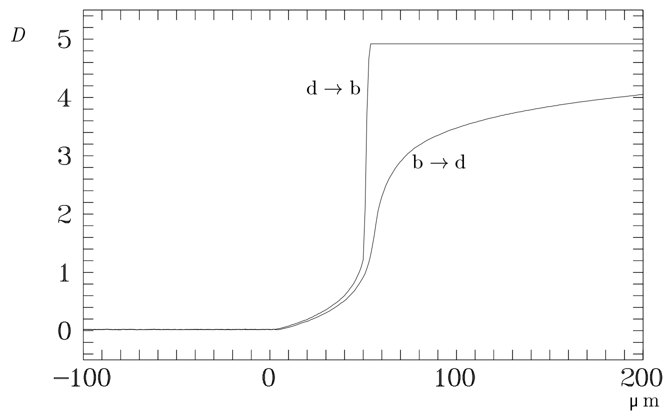

Figure 7: Scans with the analogue logarithmic amplifier over a sharp edge moving with a speed of 25 mm/s in 2 opposite directions.

both curves are different and none fits the reference. Even if we use the slowest speed of the microdensitometer, we get some distortions while scanning over large density gradients. These distortions cannot be corrected by any later mathematical process.

3.3 The new logarithmic amplifier/converter

For a faster logarithmic amplifier a completely new concept is needed. If we use analogue amplifiers in the linear mode, they are much faster and the cutoff frequency is independent of the input signal.

The new logarithmic amplifier/converter uses the principle of adaptive amplification. The schematic can be seen in Figure 8. The amplification is switched in such a way to provide the optimal input voltage range of the ADC. The amplification is switched in 5 steps between 1 and 10 000. If we know the factor of amplification and the digitized voltage, we can use a table to look up the real

