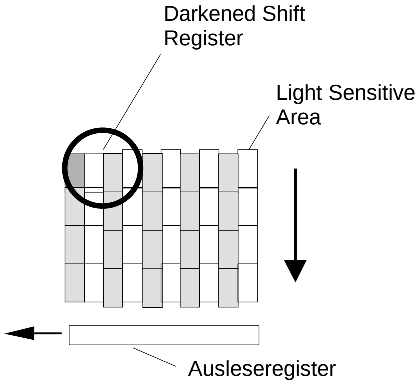
Smear in CCD-Sensors

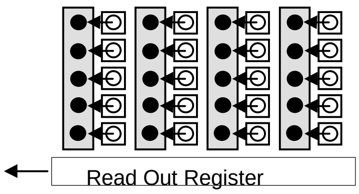
1. Survey and Principles

1.1. Interline-Transfer-Sensor

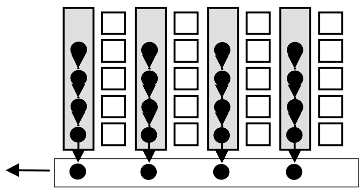
Sensor Structure



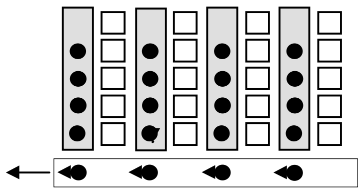
The sensor is subdivided in light sensitive and storage areas, placed as arrays. It is the light sensitive area (image sensor area) of a CCD chip that captures the information and transforms it into electrical charges. A connection between image sensor area and vertical shift register transfers in parallel the generated charges within an extremely short time (2.5µs) to the darkened shift register cell (storage area). The charges of the vertical shift register are now transferred, row by row, into the horizontal shift register (read out register) and from there serially read out.



Parallel Charges Transfer, about 2.5µs duration



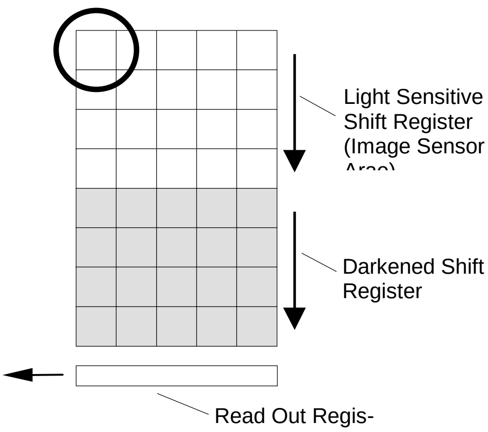
Vertical Shift into the Read Out Register



Horizontal, Serial Readout, Row by Row

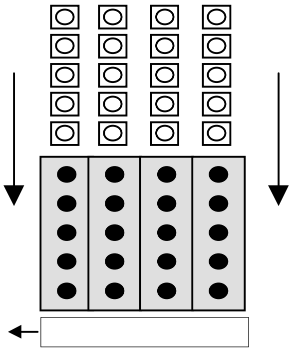
1.2. Frame-Transfer-Sensor

Sensor Structure

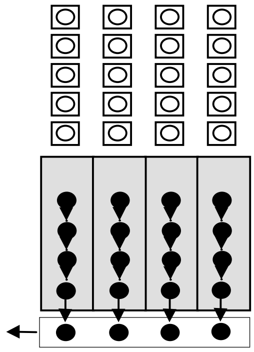


The Frame Transfer sensor consists of two large blocks, the light sensitive area and the storage area. The whole CCD area is about double the size of an Interline Transfer Sensor.

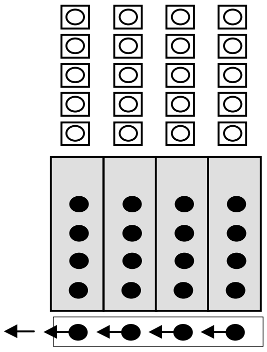
The shift register of this sensor are light sensitive too. All charges are shifted within approx. 500µs through the whole transfer register into the darkened shift register, then vertically shifted into the read out register and from there read out serially (e.g. in about 64µs per row).



