(Re)building a CdS meter

Marek Lewandowski

April 27, 2010

Revision history

0.1 initial release, basics

0.2 mercury cell type meter described in rough outline, calculation example provided

0.2b fixed some punctuation issues

Contents

1 Some background and basic physics

1.1 LDR — the ideal case

CdS cell, also known als LDR (light dependant resistor), or photoresistor, is a chunk of semiconductor in a transparent casing. As long, as it's kept in total darkness, there are no free electrons in it, so no current can flow, no matter what voltage is applied. But as soon, as surface of CdS cell is exposed to light, photons start to break electrons free. If voltage is applied, these electrons will travel across the semiconductor and thus form an electrical current. The magnitude of this current is proportional to light intensity (so how many photons per second fall on this piece of semiconductor) and to voltage applied (higher voltage leads to electrons moving faster). The latter leads to the conclusion, that CdS cell acts as a resistor (current proportional to voltage = Ohm's law).

It is easier to talk about CdS cells in terms of *conductance* G instead of *resistance* R. Conductance is reciprocal of resistance, and is expressed in siemens (S),

$$1\,S = \frac{1}{\Omega}$$

Since the flowing current is directly proportional to voltage *and* light intensity, one might write:

$$I = U \cdot G = U \cdot k \cdot E$$

where the conductance is

$$G = \frac{I}{U} = k \cdot E$$

and k is a material constant.

1.2 LDR — the more real case

In reality, even in the deepest darkness there will be some free electrons in the chunk of semiconductor. First, it isn't dead stone cold, so some electrons are free due to thermal reasons, second, it isn't ideal pure semiconductor to start with. So every photoresistor has its *dark resistance*, i.e. the maximum resistance it can have in the darkest darkness. This sets a limit for low-light application.

Also, under very strong illumination the photoresistor should have almost zero resistance. But there's a limit on how many electrons can be freed, the leads have resistance, the electrodes too, so the conductance will increase with illumination only till some point before capping. This is usually less of a limit in photographic use, as the necessary illumination levels are usually way above experienced in a light meter.

In a real semiconductor, electrons don't "live" indefinitely long, so not all of them can reach "the other shore". Effectively, this leads to a bit different equation for conductance:

$$G = k \cdot E^{\gamma}$$

If $\gamma = 1$, this leads to the previous equation. Commercially available LDRs have $\gamma = 0.5 \ldots 0.99$.

1.3 A word on linearity

CdS cells can be made *very* linear. Analog gauges can be made pretty linear. Resistors are by nature almost perfectly linear. The problem is, we aren't looking for *linear* in photometry. We need *logarithmic*. We speak of "linear" when it follows the common

EV scale, forgetting, that each EV stop isn't *adding* some constant amount of light, it's *doubling* the amount of light.

For an evenly distributed scale of 15 EV, like Pentax Spotmeter has, the lowest step, from 1 to 2, is worth about 3 lux. The last step, from 14 to 15 is worth 40'000 lux. All steps are equally wide on the scale. This is anything except *linear*.

Hence, all efforts in designing an exposure meter go towards approximation of $\log_2 E$ on the meter's scale (!).

1.4 Meter movements

Let's consider the available technology at the time our mechanical cameras were designed. The primary "display" unit was a galvanometer, a moving coil instrument, that reacted to *current* passing through it and indicated the magnitude of it by deflection of a needle.

Since current is sensed using a coil suspended in magnetic field, the more windings the coil has, the more sensitive the device is going to be. More windings require use of a thinner wire (space isn't infinite), altogether leading to a noticeable series resistance of the more sensitive devices, often in the range of 2-3 kΩ for FSR[1] of 5-10 μA.

Other factors influencing movement sensitivity are magnetic field strength (which can be influenced only to a limited extent, as maximum available field strenght is defined by magnetic material used) and spring tension. The lower the spring tension is, the lower is the force necessary to deflect it, so the higher the movement sensitivity. Still, the springs have to be strong enough to reliably overcome bearing friction, otherwise needle deflection will be erratic and the meter — imprecise, which sets the limit on how weak the springs can be.

