ELECTRO-OPTICAL TEST METHODS

FOR CHARGE COUPLED DEVICES

ESCC Basic Specification No. 25000

Issue 2	January 2014

Document Custodian: European Space Agency – see https://escies.org

LEGAL DISCLAIMER AND COPYRIGHT

DOCUMENTATION CHANGE NOTICE

(Refer to https://escies.org for ESCC DCR content)

DCR No.	CHANGE DESCRIPTION
797	Specification upissued to incorporate technical and editorial changes per DCR.

TABLE OF CONTENTS

1 PURPOSE

This specification defines the basic test methods applicable to electro-optical tests on Charge Coupled Devices (CCDs). The requirements for measurements (i.e. which measurements are to be performed and how) shall be given in the Detail Specification.

1.1 APPLICABILITY

This specification is applicable to all CCDs. A non-exhaustive list of CCD types is:

- Linear CCD
- Time Delay Integration (TDI) CCD
- Full Frame CCD
- Frame Transfer CCD
- Interlined CCD (TV format)
- Electron Multiplying CCD (EMCCD)

CCDs are available in many variant forms and the test methods must be chosen with consideration for the variant under test. A non-exhaustive list of variants are:

- Front illuminated / Back-Side illuminated
- MPP (Multi-Phase Pinned) / IMO (Inverted Mode Operation)
- Open electrode / Photodiode
- High resistivity
- Specialised coatings

2 RELATED DOCUMENTS

The following ancillary specification is applicable to, and therefore relates to, this Basic Specification:

ESCC 2139020 – Terms, Definitions, Abbreviations, Symbols and Units for Charge Coupled Devices.

3 TERMS, DEFINITIONS, ABBREVIATIONS, SYMBOLS AND UNITS

The terms, definitions, abbreviations, symbols and units as specified in ESCC Basic Specification No. 21300 shall apply. Other symbols and abbreviations are defined, as applicable, within the document referenced in Related Documents herein and in the text of this document.

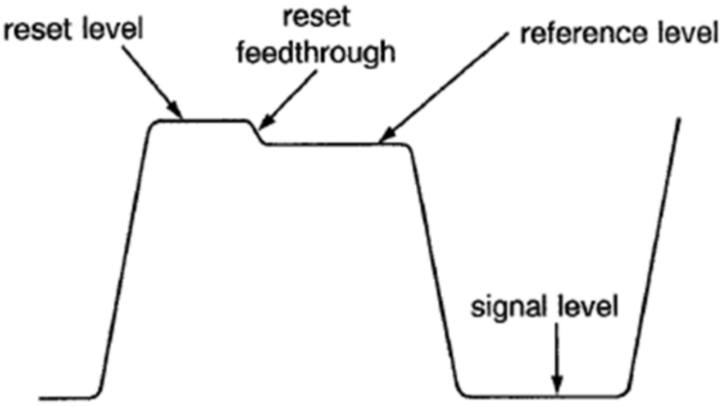
4 REQUIREMENTS

4.1 GENERAL REQUIREMENTS

The device operating temperature must be specified in the Detail Specification. The CCD temperature shall be monitored and calibrated to the active silicon sensor and held within the limits specified in each test method. Unless otherwise specified in the Detail Specification or herein, the sensor temperature is to be regulated within ±1°C of the specified operating temperature.

The choice of light source may vary depending on the parameter under test. The illumination should be calibrated and the spectrum defined as specified in the Detail Specification.

In this specification all CCD output signals are to be measured as the difference between the reference and signal levels of a given pixel, herein referred to as ‘output signal’:



Depending on the parameter under test the absolute reference must be clearly defined. Possible reference levels are listed below and the exact analysis such as position, number and averaging of pixels/images should be defined for each test:

- Pre-scan pixels
- Post-scan pixels
- Dark reference pixels (i.e. optically shielded image area pixels)
- Zero integration time image(s) in darkness
- Dark image(s)

CCD operating conditions, applied biases and clock waveforms are as defined in the Detail Specification but may be varied for a parameter under test if required by a specific test method. Test methods shall be defined in the Detail Specification.

In order to accurately describe the voltage amplitude of the signal at the output of the CCD, the test equipment must be characterised. For example it is important to characterise the test camera gain.

The test camera gain (ADC counts/µV) is measured by introducing a representative signal voltage (in terms of amplitude and frequency) into the test camera video processing chain and measuring the output from the ADC.

5 ELECTRICAL AND ELECTRO-OPTICAL TEST METHODS

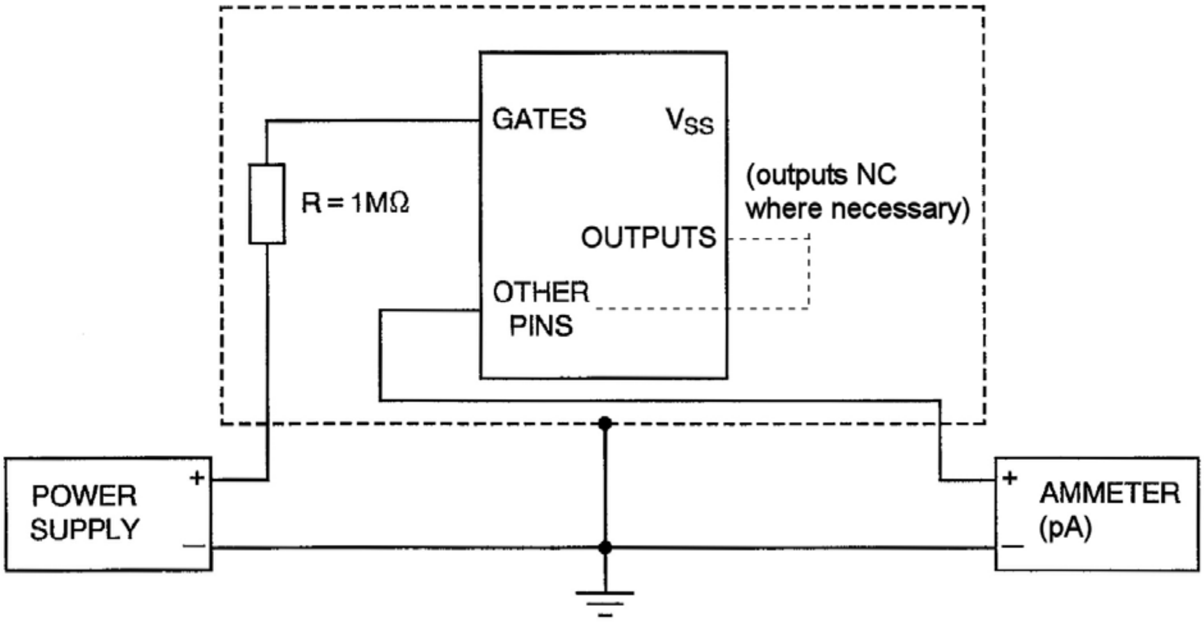
5.1 TOTAL LEAKAGE CURRENT ON INPUT GATES (I_L)

5.1.1 Definition

Total leakage current on input gates is the current, with respect to the channel, which indicates the quality of the dielectric beneath the electrodes and diode integrity.