Vertical charge Transfer (shift),
e.g. every 20ms
Duration approx. 500µs



Vertical shift into the Read Out Register



Horizontal (serial) Read Out
(e.g. within 64µs per row)

2. Smear

„Smear“ is an undesired signal which appears as a brighter vertical (from top to bottom) stripe emanating from a bright part of the image. Depending on type of sensor there are different reasons for this phenomenon:

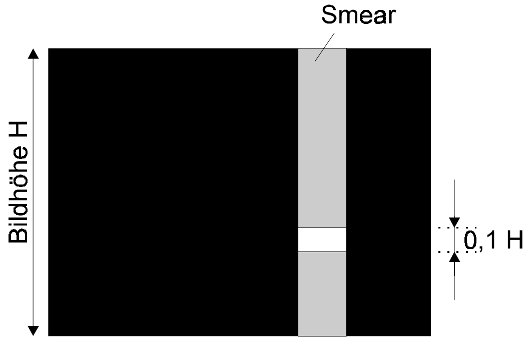
a) Frame-Transfer-CCD
Smear is produced by incident light while the already generated image is shifted from the image sensor area to the storage area (so called frame shift)

b) Interline-Transfer-CCD
In this case it is produced by scattered photons tunnelling into the darkened vertical shift register rather than being collected in the photodiodes of the image sensing area.

c) MOS-XY Sensors
Here the smear effect has the same origin as with Interline Transfer CCDs.

d) CID Sensors
Charge Injection Devices (CID) do not present smear effects

2.1. Measuring Method



For measuring the smear effect commonly following setup is used:
White rectangle (100% signal) with 10% of the total image height on a black background (0% signal)

a) Frame-Transfer-CCD:
For t_{int} as exposure time (image integration time) and t_{tr} as time to transfer the image from the image sensor area to the storage are (frame shift):

$$smear = \frac{1}{10} \cdot \frac{t_{tr}}{t_{int}}$$

t_{int} exposure time [s]
t_{tr} transfer time [s]

b) Interline-Transfer-CCD:
As T_{int} being the exposure time and t_{rd} the CCD read out time, the smear becomes:

$$smear = V_{SM} \frac{t_{rd}}{t_{int}}$$

t_{int} exposure time [s]
t_{rd} read our time [s]
(Video = 20ms)
V_{SM} = Vertical Smear Factor,
typ: 1/20.000

2.2. Examples

Example A:

At 10ms exposure time and 500µs transfer time a Frame Transfer CCD pro duces following smear:

$$Smear = \frac{1}{10} \cdot \frac{500\mu sec.}{10ms} = 0{,}5\%$$

Remark:
This is valid for the typical test with the white rectangle (100% signal) with a 10% of the total image height, as described above. In most of the practical cases, however, bright spots are more than 100% exposed . For example, at a 10 times overexposure, as produced e.g. by an incandescent filament, the smear increases also 10 times.

Example B:

How much is the smear effect of an Interline Transfer CCD at an exposure time 10ms and a readout time of 20ms?

$$Smear = \frac{1}{20000} \cdot \frac{20msec.}{10msec.} = 0{,}01\%$$

Even at a local overexposure the smear effect is negligible.

Example C:

The situation changes at short exposure times (shutter times). An Interline Transfer CCD may have a 5µs electronically shuttered exposure time and a readout time of 20ms, while the illumination is continuously on:

$$Smear = \frac{1}{20000} \cdot \frac{20msec.}{5\mu sec.} = 20\%$$

This is a noticeable smear effect which can be reduced by using a mechanical or electro-optical shutter which blocks off the light from the sensor. Commonly a flashed light source is used, acting like a „read out time reduction“. For ex-ample, a fotoflash of 1/5000s duration reduces the smear in above example by a factor of 100.

3. How to reduce smear

3.1 Frame Transfer CCD

Since smear effects in a Frame Transfer Sensor appear only during charge transport form the image sensor area to the storage area, an illumination cut off during this time will totally eliminate the smear effect, for example by an external mechanical shutter in front of the CCD. Basically the same proposals for avoiding smear effects as described below apply.

3.2. Interline Sensors

During a continuous illumination scattered photons and erratic or misleaded electrons tunnel into the darkened shift register. These results while shifting the image in the darken shift registers an additional signal which results in vertical lines over the complete image. As long as the charges are not moved, the stray electrons appear in the same place as the original image, therefore not deteriorating the original image. When shifting the stored image, the charges additionally generated by the stray electrons will cause the smear effect.

The vertical stripe above a bright spot is generated by shifting the previous image, while the smear stripe below is produced during the shift of the actual image.

To reduce the smear effect the light source should be switched off before and after an exposure. This might be done, for example by using a mechanical or a LCD shutter. Using a pulsed or flashed light source eliminates the problem, so that a pulsed light of 1/10.000 duration is sufficient in most cases to allow an extremely short 100ns exposure without smear effect.

Mechanical shutters of a 25mm useful iris aperture show typically 3-4ms on/off time. This might be good enough for most applications, but not for very short exposure times (typically <10µs), since a lot of smear is still produced. If shutters are not used in front of the camera but, e.g. to cut off a laser beam, they may have a smaller iris, achieving then on/off times of less than 1ms.

Another improvement is the use of LCD shutters. They have an on/off time of approx. 100µs but an on/off ratio of approx. 100:1, a transmission efficiency of about 30% and a limited spectral transmission range.

Not to shift the image in the shift registers during the opening and closing of the shutter may also be helpful. This may be done by setting of delay times before and after an electronically shuttered acquisition.