This leaves the aforementioned number of movement's coil windings as the last "free" factor that can influence sensitivity.

While one can use a galvanometer as a voltmeter — applying some voltage to the coil will result in current flow depending on coil resistance — it is important to remember, that it is *currrent* that deflects the needle. Since coil wire resistance depends on temperature, meter design should — as far as possible — not depend on coil resistance to be constant. E.g. for a voltmeter, one would rather choose a more sensitive movement and put a resistor in series in it, to limit influence of coil resistance.

1.5 Reference value

Any meter, of whatever kind, measuring about anything in whatever units, needs some kind of a reference. When you measure a bookshelf, you compare its dimensions to a length of measuring tape. You assume, that this tape is accurate and did not change its length since its scale was printed on it. This measuring tape is your reference, your measurement is only as accurate, as the tape is. If the tape is made of rubber, you will not be able to measure accurately.

Similarly, a meter needs something constant to compare the measured value to, and means to do the actual comparison. Galvanometer, discussed in the previous paragraph, uses spring tension and magnetic field as reference for measuring current. Since springs and magnets don't age much, galvanometers can stay accurate over many decades of service.

Simple meters, these with selenium cells, used a galvanometer as both, reference and indicator. There was no other reference necessary, as selenium cells deliver photocurrent proportional to illumination, and galvanometers can measure current directly[2].

[1] full scale range, i.e. value resulting in "max" display

[2] Actually, the trick is a bit more complicated, but let's leave it for now.

CdS cell based meters need some second reference, as LDR vary their conductance, and conductance is a *factor* between voltage and current. Basically there are three ways out, and a multitude of their combinations:

1. Use a voltage reference. Since $I = G \cdot U$, having an accurate U, G depending on light intensity in a known fashion, and being able to measure I, we should be able to compute E.

2. Use a resistive reference set. If we can procure a set of known resistances and somehow compare them to the momentary LDR resistance, we could determine scene illumination.

3. Use a mechanical reference. By attenuating light falling on LDR by a set of e.g. ND filters or a sort of mechanical aperture, we can bring the resistance to a predetermined level. If this predetermined level corresponds to 5 EV, and we have 6-step ND filter on the cell, then the illumination level must be 11 ev.

2 Mercury cell type meters.

2.1 General theory

The first solution is to look for a voltage reference. Since CdS meters started way before microelectronics age, putting a small voltage regulator chip or a cheap silicone zener diode wasn't an option. They simply did not exist. This led to chemical references, and one such is the long popular mercury battery. Since this type of battery has very flat discharge curve, the battery voltage can be taken as reference directly.

The simpliest design of a meter using a CdS cell and a mercury battery is just a series connection of the battery, LDR and a galvanometer. Since we know, that

$$G = k \cdot E^{\gamma}$$

automatically

$$I_{galvano} = U_{batt} \cdot k \cdot E^{\gamma}$$

Simple, huh?

The problem only, we wanted the scale to show EV, not lux. In other words, the scale isn't very logarithmic yet.

But the course of action that brought us till here, will help us further: simply connecting a resistor in series with LDR (and the galvanometer) will shape the conductance curve over some range much towards the desired logarithmic form. Actually, the coil resistance of these more sensitive galvanometers can be high enough to fulfill the function of this series resistance (almost) alone[3].

Let's consider:

$$G = \frac{1}{R} = \frac{1}{R_{galvano} + R_{series} + R_{LDR}}$$

One can easily calculate it, or experiment with formulas in a spreadsheet of choice, so I will only provide the solution: Meter will be nicely logarithmic around the exposure point, for which

$$R_{galvano} + R_{series} = R_{LDR}$$

[3] Even so, you will have to add some way of trimming it — e.g. a series trimm pot — as LDRs are a crapshot — resistance for given illumination can vary a lot within one batch