5.1.2 Measurement Principle

The pins connected to CCD gates are connected together to a DC test voltage. All other pins (including diodes) are connected to substrate (if required by design, however, the video output pins can be non-connected). The sum of leakage currents from gates to substrate is read by a picoammeter connected between substrate and ground of the power supply as shown:



NOTES:

1. There may be additional leakage current due to the device package.
2. The leakage current of the test socket should be insignificant.
3. The resistor between gates and power supply is for protection purposes as there may be voltage or current spikes at switch on.

5.1.3 Measurement Conditions

- Device in darkness.
- Test system to serve as a Faraday cage.
- All gate pins connected together are to be specified in the Detail Specification.
- DC test voltage is as specified in the Detail Specification (corresponding to at least the value typically used for the clock high level).
- The device is biased for a specified period, before taking the measurement, to allow the reading to settle.

5.2 INSULATION LEAKAGE CURRENT BETWEEN PINS AND ELECTRICAL INTEGRITY (I_E)

5.2.1 Definition

Insulation leakage current between pins is a set of measurements performed on each of the device pins in order to detect any short-circuits, or faulty connections, inside the device.

5.2.2 Measurement Principles

The device electrical integrity and insulation leakage currents can be detected by one of two principles.

5.2.2.1 *Measurement Principle 1 – Single Pin to Ground*

The pin under test is biased at a positive voltage. All other pins are connected to the substrate which is connected to ground (output pins can be non-connected and if the pin under test is a diode, the other diodes must be non-connected). The current supplied to the pin under test is measured and verified to be below the specified limit. The measured current indicates leaks to the substrate and/or other pins.

5.2.2.2 *Measurement Principle 2 – Pin to Pin Connections*

The pin under test is biased with respect to another pin. All other pins are non-connected. The voltage required to force a specified current between each pair of pins is measured.

NOTES:

1. Principle 1 is an indirect measurement of the insulation leakage current between two gates; correlation between two neighbours with leakage paths to the substrate may be identified. This test is well adapted to detecting unacceptable leakage due to many low level leakage paths from one pin.
2. Principle 2 is a more complicated matrix of tests combining each pin with a combination of the others in order to give a direct measurement of the insulation current between two pins.
3. The electrical integrity testing is typically carried out at several manufacturing stages, such as wafer probe testing and final assembly testing.

5.2.3 Measurement Conditions

- Device in darkness.
- Each pin (or bond pad) is successively addressed.
- A maximum voltage is specified for each test in order to avoid excessively stressing the device.

5.3 OUTPUT AMPLIFIER POWER SUPPLY CURRENT (I_{DD})

5.3.1 Definition

Output amplifier supply current is the mean current drawn by each output amplifier.

5.3.2 Measurement Principle

The current drawn by the output amplifier(s) is measured by an ammeter in series with the power supply bias.

5.3.3 Measurement Conditions

- Device in darkness.
- If required by design, the appropriate load has to be connected to the output pin.
- CCD operating biases can be dynamic or static (to be specified in the Detail Specification).

5.4 POWER DISSIPATION

5.4.1 Definition

Power dissipation is the energy per unit time that is emitted by a device operating under a specific set of conditions. Power dissipation has two main components: the static component from the DC power of biasing of the output transistors and a dynamic component which is an AC component from the charging and discharging of clock electrode capacitances through finite impedances.

5.4.2 Measurement Principle 1 – Total Heat Dissipation

A cooling system is set to maintain a fixed temperature at the CCD (with the CCD operating). The CCD is then replaced by a heat source. With the cooling system set as was required for the CCD, the heat source is operated such as to stabilise at the CCD temperature. The power applied to the heat source therefore corresponds to the CCD total dynamic power dissipation.

5.4.3 Measurement Conditions for Total Heat Dissipation

- Device in darkness.
- Operating conditions, bias and clock voltages to be specified in the Detail Specification.

NOTES:

1. The power dissipation inside the CCD depends on the characteristics of the electronics. The associated electronics need to be representative with respect to the application.

5.4.4 Measurement Principle 2 – Supply Current and Clock Capacitance

The power dissipation is calculated from measurements of the output amplifier supply current and the capacitance of the clock gate electrodes.

The output amplifier supply current is measured (see Para. 5.3). Using the current and the output amplifier applied bias voltage, the static component of the power dissipation is calculated as follows:

$P = I \times V$ [W]

Where:

P: Power dissipation [W].
I: Output amplifier supply current, I_{DD} [A].
V: Output amplifier supply voltage, V_{DD} [V].

The capacitance for each clock driver is measured (see Para. 5.7). Using the capacitance, applied bias voltage and the clock frequency, the dynamic component of the power dissipation is calculated as follows for each clock driver:

$P = CV^2F$

Where:

P: Power dissipation [W].
C: Capacitance [F].
V: Applied voltage [V].
F: Clock frequency [Hz].

The total power dissipation is given by the sum of power dissipated by all output amplifiers and all clock drivers.

5.5 DC OUTPUT LEVEL (V_{DC})

5.5.1 Definition

DC output level is the voltage corresponding to the mean output voltage of the output amplifier with respect to ground i.e. the DC voltage across the output load with the CCD in darkness.

5.5.2 Measurement Principle

In order to protect the CCD and to have a good impedance matching, the output voltage is sensed after a DC coupled buffer amplifier.

5.5.3 Measurement Conditions

- Device in darkness.
- Mode and frequency of operation to be specified in the Detail Specification.

NOTES:

1. The electrical reference for this measurement is defined as ground and this must be taken into account if the CCD substrate voltage is not equal to ground.
2. Any DC offset from the buffer amplifier must be corrected.

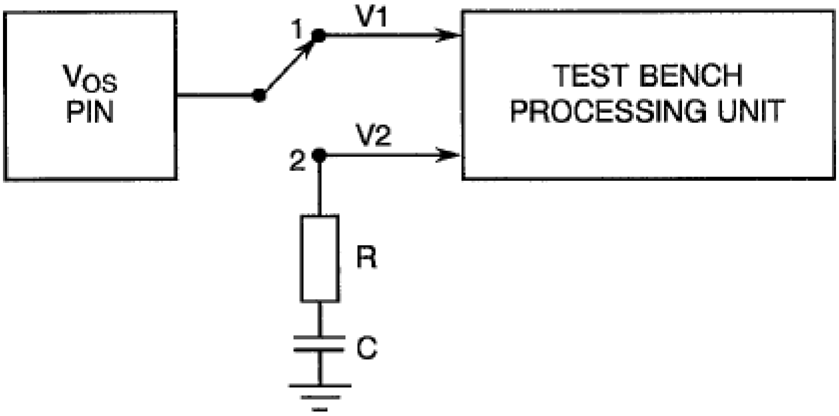
5.6 OUTPUT IMPEDANCE (Z_S)

5.6.1 Definition

Output impedance is the dynamic output impedance of the CCD output amplifier.