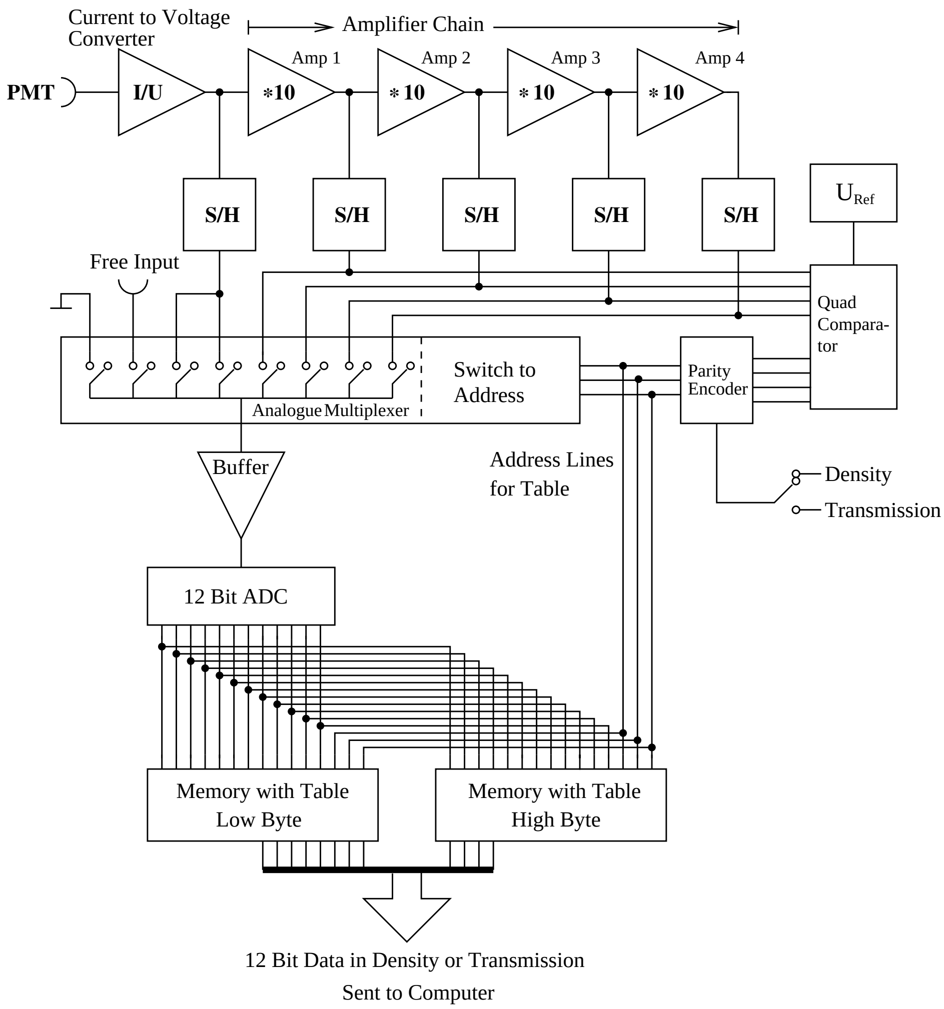

Figure 8: Schematic of the new logarithmic amplifier/converter

density value.

In practice, it is necessary to use operational amplifiers with very low noise and very low temperature drift. Nowadays, such amplifiers are widely available.

In Figure 9 we see scans over a sharp edge using the new amplifier/converter. The parameters are the same as in the scan which gave Figure 7. Again, two scans are shown, one from bright to dark and one from dark to bright. Both curves are nearly identical. Only the noise at high density is different (photon noise). Both curves also fit the reference curve.

Now it is possible to obtain scans with no distortions even at maximum speed.

3.4 Photon Noise

With the new amplifier/converter one can see something, which was invisible with the original amplifier: the photon noise. Photons are no continuous stream,

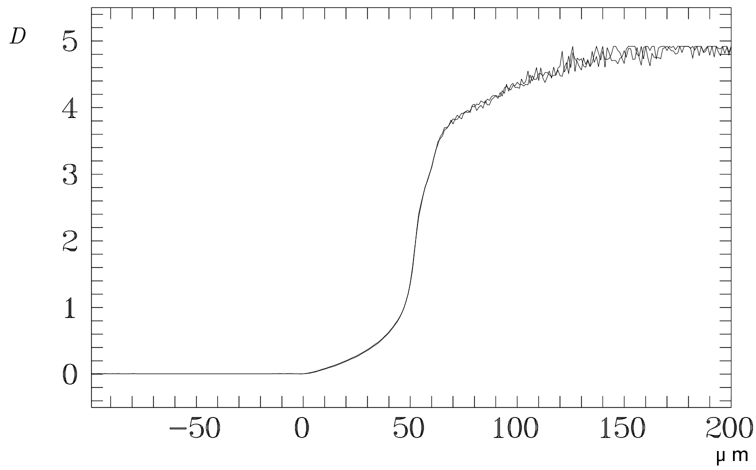

Figure 9: Scans with the new amplifier/converter over a sharp edge moving with a speed of 25 mm/s. Note that two scans are shown in which the edge moved in opposite directions (cf. Fig. 7 for identical scans with the analogue logarithmic amplifier). Both curves are indistinguishable from the reference curve (see Fig. 6).

they are statistical events. If the density of the photographic plate is very high, only a few photons will be transmitted. Then, the current is so low, that the lowpass filter inherent in the original amplifier filters the photon noise. Note that this filter effect is the same which causes the systematic distortions seen in Figure 7.

The amplifier/converter is fast enough to measure single photon events at high densities causing high amplitude noise. To avoid this, an analogue integration is used. The integration time is chosen according to the maximum mechanical speed of the microdensitometer. The amplifier/converter of the PDS 1010 microdensitometer in Sofia uses an integration time of about 30 μs. Bigger and faster machines, like the PDS 2020 GM microdensitometer used in Münster [2] need shorter integration times of about 10 μs.

The photon noise depends on the density of the photographic plate: the higher the density, the higher the noise. It also depends on the size of the measuring slit; with smaller slits the photon noise increases. The density at which the photon noise becomes dominant depends both on the instrumentation via the lamp output and the photographic grain noise. Therefore, multiple scans over very high density regions may be useful.