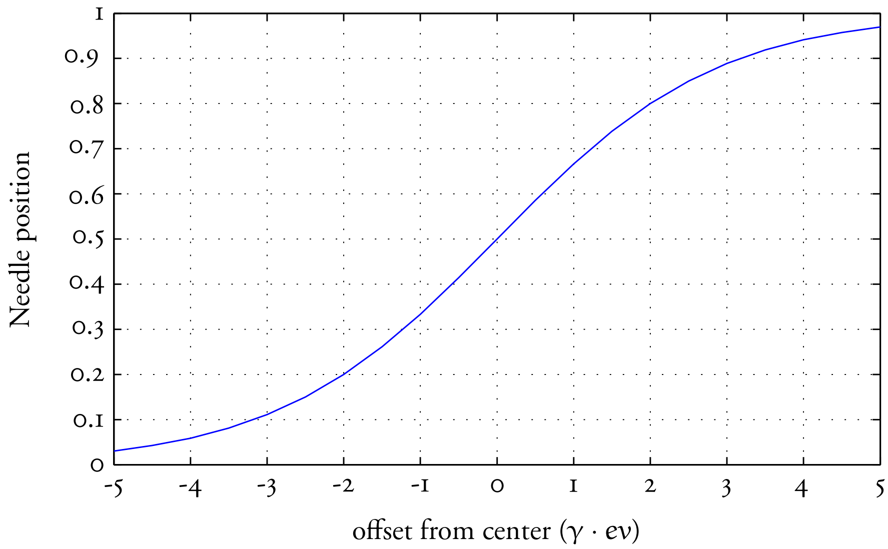

Figure 1: Plot of the light dependant part of equation 1

Since there's no reason to consider resistance of circuit elements around LDR separately at this point, let's make our lives easier, by calling them all together R_s, for now:

$$R_s = R_{galvano} + R_{series}$$

Knowing, that:

$$R_{LDR} = \frac{1}{k \cdot E^{-\gamma}} = k^{-1} \cdot E^{-\gamma}$$

and assuming our scale midpoint will be at E_o, we get:

$$G = \frac{1}{R_s + R_{LDR}} = \frac{1}{k^{-1} \cdot (E_o^{-\gamma} + E^{-\gamma})}$$

E is still a linear value, in lux. But our scale should be in EV, centered about E_o. We could substitute E with:

$$E = E_o \cdot 2^{ev}$$

where ev is offset from scale center (positive or negative) in EV. Hence:

$$G = \frac{k}{E_o^{-\gamma} + (E_o \cdot 2^{ev})^{-\gamma}} = \underbrace{\frac{k}{E_o^{-\gamma}}}_{\text{constant}} \cdot \underbrace{\frac{1}{1 + 2^{-\gamma \cdot ev}}}_{\text{light dependent}} \tag{1}$$

There are two conlcusions that we have to draw from the last equation:

First, the variable part isn't linear, but as long as $(ev \cdot \gamma)$ is small, it is *close* to linear.

Second, the constant part has no parameters we could influence. More on why this is important later.

Exactly how small does $(ev \cdot \gamma)$ need to be, for the meter scale to stay linear?

First, have a look at Figure 1. This is a plot of (effectively) the needle deflection vs. $\gamma \cdot ev$. Let's assume, that we'd take the best fitting straight line, and see, how much does it deviate from the characteristic curve at the worst point. The result can be seen in table

1. The first column is the normalized metering range $(\gamma \cdot \Delta ev)$ — effectively the factor, by which LDR resistance will change across the metering range, or how wide a chunk from Figure 1 we cut from the middle. The second column shows, by how much will the effective scale deviate from an ideal straight.

$(ev \cdot \gamma)$ range	Δ ev (worst point)
-2..+2	0.1 ev
-2.5..2.5	0.15 ev
-3..3	0.3 ev
-4..4	0.5 ev
-5..5	0.85 ev

Table 1: Worst deviation of best-fit straight line over normalized metering range

In plain words: the further away R_{LDR} will drift from the centerpoint, the further will the resulting curve stray from ideal. This is not really a problem, we don't have to print our meter's scale with EV marks at even intervals, but since the characteristic curve gets more and more 'S'-shaped with increasing metering range, the ends of scale will get more and more crowded.