5.6.2 Measurement Principle

Under constant illumination the sensor delivers an average signal V1 in a given pixel (or averaged over a group of pixels). If a load resistor R and a serial capacitor C are connected between the output pin and ground, the average signal is then V2:



Measuring V1, V2 and knowing R enables the calculation of the output dynamic impedance:

$$V2 = V1 \times \frac{R}{R+Z_S} \Rightarrow Z_S = R\left[\frac{V1-V2}{V2}\right] \qquad \text{equation (1)}$$

This assumes no external load is applied to the CCD output and that the input impedance of the video electronics/test bench unit used to make the measurement is high enough to present a negligible load to the system. If an external load with impedance Z_L is applied to the output then the output dynamic impedance Z_S is given by

$$\frac{1}{Z_S} = \frac{1}{Z_T} - \frac{1}{Z_L}$$

Where:

Z_S: CCD output dynamic impedance.
Z_T: Total impedance measured as per equation (1) and the above diagram.
Z_L: External load impedance.

5.6.3 Measurement Conditions

- Uniform illumination.
- Mode and frequency of operation to be specified in the Detail Specification.

NOTES:

1. R and C values to be specified in the Detail Specification (calculated from the predicted CCD output amplifier impedance, V_{DC}, current and cut-off frequency).

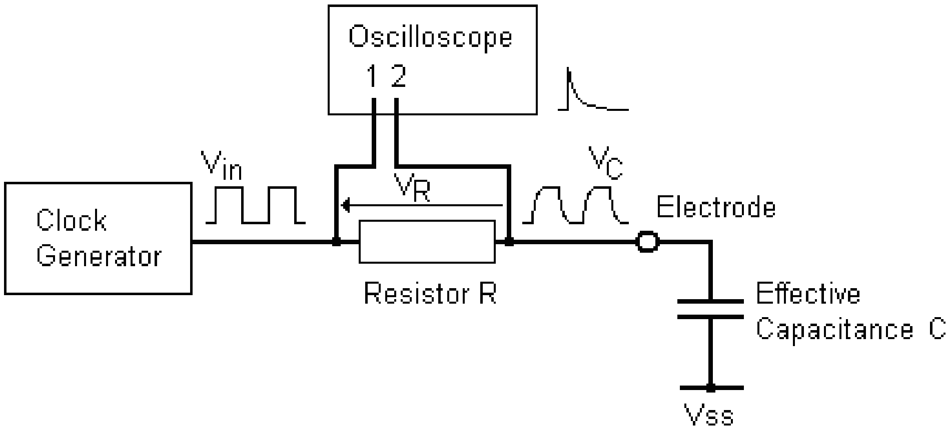
5.7 ELECTRODE CAPACITANCE

5.7.1 Definition

Electrode capacitance, or clock capacitance, is the capacitive load experienced by the external driver circuit when connected to a given clock input. This effective capacitance arises from three separate components: the gate dielectric capacitance, the depletion region capacitance and the inter-electrode capacitance.

5.7.2 Measurement Principle

The gate under investigation is clocked with a square waveform generated by a signal generator, the magnitude of which is comparable to the clock high potential that is intended for standard device operation. A resistor R is located in the circuit between the clock generator and the gate electrode. This forms an RC network with the capacitance of the clock gate which causes a decay of the initial waveform. The voltage drop across the resistor, V_R, is the difference between the voltage at the electrode, V_C, and the input voltage, V_{in}. These are recorded by an oscilloscope as shown below:



The total charge Q transferred to or from the gate electrode is determined by integrating $V_R(t)$ over the total time to charge/discharge the capacitor (T) and dividing by the resistance R. The effective capacitance can then be found by dividing the total charge by the input voltage:

$$C=\frac{1}{V_{in}\,R}\int_{t=0}^{t=T}V_R(t)\,dt$$

NOTES:

1. The resistance of the electrode and signal path within the CCD are considered negligible compared to the external resistor. Where this is not the case correction has to be made to the value of R used in the above calculations.
2. An exponential fit to the RC decay cannot be used to calculate the RC time constant and hence the capacitance. This is because the capacitance alters between clock levels and therefore the decay cannot be described by a single exponential.

5.7.3 Measurement Conditions

- Device at room temperature in darkness (representing the worst case), or to be specified in the Detail Specification.
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.

NOTES:

1. The depletion region capacitance depends on stored charge and so the total electrode capacitance varies with illumination level. Measurements obtained at room temperature in darkness will provide enough charge to be representative of the worst case capacitances in operation.
2. All adjacent gates should be clocking as per nominal operating conditions such that the inter-electrode capacitances are charged according to the total current drawn e.g. in both clock drivers for a two phase structure. Adjacent gates may be held at a static clock high level and not clocked if in nominal operating conditions there are large clock overlaps such that only one electrode is changing level at any one time, e.g. devices with a 3 or 4 phase (non-compensated) structure.
3. The resistor value should be chosen based on the predicted capacitance and input signal frequency such that the discharge times and voltage drop across the resistor are sensible for the required measurement.

5.8 OUTPUT SIGNAL WAVEFORM FEATURES

5.8.1 Definition

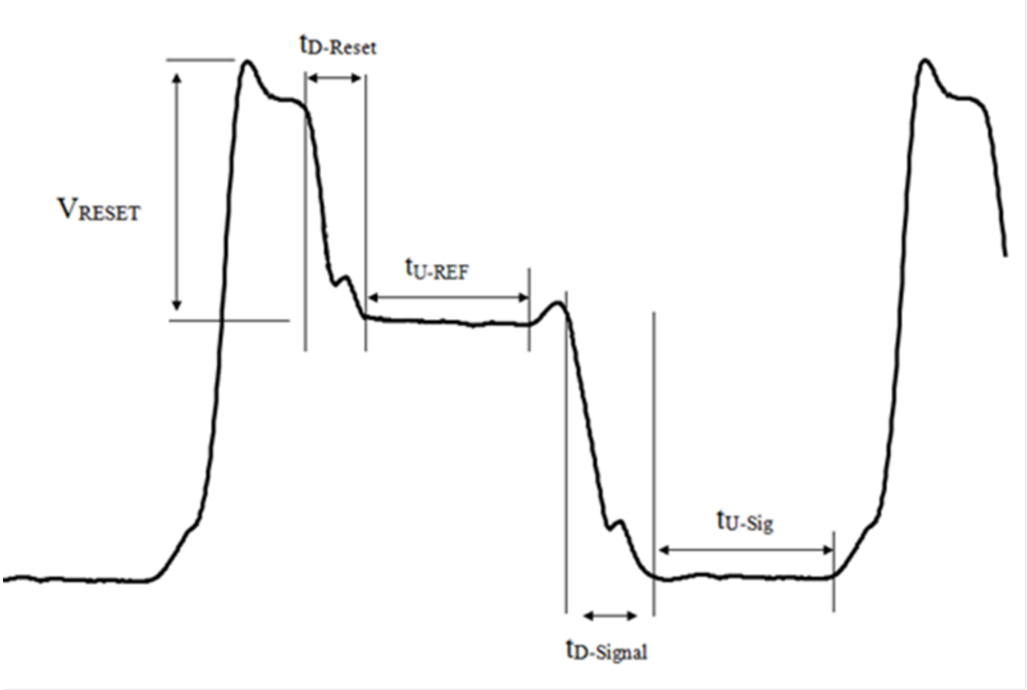
Output signal waveform features include the duration (i.e. settled time) of both the reference level and the signal level and amplitude of the reset feedthrough.