The measurements of the photon noise, which are shown in Figure 10, were obtained with a PDS 2020 GM microdensitometer in Münster. Seven different constant densities were realized with neutral filters. The figure shows the standard deviation of the density vs. the density. Since the standard deviation is plotted logarithmically, we expect a linear curve. Any additional noise source would create a deviation from the linear curve. As we can see in the figure, the most significant noise source is photon noise. At the same time it demonstrates that the amplifier/converter does not introduce any significant perturbations.

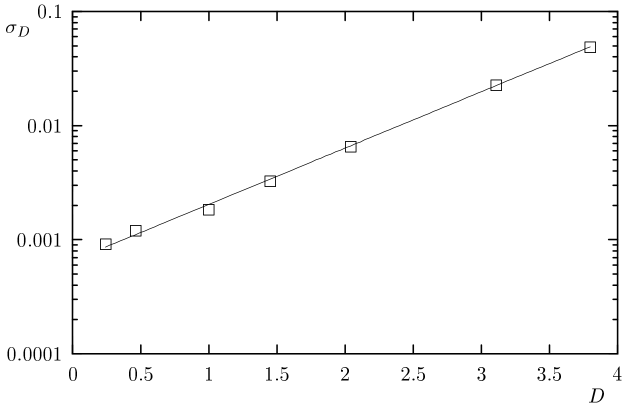

Figure 10: Standard deviation of density versus density with the new amplifier/converter. Note that $\lg \sigma_D \propto D$ is expected, if the only noise source is photon noise.

For the PDS 1010 microdensitometer in Sofia, less photon noise is expected, because the integration time is much longer, but the shape of the curve should be the same.

4 Photometry from photographic plates

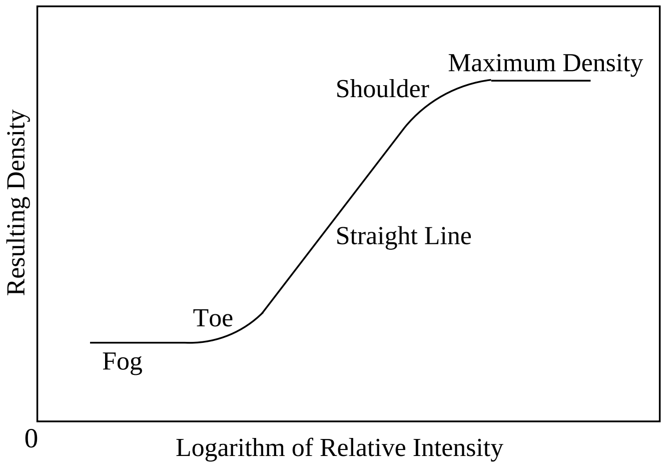

Figure 11: A schematic characteristic curve of a photographic plate.

To get intensities from a photographic plate, it is necessary to know its transfer function. This is the relation between the irradiated intensity and the resulting density. It is called the characteristic curve. In Figure 11 we see a schematic characteristic curve. It depends on the kind of emulsion, the details of the developing and fixing processes, the storage of the plate before and after the process and many other parameters.