Exactly how wide the exposure metering range will be, depends on the γ constant. The lower the gamma, the less will LDR's resistance change per EV stop, hence the wider the "linear" metering range will be (see table 1). Gamma of 1 will result in a pretty linear scale over about 6 stops, whereas gamma of 0.6 will yield close to 10 stops. If you can live with a meter dial that has numbers squished somewhat close to both ends, you can get 8-10 stops out of gamma=1 and more than 12 stops at gamma=0.6. It does not make sense to aim at wider metering range, you have to pack the readout onto a galvanometer dial. Since most galvanometers are accurate to 0.02 of their scale length, putting more than 50 steps on it (and 12EV in 1/3 stops is 48 steps) makes little sense.

2.2 Example calculation — handheld meter

Why would we want to build a meter? There are plenty cheap ones available second hand…

The answer is simple: we don't. But we might need to *rebuild* one rather than tweak settings blindly in hope it would work better. Yet, not to suggest solutions, I will demonstrate, how to build a meter from scratch.

2.2.1 Galvanometer

The greater sensitivity, the better, at least as far as meters go. Since it is unlikely you would want to buy a new one for the purpose of building a meter, I will assume that you have one already, but you just don't know anything about it yet. Whether it is from (or in) an otherwise faulty light meter, or from a multimeter, does not make any difference at this point.

The usual range of moving coil instruments' sensitivity sits between about 3 μA and 1 mA for full needle deflection.

How to test it?

Take a fresh AA battery and a few resistors: 150 kΩ (corresponds to ca. 10 μA from 1.5 V), 27 kΩ (50 μA), 10 kΩ (100 μA), 2.7 kΩ (500 μA) and finally 1 kΩ (1mA).

You might have noticed, that the currents in brackets apparently deviate from Ohm's law, that's because the given resistor values take already the expected coil resistance into consideration. 10-50 μA meter is expected to have something like 2-6 kΩ coil, while 1 mA will measure only about 600 Ω.

You start with the largest resistor and work your way down till you get full (or near full) needle deflection. Galvanometers often have "round" numbers as their FSR, i.e. 10, 50, 25 of whatever unit, but don't take it for granted. It is not important to know the absolutely *exact* FSR value at this point, because the meter will need to be trimmed at the end anyway, or, worst case, you might find it impossible to use this given galvanometer in combination with your LDR cell at all. It's okay to make an educated guess by reading "it's 5/8th of the scale at 50 μA so full scale will be close to 80 μA".

If the galvanometer sat in a light meter before, it will be most likely on the more sensitive end (5-50 μA). If you try to adapt a gauge from a multimeter, you can usually roughly guess the galvanometer sensitivity, it will be around the lowest DC current measuring range. Unfortunately, many simple meters have relatively insensitive gauges. This is also the case for my cheap $5 analog chinese multimeter, its lowest range is 500 μA DC. I will use this multimeter as galvanometer in this example (on 500 μA setting its leads are connected directly to the movement coil).

The second parameter we need to know about our instrument is the coil resistance. To find it, any ordinary multimeter that can measure resistance in the 500 Ω-10 kΩ range will do.

For further reference I will call the current needed to deflect galvanometer needle to 100% "I_{Gmax}" and the galvanometer coil resistance "R_G".

For my galvanometer:

$$R_G = 650\,\Omega$$

$$I_{Gmax} = 500\,\mu A = 0.5 \cdot 10^{-3}\,A$$

2.2.2 The photocell — the LDR

If you try to rebuild an existing meter, then you most likely have a working cell in it already. It is rather rare, that a CdS cell would go bad.

If you are looking for a new cell, then try to get one with as low γ, as possible, since it will give you more measuring range.

How to test it?

First of all, you have to have the cell assembled in the meter. If you are trying to build one, see section "So where's the rub?". Measuring anything about a CdS cell while it's still on your table won't do any good.