The settled time of the reference level and the video level are shown in the timing chart below ($t_{U\text{-}Ref}$ and $t_{U\text{-}Sig}$), and are defined as specified in the Detail Specification. For example the definition can require the duration the signal remains within a certain error band of a maximum signal level change in amplitude, or require the measured change in amplitude for a given duration. Specification of the form of the signal within the error bands may be given.

When the ØR pulse is applied in order to reset the output floating diode there is a capacitative feedthrough of this pulse onto the output video waveform. The amplitude of this reset feedthrough is defined as the difference between the waveform peak and the mean signal measured during the defined reference level (V_{RESET}).

Further features such as the settling time from clock falling edge to settled time may be requested (such as $t_{D\text{-}Reset}$ and $t_{D\text{-}Signal}$ in the timing chart below).

TIMING RELATIONS USED FOR OUTPUT SIGNAL WAVEFORM MEASUREMENTS



5.8.2 Measurement Principle

The CCD output signal is sensed directly at the output of a buffer amplifier with a digital oscilloscope. The bandwidth of the sensing electronics must be at least 5 times the readout frequency.

The serial register transfer clocks are used for the time reference of signal level measurement. The reset clock ØR is used for the time reference of the reset level measurement.

If the reference signals are sensed at the input to the clock driver circuits (TTL level) then the delays produced by the driver circuits shall be allowed for in the measurement.

NOTES:

1. The sensing electronics' capacitance, filtering, averaging and voltage scale should be carefully chosen and supplied.
2. The output signal waveform features are dependent on the clock driver signals and certain parameters that describe the driver signals may also be supplied.

5.8.3 Measurement Conditions

- Uniform illumination (signal levels to be specified in the Detail Specification).
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.

5.9 OFFSET VOLTAGE (V_{OFFSET})

5.9.1 Definition

Offset voltage is the voltage difference between the reference and signal levels for pre- (or post-) scan elements of the output waveform: i.e. those which do not contain image (and store) area signal. Offset arises from the clock feedthrough of readout register clocks onto the output node. Pre- or post- scan elements contain not only offset voltage, but also any dark signal accumulated in the CCD register during readout.

5.9.2 Measurement Principle

The voltage difference between the reference and signal levels for pre-scan or post-scan elements (as specified in the Detail Specification) is measured and averaged over several such elements. This output signal is measured at the CCD output. In order to protect the CCD and to have good impedance matching, the output voltage is sensed after a DC coupled buffer amplifier.

NOTES:

1. The difference between the reference level and the signal level in the pre- or post- scan elements contains the clock feedthrough and the register dark signal. Measurements using the pre-scan elements may give different results to the post-scan elements.
2. Any DC offset from the buffer amplifier must be corrected.

5.10 LINEARITY ERROR (LE)

5.10.1 Definition

The linearity error of the output signal voltage is defined as the discrepancy (in the output axis, unless otherwise specified in the Detail Specification), expressed as a percentage of the signal level, between the output signal and a straight line determined from the plot of output signal versus input exposure (=irradiance(E)×exposure time(T_{int})). It is also known as non-linearity.

The linearity error is always specified and supplied with the dynamic range over which it is applicable.

5.10.2 Measurement Principles

The output signal is measured by taking images with increasing input exposure. This can be done in a number of ways and should be defined in the Detail Specification.

5.10.2.1 Measurement Principle 1 – Multiple Exposure Time Images

An initial zero image (zero integration time image) is acquired with the device in darkness. The mean value of the zero image is subtracted from all subsequent illuminated frames to subtract the offset level. A series of at least 10 image frames are taken with increasing integration times at a fixed irradiance. The initial integration time should give an output signal below the minimum of the dynamic range over which linearity error is to be measured (given in the Detail Specification). The final integration times correspond to device saturation. The output signal at each integration time is determined from the mean pixel signal from the active area of the image. The output signal is plotted against integration time and a straight line fitted to the data (see Para. 5.10.3). The linearity error is calculated for each output signal. The maximum absolute value is reported as the device linearity error.

5.10.2.2 Measurement Conditions for Multiple Exposure Time Images

- Uniform illumination.
- Light output should be stable over the range of integration times used.
- Temperature should be stable over the range of integration times used.
- If a mechanical shutter is used, the integration times should be significantly longer than the shutter open/close times. Ideally a pulsed light source should be used.
- Antiblooming control to be specified.

5.10.2.3 Measurement Principle 2 – Multiple Irradiance Images

With a fixed integration time, an initial dark image is acquired. The mean value of this dark image is subtracted from all subsequent illuminated frames to subtract the offset and dark signal level. A series of at least 10 image frames are taken with increasing irradiance at the same fixed integration time. The initial irradiance should give an output signal below the minimum of the dynamic range over which linearity error is to be measured (given in the Detail Specification). The final irradiance levels correspond to device saturation. The output signal at each irradiance level is determined from the mean pixel signal from the active area of the image (minus the dark image value). The output signal is plotted against irradiance and a straight line fitted to the data (see Para. 5.10.3). The linearity error is calculated for each output signal. The maximum absolute value is reported as the device linearity error.

This method is suited to TDI operation devices where the integration time is fixed.

5.10.2.4 Measurement Conditions for Multiple Irradiance Images

- Uniform illumination (wavelength as per Detail Specification).
- The light source colour temperature, or spectral content, should remain fixed at each irradiance.
- Irradiance measured in real time for each illumination level.
- Temperature should be stable over the duration of the test (and/or dark images should be measured with each irradiance level).
- Ideally a stepped aperture should control the irradiance levels.
- Antiblooming control to be specified.

5.10.2.5 Measurement Principle 3 – Single Image Increasing Exposure Time

The image area of the device is clocked out to remove any residual charge. An image is acquired initially in darkness, but during readout the shutter is opened to a flat field illumination after the first few rows of the image area have been clocked out (typically 20 rows). For each subsequent row that is read out, the exposure to light will increase by one line period, thus increasing the exposure linearly as a function of row number. The level of illumination combined with the readout rate should be set so that there are a number of rows (typically 20) below the minimum of the dynamic range over which the linearity error is to be measured (given in the Detail Specification) and also so the image saturates before the final rows (typically 20) of the device have been read out. The signal in each row is determined from the mean image pixel value minus the mean post scan level for that row. Alternatively where no post scan is available a reference image can be acquired in darkness for the offset subtraction.