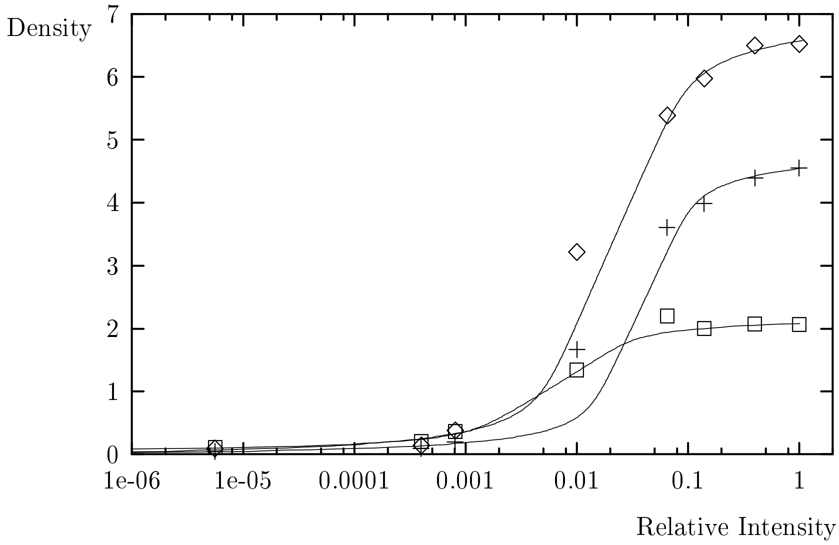

Figure 12: Characteristic curves of a Kodak IIIa–J emulsion after using different developers: Dokumol ◇; Rodinal +; Ultrafin □

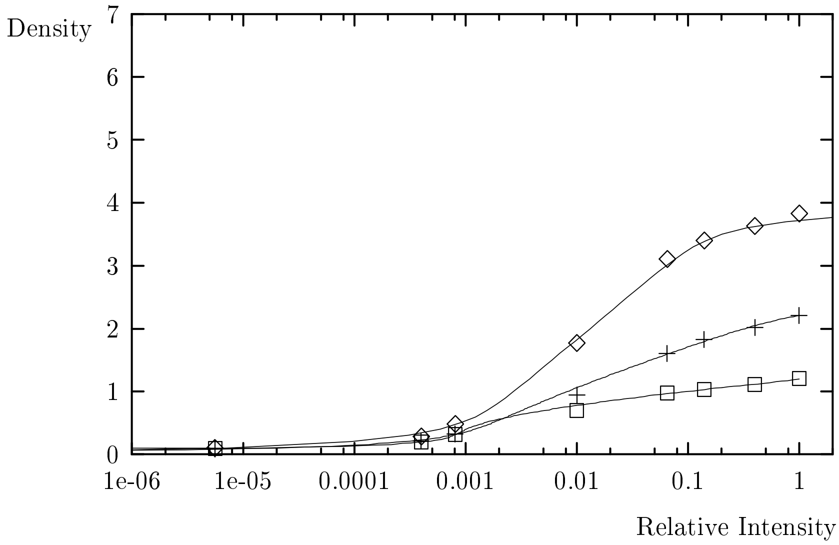

Figure 13: Characteristic curves of a Kodak IIa–O emulsion after using different developers: Dokumol ◇; Rodinal +; Ultrafin □

In Figure 12 we see three characteristic curves of IIIa–J plates, each developed with another developer (Dokumol 1:10, Rodinal 1:25, Ultrafin Liquid 1:20). In Figure 13 we see characteristic curves of Kodak IIa–O plates with the same developers as the IIIa–J plates. Obviously, they are very different. To be certain to have all parameter of the image and of the calibration similar, it is necessary to treat both, the image and the calibration, as much as possible in the same way.

To obtain such calibrations it is common to expose the photographic plate with different, well–defined intensities. For the calibrations of Figures 12 and 13, 8 spots were used, whose densities were measured with a PDS microdensitometer.

The characteristic curve can be parameterized by the Honeycutt–Chaldu formula [3] in the representation given by Tsubaki & Engvold [4].

$$\lg E = A_1 D + A_2 \ln (e^{BD^{C_1}} - 1) + A_3 e^{BD^{C_2}} + A_4 \tag{1}$$

E is the exposure ($E = I \cdot t$) and D the density above the fog. There are seven parameters which have to be optimized. This formula is able to reproduce the shapes of all characteristic curves, but it is not based on any physical understanding of the photographic process.

As one can see, the calibration of a photographic plate is much more complicated than the calibration of CCD–images and it is less accurate. As long as the densities of the pixels from the background to the peak are not too far from the linear part of the characteristic curve, after the calibration the same procedures used for CCD–images may be used to obtain magnitudes of astronomical objects. However, due to the uncertainties of the intensity calibration and the usually high grain noise, photographic magnitudes are rarely better than about 0.1 mag.

References

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[4] Tsubaki, T., Engvold, O., 1975: AAS Photo–Bulletin 9, 17