For a reflected light meter: Unless you have some reference light source, you will have to find surfaces with various levels of illuminance. A white wall in a sunny spot will give you anything in the range of EV15 to 17, same wall in shade will be about 2 stops darker, an inside wall in an apartment will read EV8-12 depending on how big your windows are and what time it is. With a bit of patience you will be able to collect some data about your CdS cell and housing assembly.

Things are somewhat more complicated for an incident light meter, but if you take several measurements for several places with different illumination sources and angles you will have a rough set of data to work with too.

You need to keep in mind, that although in theory it is enough to know two points on the CdS curve to find k and γ, in reality you need to take at least one reading for each EV stop along the intended scale and then try to best-fit the two parameters. Note, that there are LDRs types out there, that have really non-linear characteristic curves, especially in the low-light range (the resistance rises faster than it "should" when light levels get low).

Data for my test-cell are listed in table 2. Since I shoot mainly ASA100 material, this metering range is more than enough for hand-held photography.

EV	Scene illumination	Measured R	Best-fit straight R	Example exp.
15.0 ev	88474 lux	100 Ω	107 Ω	$^1/_{125}$ s, f : 16
14.0 ev	44237 lux	150 Ω	167 Ω	$^1/_{125}$ s, f : 11
13.3 ev	27231 lux	270 Ω	229 Ω	$^1/_{125}$ s, f : 8
12.0 ev	11059 lux	420 Ω	412 Ω	$^1/_{60}$ s, f : 8
11.0 ev	5530 lux	540 Ω	646 Ω	$^1/_{60}$ s, f : 5.6
10.0 ev	2765 lux	1190 Ω	1014 Ω	$^1/_{30}$ s, f : 5.6
9.0 ev	1382 lux	1650 Ω	1591 Ω	$^1/_{15}$ s, f : 5.6
8.0 ev	691 lux	2340 Ω	2496 Ω	$^1/_{15}$ s, f : 4
7.0 ev	346 lux	3320 Ω	3917 Ω	$^1/_8$ s, f : 4

$$k = 175\,\text{k}\Omega \quad \gamma = 0.6$$

Table 2: My test CdS cell data in incident light meter assy

I have collected data for 8 ev range. The CdS cell has $\gamma = 0.6$, so:

$$(ev \cdot \gamma) = 0.6 \cdot 8 = 4.8 = -2.4 \ldots 2.4\,\text{ev}$$

Table 1 shows, that for a range of −2.5..2.5 ev one should expect non-linearity error of less than 0.15 ev, provided I center my scale around middle of my dataset base (so about EV11). That's perfect.

2.2.3 Resistors and trimm-pots

Now it's time to get our 2+2 solved. From the short introduction provided in section 2 it is known, that for best result, at scale center $R_s = R_{LDR}$. This leads to

$$R_s = R_{LDR}|_{EV11} \approx 645\,\Omega$$

Note: you don't need to worry about galvanometer range, if you put this point at scale center. In brightest light, when LDR drops its resistance to zero, your meter will hit... 100%. In the total darkness it will show 0. This, however, means, that in normal use there will be some scale unused at each end.

Assuming we use an SR44 battery (one or more) to power our meter, current flowing at this time will be:

$$I_m = \frac{1.55\,\text{V}}{R_s + R_{LDR}} = \frac{1.55\,\text{V}}{1280\,\Omega} = 1.2\,\text{mA}$$

This is much too much for our galvanometer. It has $I_{Gmax} = 500\,\mu\text{A}$, so at half scale it should get only 250 μA. Part of the current will have to bypass the galvanometer. This means connecting a parallel resistor — a shunt. We need to bypass

$$\frac{250\,\mu\text{A}}{1.2\,\text{mA}} = 20.6\%$$

of the current, so

$$\frac{R_P}{R_G} = \frac{20.6}{100 - 20.6} = 0.26 \Rightarrow R_P = 0.26 \cdot R_G = 169\,\Omega$$

Since this calculation is made based on experimental data that is inherently inaccurate, we want this parameter to be adjustable. Hence, I will take a 330 Ω trimm-pot instead of a fixed resistor.