A flat field correction to allow for any non-uniformity in the illumination or device response as a function of row number has to be applied. The flat field correction is determined from a PRNU image, illuminated under the same conditions as the linearity image, with a dark image subtraction to remove any offset. The mean signal M of each row is determined as above, as well as the overall mean signal of the image $\overline{M}$. A correction factor C is then determined for each row (n=1 to N) such that:

$$C(n)=\frac{\int_{1}^{n}\frac{M}{\overline{M}}\partial n}{n}$$

The correction factor is applied to the test data, where the first illuminated row in the test data is corrected by the factor for row n=1, as this row will be in the bottom most row of the device when it is illuminated. All subsequent rows are corrected by the factors for the rows 2 to N. The output signal is plotted against row number and a straight line fitted to the data (see Para. 5.10.3). The linearity error is calculated for each output signal. The maximum absolute value is reported as the device linearity error.

This method is suited to large devices with many rows as this increases the step resolution. It is also of benefit for devices with multiple outputs as test time can be significantly reduced.

5.10.2.6 Measurement Conditions for Single Image Increasing Exposure Time

- Uniform illumination (wavelength as per Detail Specification).
- Shutter opening time should be in the order of a line transfer period.
- Any rows where the shutter is partially open or not settled should be excluded from the analysis.
- PRNU and dark image for the flat field correction to be taken with the same readout rate and same illumination as the linearity image (but without the shutter opening during readout).
- Antiblooming control to be specified.

5.10.3 Line Fit Principle

The method of straight line fitting to the plot of output signal versus input exposure has a significant influence on the determined linearity error. For this reason it should be clearly defined in the Detail Specification (e.g. line fit principle, fit through zero or offset, and range of points used in calculation).

5.10.3.1 Line Fit Principle 1 – Minimum Percent Line Fit

A line is fitted to the actual data points such as to minimise the percentage differences (in the output axis) between the data values and the line.

5.10.3.2 Line Fit Principle 2 – Least Squares Line Fit

A line is fitted to the actual data points such as to minimise the sum of the squared absolute differences (in the output axis) between the data values and the line.

5.10.3.3 Line Fit Principle 3 – 2 Point Line Fit

One data point is defined as a calibration or reference point such that the linearity error is set to zero. A straight line is fitted from this point through the theoretical zero point. This is commonly known as integral linearity error.

5.11 SATURATION VOLTAGE FOR THE IMAGE AREA (V_{SAT-IM})

5.11.1 Definition

Linearity deteriorates rapidly on approaching saturation either due to the approach to pixel full well capacity (degradation of vertical transfer efficiency), to register capacity (degradation of horizontal transfer efficiency), or to the onset of large non-linearities in the output amplifier. CCD designs and operating conditions are typically set such that the pixel saturation occurs at a lower signal level than the register and output amplifier saturation.

Saturation voltage for the image area, V_{SAT-IM}, is the output voltage below which the linearity is within a specified error.

5.11.2 Measurement Principle 1 – Linearity Error

The methods used in Para. 5.10 will measure the linearity error as a function of output signal. Saturation of the image area can be defined as the signal level where the linearity error exceeds a specified level, typically 3%. If the saturation point falls between 2 images, interpolation of the curve can be used to measure V_{SAT-IM}. A global value for saturation will be given if the whole image is averaged. With uniform illumination, specific areas of the image can be analysed separately to measure any local saturation non-uniformity, for example to measure the minimum pixel or column capacity.

5.11.3 Measurement Conditions for Linearity Error

- See Para. 5.10.
- Binning factors must not be applied.
- Maximum allowed linearity error for definition of LE_V_{SAT-IM} = 3% (unless otherwise specified in the Detail Specification).
- Antiblooming control to be specified.

5.11.4 Measurement Principle 2 – Charge Transfer Efficiency (CTE) Degradation

For steadily increasing uniform illumination images, as in Para. 5.10, the signal in the first over-scanned row can be measured as a function of signal in the last useful line. At saturation the signal in the first over-scanned row starts to increase, i.e. CTE decreases. Vertical CTE versus signal in the last useful row is plotted and the signal level corresponding to a minimum specified value of CTE defines V_{SAT-IM}. If the saturation point falls between 2 images, interpolation of the curve can be used.

Alternatively, illumination provided by a light source of varying intensity across the device columns can be used. The signal in the first over-scan row is plotted against the signal in the last active row for each column. The signal level corresponding to a sharp rise due to the charge spilling into the over-scan row defines V_{SAT-IM}. More precisely, the point at which the edge response CTE drops below a minimum specified value is the saturation level.

5.11.5 Measurement Conditions for Charge Transfer Efficiency (CTE) Degradation

- See Para. 5.10.
- Binning factors must not be applied.
- Minimum specified CTE for definition of V_{SAT-IM} to be specified in the Detail Specification.
- Saturation level can be defined alternatively by a fixed number of over-spill electrons.
- Antiblooming control to be specified.

5.12 SATURATION VOLTAGE FOR THE READOUT REGISTER ($V_{SAT-REG}$)

5.12.1 Definition

Saturation voltage for the readout register, $V_{SAT-REG}$, is the output voltage below which the linearity of the signal transferred in the register is within a specified error.

5.12.2 Measurement Principle 1 – Linearity Error

The methods used in Para. 5.10 will measure the linearity error as a function of output signal. Saturation of the readout register area can be defined as the signal level where the linearity error exceeds a specified level, typically 3%. For the measurement of register saturation, image area rows are binned into the register. The number of binned lines shall be chosen such that saturation occurs in the readout register before it occurs in the image area of the CCD (the number of binned lines, N, to be specified in the Detail Specification, a typical number being 4 lines). If the saturation point falls between 2 images, interpolation of the curve can be used to measure $V_{SAT-REG}$.

5.12.3 Measurement Conditions for Linearity Error

- See Para. 5.10.
- Parallel binning of image rows into the register with a factor of typically 4.
- Illumination level to exceed register saturation after binning but below image area saturation at all times.
- Maximum allowed linearity error for definition of $LE\_V_{SAT-REG}$ = 3% (unless otherwise specified in the Detail Specification).
- Antiblooming control to be specified.

5.12.4 Measurement Principle 2 – Charge Transfer Efficiency (CTE) Degradation

For steadily increasing uniform illumination images, as in Para. 5.10, the signal in the first post-scan pixel can be measured as a function of signal in the last useful pixel of the register. At saturation the signal in the first post-scan pixel starts to increase, i.e. CTE decreases. Horizontal CTE versus signal in the last useful register pixel is plotted and the signal level corresponding to a minimum specified value of CTE defines $V_{SAT-REG}$. If the saturation point falls between 2 images, interpolation of the curve can be used.

5.12.5 Measurement Conditions for Charge Transfer Efficiency (CTE) Degradation

- See Para. 5.10.
- Parallel binning of image rows into the register with a factor of typically 4.
- Illumination level to exceed register saturation after binning but below image area saturation at all times.
- Minimum specified CTE for definition of $V_{SAT-REG}$ to be specified in the Detail Specification.
- Saturation level can be defined alternatively by a fixed number of over-spill electrons.
- Antiblooming control to be specified.

5.13 SATURATION VOLTAGE FOR THE OUTPUT NODE ($V_{SAT-OUTPUT}$)

5.13.1 Definition

Saturation voltage for the output node, $V_{SAT-OUTPUT}$ (normally a floating diode), is the output voltage below which the linearity of the signal at the output node is within a specified error.

5.13.2 Measurement Principle – Linearity Error

The methods used in Para. 5.10 will measure the linearity error as a function of output signal. Saturation of the output node can be defined as the signal level where the linearity error exceeds a specified level, typically 3%. For the measurement of output node saturation, register pixels are binned into the output node without resetting. The number of binned pixels shall be chosen such that saturation occurs in the output node before it occurs in the image area or register of the CCD (the number of binned pixels, N, to be specified in the Detail Specification, a typical number being 4 pixels). If the saturation point falls between 2 images, interpolation of the curve can be used to measure $V_{SAT\text{-}OUTPUT}$.

5.13.3 Measurement Conditions for Linearity Error

- See Para. 5.10.
- Serial binning of register pixels into the output node with a factor of typically 4.
- Illumination level to exceed output node saturation after binning but below image area and register saturation at all times.
- Maximum allowed linearity error for definition of $LE\_V_{SAT\text{-}OUTPUT} = 3\%$ (unless otherwise specified in the Detail Specification).
- Antiblooming control to be specified.

NOTES:

1. V_{SAT} measurements as a function of antiblooming control may be required, to be specified in the Detail Specification.

5.14 BLOOMING CHARACTERISTICS

Blooming is when charge starts to spread from an illuminated pixel into adjacent pixels at saturation. Unless antiblooming structures are present and active (see Para. 5.15) the blooming occurs predominantly in the vertical direction. Testing for blooming characteristics is specified in the Detail Specification for the region of saturation, a single (or several) optical overload level (in multiples of the saturation exposure) and the adjacent pixels to be measured. Vertical CTE testing at saturation (as per Para. 5.11.4) is typically sufficient to determine the onset of blooming.

5.15 ANTIBLOOMING OPERATION

5.15.1 Definition

Some CCD architectures have antiblooming structures which drain charge out of a pixel when saturation is reached.

Antiblooming operation is specified in terms of the optical overload (in multiples of the saturation exposure) that the sensor can experience before blooming occurs, where blooming is a non-linear increase in signal in pixels adjacent to saturated pixels.

5.15.2 Measurement Principle

A small area on the device, typically a few pixels in diameter, is illuminated with a laser, light emitting diode, or tungsten-halogen lamp coupled to a spot aperture. This initial spot is adjusted to give approximate pixel saturation with a certain integration time. Frames of images are taken with increasing integration times up to that calculated to give the maximum specified level of signal overload in the centre pixel(s).

The data is then analysed to look at the pixel signal of those pixels adjacent to the spot centre, which are initially partially illuminated.

Blooming of the saturated pixel can be detected if the signals in the pixels adjacent to the spot are plotted and the resulting plots, which should show a linear increase with integration time, show a premature increase in signal level due to the acquisition of charge spilled from an adjacent blooming pixel.

NOTES:

1. The reference pixels should be carefully chosen in order to take into account the background signal, such as dark signal.

5.15.3 Measurement Conditions

- Antiblooming voltage(s) to be specified in the Detail Specification.
- Maximum optical overload to be specified in the Detail Specification.
- Method of illumination to be specified in the Detail Specification.
- Maximum allowed linearity error for definition of blooming to be specified in the Detail Specification.

5.16 CHARGE TRANSFER EFFICIENCY (CTE)

5.16.1 Definition

Charge transfer efficiency, CTE, is the proportion of charge correctly transferred from one stage to the next under a specific set of operating conditions. A stage corresponds to one pixel area (or register pixel area i.e. a set of four gates on two phase and four phase CCD designs or a set of three gates on three phase designs).

The charge transfer inefficiency CTI = 1 – CTE

The total charge transfer efficiency is the percentage of correctly transferred charge after N stages:

$$\text{Total CTE} = (\text{CTE})^N = (1 - \varepsilon)^N \simeq 1 - N.\varepsilon$$

where ε, the charge transfer inefficiency for one stage, is <<1.

CTE (and inversely CTI) occur in both the vertical (i.e. parallel) and horizontal (i.e. serial) readout directions and are called VCTE and HCTE respectively.

NOTES:

1. CTE may be specified per stage, per clock transfer or for N total pixels. Simple conversion between these definitions assumes N stages of the same design.
2. The operating conditions such as frequency, signal level, temperature etc. are critical to the CTE performance and are as specified in the Detail Specification.

5.16.2 Measurement Principle

There are a large number of test methods possible, however they can be grouped into two categories:

(i) Methods based on measuring the signal lost from a charge packet
(ii) Methods based on measuring the signal deferred into trailing pixels.

Charge lost during a given transfer may be deferred over several pixels and can depend on the signal level, so the two types of measurement will not necessarily give the same results.

Methods of illumination can vary:

(a) Uniform illumination methods

The horizontal charge transfer inefficiency is measured either using the charge lost in the first illuminated pixel(s) (first pixel edge response) or using the deferred charge from the last illuminated pixel into the first masked or post-scanned pixel (extended pixel edge response). The same methods can apply to vertical CTE, except the signal all along the first or last row is measured.

The CCD architecture must give a sharp transition between the illuminated and non-illuminated pixel(s).

The number of pixels across which lost or deferred charge is measured must be specified in the Detail Specification.

(b) Point illumination methods

Methods of introducing charge into a single pixel or region of pixels include:

(i) Optical illumination. This has the advantage that the signal size can be varied. The number and location of pixels to be illuminated shall be specified in the Detail Specification.

(ii) Illumination with soft x-rays from a radioactive source (e.g. Cd109 or Fe55). This is only applicable to some CCD architectures where 'single pixel' x-ray events can be distinguished. The signal can only have a fixed value at a specific temperature (given in electrons by the x-ray energy, in eV, divided by the energy required to generate an electron-hole pair e.g. 3.68eV at -100°C).

(iii) Electrical injection of charge, called the periodic pulse technique. This is only applicable if the CCD has an input gate structure. Injection methods facilitate multiple measurements of CTE for improved accuracy.

(c) Imaging methods

Methods using an image focused onto the CCD, such as a grid pattern, can be useful for assessing low signal or localised CTE.

For all of the above methods, techniques exist for improving the accuracy of CTE determination. These include averaging of successive images and artificially increasing the number of charge transfers by clocking charge packets up and down (for vertical CTE measurement) or from side to side (for horizontal CTE measurement) before readout.

Only the point illumination and imaging methods are capable of identifying localised regions of poor CTE. The position of the pixel(s) under test should be taken into account to correctly identify the number of stages over which the charge has been transferred.

NOTES:

1. The CTE measurement requires an ideal fast-edge response of the detection electronics. The data acquired must be corrected for the response of the video chain.