Okay, now our galvanometer with its bypass will show "50%" when 1.2 mA flow through it. The effective resistance is, however, about:

$$R'_G = R_G \parallel R_P = \frac{650 \cdot 169\,\Omega^2}{650\,\Omega + 169\,\Omega} \approx 135\,\Omega$$

We just calculated, that for the scale to be linear, R_s connected in series with LDR hast to be about 645 Ω. This means connecting an additional resistor in series, as mentioned at the beginning of this section. It needs to be:

$$R_{series} = 645\,\Omega - 135\,\Omega = 510\,\Omega$$

Again, this value is based on experimental data, so we want this trimmable. A 1 kΩ trimm-pot will do.

The final circuit looks like this:

1. from battery ⊕ pole to LDR
2. from LDR to 1 kΩ pot
3. from 1 kΩ pot to parallel: galvanometer and 330 Ω pot
4. from the other joint of parallel: galvanometer, and 330 Ω pot, through a power switch, to battery ⊖ pole.

When adjusting the meter, the series pot is the slope, and the parallel one — offset (don't take these names too seriously).

2.2.4 The scale

One has to keep in mind, that the calculations made in previous point will lead to scale close to most symmetrical and most linear possible, but it will not utilize full galvanometer range. Although you can't make the scale start at zero, you can stretch it so, that 15 ev (or whatever your max is) is at 100%.

To do so, repeat previous calculation, but take the "max" as reference, instead of mid-point, i.e:

$$I_m|_{15ev} = \frac{1.55\,V}{R_s + R_{LDR|_{15ev}}} = \frac{1.55\,V}{640 + 100\,\Omega} = 2.07\,mA$$

since $I_G = 500\,\mu A$:

$$R_P : R_G = 500 : 1570 \Rightarrow R_P = \frac{R_G}{3.1} \approx 210\,\Omega$$

The effective resistance is now:

$$R'_G = R_G \parallel R_P = \frac{650 \cdot 210\,\Omega^2}{650\,\Omega + 210\,\Omega} \approx 160\,\Omega$$

thus making a series resistance of

$$R_{series} = 645\,\Omega - 160\,\Omega = 485\,\Omega$$

ev	right-shifted scale	centered scale
17.0 ev	110%	93%
16.0 ev	106%	90%
15.0 ev	101%	85%
14.0 ev	93%	79%
13.3 ev	87%	73%
12.0 ev	72%	61%
11.0 ev	59%	50%
10.0 ev	46%	39%
9.0 ev	34%	29%
8.0 ev	24%	20%
7.0 ev	17%	14%
6.0 ev	11%	9%
5.0 ev	7%	6%
4.0 ev	5%	4%
3.0 ev	3%	3%

Table 3: Scale marks' positions for centered and right-shifted scales

Which scale you will choose, is up to you. The centered version will allow for extending scale past design extremes symmetrically, and has the advantage, that even in brightest light meter movement will not exceed the "max" mark. The right-adjusted scale will make better use of your galvanometer movement range, but the gain is only slight. In my example case listed above you could test both options, trimmpots allow for enough adjustment.

Table 3 shows, where the scale marks will fall in each case (referenced to FSR). As you can see, although the steps get pretty small when you move away from the center, if we give up evenly spaced marks on the scale, the meter could be useful over a wider illumination range — about 7–16 ev.

Figure 2: Gossen Lunasix — note the straight scale

2.2.5 Expanding scale — geometric tricks

An observant reader might have noticed, that many light meters don't use an arc-shaped scale like multimeters do (for those slightly less observant — or just not familiar with all meter makes — see figure 2). While it might appear to be purely an aesthetic choice, it isn't.

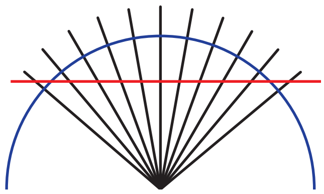

Figure 3: Creative use of tan α, or how to make meter scale easier to read.