There will be smearing in the image if the transfer is made under illumination, since incident photons add spurious charge to those which have been accumulated during integration time. The total smearing factor of the signal read out is given by:

$$NS = \frac{T_t}{T_i}$$

Where:

NS: Total Smearing Factor.
T_t: Total transfer time whilst under illumination.
T_i: Integration time.

The data must be corrected for charge due to smearing before obtaining the level of the transfer inefficiency.

N.B.:
The smearing can be disabled if a pulsed light source or shutter is used instead of a halogen lamp.

5.16.3 Measurement Conditions

- Method of illumination, and pixels to be measured to be specified in the Detail Specification (e.g. number of post-scan pixels or rows for deferred charge methods).
- Signal level to be specified in the Detail Specification.
- Background signal (optical or dark signal) and signal due to smearing to be specified.
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.
- Status of antiblooming control, if applicable (i.e. ON or OFF) to be specified in the Detail Specification.

5.17 TRAPS

5.17.1 Definition

A trap is a pixel that captures more than a given number of electrons (typically 200) and releases them at a later time.

5.17.2 Measurement Principle

Two images are taken with at least 10 over-scan rows, one low light level (or dark image with sufficient dark signal) and one with zero integration time. For the last active rows (e.g. ten) and first ten over-scan rows these images are subtracted pixel-by-pixel. The signals from the ten over-scan pixels in each column are added together. The median of these values is then subtracted to represent the background level. Any column with accumulated over-scan values above the trap threshold, and where the first over-scan pixel is greater than 10 electrons (to avoid false counting due to background noise), are reported as traps.

5.17.3 Measurement Conditions

- Average image area signal (either from optical illumination or dark signal) to be specified in the Detail Specification, typically 1000 electrons/pixel.
- Trap threshold to be specified in the Detail Specification, typically 200 electrons.

5.18 RESPONSIVITY (R)

5.18.1 Definition

Responsivity is the ratio of useful signal voltage (i.e. excluding dark signal) to exposure for a given wavelength band of illumination.

It is a function of two parameters: photo-element quantum efficiency and charge-to-voltage conversion factor, CVF, and is dependent on various factors such as pixel area, fill factor, wavelength, temperature, device and illumination non-uniformities.

5.18.2 Measurement Principle

In a given spectral band, for a given incident illumination (in the linear operating range) and a fixed integration time, the average output signal (in mV) is measured. The incident irradiance is also measured. With the same integration time and settings, a mean dark image is acquired (where temporal noise is negligible).

The response R [V/(µJ/cm²)] is defined as: $R = \frac{10 \cdot (V_a - V_{DS})}{T_i \cdot E}$.

Where:

V_a [mV]: Mean output signal under illumination (averaged over several pixels or for a single pixel).
V_{DS} [mV]: Mean dark signal.
E [mW/m²]: Incident irradiance.
T_i [ms]: Integration time.

5.18.3 Measurement Conditions

- Uniform illumination (or a spot covering several pixels).
- Irradiance measured in sensor plane.
- Average signal = $V_{SAT}/2$ (unless otherwise specified in the Detail Specification).
- Number of pixels to be averaged to be specified in the Detail Specification.
- Number of locations on the CCD to be specified in the Detail Specification.
- Wavelength range, spectral resolution and bandwidth to be specified in the Detail Specification.

5.19 SPECTRAL RESPONSIVITY

5.19.1 Definition

Spectral responsivity is the ratio of useful signal voltage (i.e. excluding dark signal) to exposure measured in various spectral bands (responsivity measurement). From these values, a curve can be derived, giving the shape of the responsivity over a broad spectrum containing each elementary spectral band.

5.19.2 Measurement Principle

As for responsivity, the average output signal, incident irradiance and dark signal are measured for each spectral band.

The response R [V/(µJ/cm²)] at each wavelength is defined as: $R = \frac{10 \cdot (V_a - V_{DS})}{T_i \cdot E}$.

Where:

V_a [mV]: Mean output signal under illumination (averaged over several pixels or for a single pixel).
V_{DS} [mV]: Mean dark signal.
E [mW/m²]: Incident irradiance.
T_i [ms]: Integration time.

Typically the incident illumination in each spectral band is produced using narrow band filters. Alternatively a Monochromator can be used to project narrow band illumination onto the CCD, with the advantage that many more steps across the spectrum are practically possible. An FTIR instrument can also be used.

5.19.3 Measurement Conditions

- Uniform illumination (or a spot covering several pixels).
- Irradiance measured in sensor plane, and over a surface area where the incident illumination is uniform with respect to the illuminated area of the CCD.
- Average signal = $V_{SAT}/2$ (unless otherwise specified in the Detail Specification) (when using a Monochromator or an FTIR, the irradiance level depends on the wavelength and may be very low).
- Number of pixels to be averaged to be specified in the Detail Specification.
- Number of locations on the CCD to be specified in the Detail Specification.
- Wavelength range, spectral resolution and bandwidth to be specified in the Detail Specification.

5.20 CHARGE TO VOLTAGE CONVERSION FACTOR (CVF)

5.20.1 Definition

Charge to voltage conversion factor, CVF, of the output amplifier, is the ratio between the average output voltage and the number of electrons stored in the readout diode of the CCD.

5.20.2 Measurement Principle 1 – Reset Drain Current Methods

5.20.2.1 Single Image Method

The charge to voltage conversion factor at the output can be calculated by measuring the reset drain current of the readout capacitance. Since all charge deposited by the CCD on the output node flows through the reset drain, the average reset drain current when a uniform image is read out is proportional to the charge contained in each pixel. The constant of proportionality is the number of pixels read out per unit time, obtained from the clocking speed of the CCD.

The output voltage is measured by taking the mean signal of the image in ADC counts and dividing by the test camera gain in ADC counts/µV. The ratio of the mean output voltage to the mean pixel charge calculated is the CVF ($\mu V/e^-$).

Alternatively, if the output voltage is sampled directly instead of acquiring an image then:

$$CVF(\mu V/e^-) = \frac{V_a}{n} = \frac{V_a}{I_{RD} \times T_i} \times q \times N \times 10^{15}$$

Where:

V_a (mV) = Average output signal under illumination (see Note 1).
n = Number of electrons in the readout diode.
I_{RD} (nA) = Average current supplied by the Power supply that is connected to the Drain of the reset transistor of the readout capacitance.
T_i (ms) = Integration time (see Note 2).
N = Total number of useful pixels.
q = 1.6×10^{-19} coulomb (electron charge).

NOTES:

1. The voltage (V_a) corresponds to the signal without the offset voltage. Where the register dark signal is negligible, the pre- or post-scan pixels can be used as reference. If the offset voltage cannot be accurately measured the Differential method should be used to measure the CVF.

2. T_i is the time period over which the average output current is being measured. The T_i used for CVF calculation is therefore dependent on the device type and the readout timings. For example, the time for any reference pixel readout and line transfer should be taken into account since they reduce the average current measured. The T_i is not necessarily the time over which all the charge in the pixel was optically accumulated.