Galvanometer needle deflection is proportional to current. Say, we take my galvanometer from the last example. It has FSR of 500 μA and the needle travels close to 100° between zero and max[4]. If I increased the current flowing through my galvanometer 50 μA at a time and each time drew a line on the dial face, I would end up with a fan of eleven equally spaced lines meeting at the needle pivot point (compare Figure 3, black lines). If I draw a circular scale, an arc with the center where the needle bearing is, my "needle marks" will divide this arc in equal parts (Figure 3, blue line).

However, if instead of taking an arc I'd take a straight, horizontal line, my "ticks" would be further apart at scale ends, and closer together around the center (Figure 3, red line). Now think the other way around: If I made my "ticks" evenly spaced on my straight line, the needle would have less angular travel tick-to-tick at the beginning and at the end of the scale, than around center. If you refer to table 3, you will recall, that our meter's non-linearity increases towards scale ends crowding the EV stops there. These two things balance each other, leading to a straight scale with more even spacing (see Figure 4).

Note, that using this trick makes only sense, if the meter's movement is accurate enough.

2.3 So where's the rub?

It might seem, that all this hocus-pocus is rather trivial, and making a reasonably-working handheld light meter is no rocket science. While it is true, that the innards hardly earn the adjective "electronic", making a meter work well isn't that easy. The first challenge lies in making the CdS cell get *only* the light we *want to* measure, then comes making the meter robust and easy for everyday use, and finally, implementing a bit wider than 10-stops measuring range.

2.3.1 Getting the light there

A bare cell will "see" in a rather wide angle closing in on 180° (albeit not equally good in all directions). Photographed scene seldom encompasses full half-sphere, and so general purpose reflected-light meters are expected to see in a roughly similar angle to a camera

[4] This is unusually long travel, common movements sweep 60-90° zero-max.

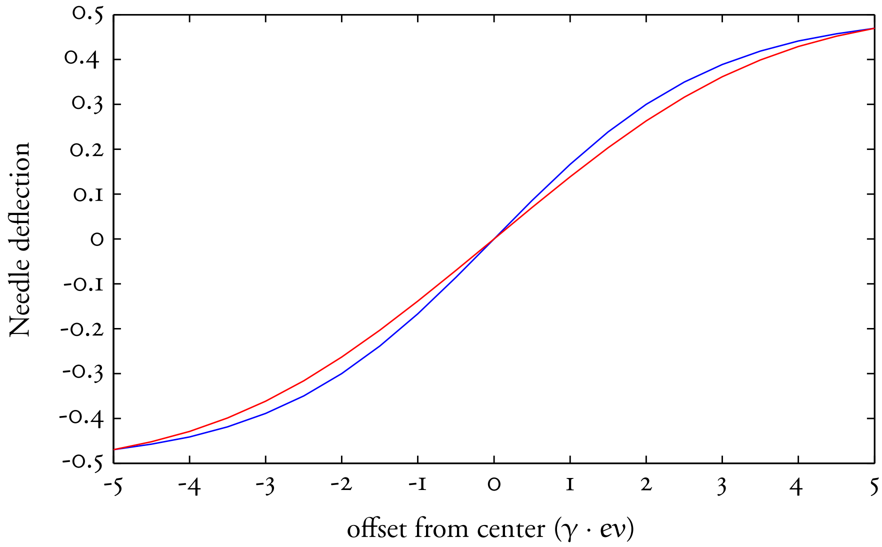

Figure 4: Uniformity of straight scale (red) vs. proportional scale (blue)

with a "normal" lens (around f=40 mm for 135 film, or f=80 mm for 6x6) or narrower (down to spot meters).

The easiest way to achieve this is to shield the sensor mechanically, i.e. put it recessed in some cavity. While this simple solution works exceptionally well, it has a small drawback: the "well" needs to be reasonably deep, so wherever size is an issue, other ways need to be found. A common solution is to put a condensing lens in front of the CdS cell, this allows a relatively shallow structure as seen e.g. in aforementioned Lunasix series meters.

3 Bridge type