5.20.2.2 *Differential Method*

The same result can be performed with a differential method. The device is operated at 2 different signal levels, the difference of the mean output signal and the mean reset drain current between image 2 and image 1 is used calculate the CVF. Alternatively, if the output voltage is sampled directly instead of acquiring an image then:

$$CVF(\mu V/e^{-}) = \frac{(V_{a2} - V_{a1})}{(I_{RD2} - I_{RD1}) \times T_i} \times q \times N \times 10^{15}$$

To avoid risk of electrical overstress when connecting a picoammeter into the reset drain line, I_{RD} can be monitored by measuring the voltage across a suitable resistor.

5.20.2.3 *Measurement Conditions for Reset Drain Current Methods*

- Uniform illumination.

5.20.3 Measurement Principle 2 – Optical Methods

The CVF (µV/e$^-$) can be calculated from the test camera gain, G_e (ADC counts/µV) and the overall gain, G_s (ADC counts/e$^-$) using:

$CVF = G_s / G_e$

The overall gain (gain of the test camera electronics and the CCD output amplifier) is given by the slope of a straight line best fit (calculated using the least squares method) to the variance versus mean plot.

When using several signal levels the variance, V, is given by:

$$V = \overline{x^2} - (\overline{x})^2$$

Where:

$$\overline{x^2} = \frac{1}{N}\sum_{i=1}^{N}(S_i)^2$$

And:

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N}S_i$$

Where:

N = Number of pixels measured at a given mean signal level.
S_i = Signal from i^{th} pixel (ADC counts).

Assuming Poisson statistics where N is large, the variance can be approximated as equal to the mean:

$$\frac{\Delta\text{Variance}\left[\text{Electrons}^2\right]}{\Delta\text{Mean}\left[\text{Electrons}\right]}=1$$

Thus:

$$\frac{\Delta\text{Variance}\left[\text{Counts}^2\right]}{\Delta\text{Mean}\left[\text{Counts}\right]}=\frac{G_S^2}{G_S}\frac{\Delta\text{Variance}\left[\text{Electrons}^2\right]}{\Delta\text{Mean}\left[\text{Electrons}\right]}=G_S\left[\text{Counts/Electron}\right]$$

Therefore the slope of the variance vs. mean curve, M = G_S (ADC counts/e^-).

5.20.3.1 *Optical Method 1: Multiple Images*

The variance versus mean data can be generated by acquiring one or many images at each signal level such that the variance at the given signal level is statistically significant (typically N > 1000). Either the temporal variance and mean of each pixel is calculated or the variance and mean over many pixels in an image area can be used provided the illumination is uniform and the PRNU is low, such that the photon shot noise dominates the variance.

Pixels with ADC saturated pixels or cosmic ray events are omitted from the calculations. In addition, the highest 2.5% mean and 2.5% variance values may also be discarded to remove the effects of any other spurious signals.

The variance for each signal level is then plotted against the mean.

5.20.3.2 *Measurement Conditions for Optical Method 1: Multiple Images*

- Uniform illumination.
- Various signal levels over a significant dynamic range, typically between 5:1 and 10:1. This range depends on the CCD type (in particular its V_{SAT}) and optical setup.

5.20.3.3 *Optical Method 2: Varying Spatial Illumination*

For a CCD with a large number of columns, the variance versus mean data can be generated in one image by operating the CCD in continuous scan mode with a spatially varying illumination. This means that each CCD column produces an output level that is constant (except for output amplifier noise and photon shot noise) and represents the integral of the light level of all the CCD pixels in that column. The illumination on the CCD is typically arranged so that the output signal from different columns varies across the CCD.

The CCD is allowed to scan for at least one whole image before gathering the data to be used in the measurement. Columns with ADC saturated pixels or cosmic ray events are omitted from the calculations. In addition, the highest 2.5% mean and 2.5% variance values may also be discarded to remove the effects of any other spurious signals.

The variance of each column is then plotted against the mean for each column.

5.20.3.4 Measurement Conditions for Optical Method 2: Varying Spatial Illumination

- Light source should give a spatially varying intensity across the CCD columns, typically between 5:1 and 10:1. This range depends on the CCD type (in particular its V_{SAT}) and optical setup.
- CCD to be operated in continuous scan mode and must be clocked out for at least one whole image before acquiring data.

5.20.4 Measurement Principle 3 – X-Ray Method

The CVF (µV/e$^-$) can be calculated from the test camera gain, G_e (ADC counts/µV) and the overall gain, G_s (ADC counts/e$^-$) using:

$$CVF = \frac{G_s}{G_e}$$

An Fe^{55} x-ray source is used to generate known quantities of charge in the image area. This quantity of charge is simply calculated from the energy of the x-ray photons (5898 eV) and the energy required to generate one electron/hole pair in silicon (3.68 eV at -100°C). The signal of detected x-ray events is plotted against row number, and a straight line fitted to the data (calculated using the least squares method). The y-intercept of this line is the signal in ADC counts without any loss due to CTI. Comparison of the signal measured in counts and that inferred in electrons from the x-ray energy gives a figure for the overall gain G_s in ADC counts per electron. The CVF (µV/e$^-$) can then be calculated using this figure and the previously determined test camera gain, G_e (ADC counts/µV).

N.B.:
The measurement must be performed at a temperature where the integration and readout dark signals are negligible compared with the x-ray photon signal.

5.20.5 Measurement Conditions for X-Ray Method

- Shuttered x-ray illumination.
- Dark signal must be negligible compared to the x-ray signal.
- X-ray flux should not be so large as to result in multiple events per pixel.

5.21 QUANTUM EFFICIENCY (QE)

5.21.1 Definition

The quantum efficiency (QE) at a given wavelength is the ratio between the number of electrons generated in the semiconductor (corresponding to useful signal, i.e. signal excluding dark signal) and the number of incident photons.

5.21.2 Measurement Principle

The quantum efficiency at a given wavelength can be deduced from the Responsivity R (see Para. 5.18):

$$QE(\lambda) = \frac{h \cdot c \cdot R(\lambda)}{A \cdot CVF \cdot \lambda} \cdot 10^{29}$$

Where:

h [J.s]: Planck constant (6.62×10^{-34}).

c [m/s]: Velocity of light (3×10^8).
λ [nm]: Centred wavelength of the spectral band used for measurement.
R [V/(µJ/cm²)]: Response at the given wavelength.
A [µm²]: Pixel area.
CVF [µV/e⁻]: Charge to Voltage Conversion Factor.

Alternatively, if Responsivity is not measured then quantum efficiency can be defined by:

$$QE(\lambda) = \frac{h \cdot c \cdot S_0}{G_s \cdot T_i \cdot E \cdot A \cdot \lambda}$$

Where:

h [J.s]: Planck constant (6.62×10^{-34}).
c [m/s]: Velocity of light (3×10^8).
S_0 [ADC counts]: CCD image signal (after dark signal subtraction and averaged over several pixels).
G_s [ADC counts/e⁻]: Overall system gain.
T_i [s]: Integration time.
E [W/m²]: Incident irradiance.
A [m²]: Pixel area.
λ [m]: Centred wavelength of the spectral band used for measurement.

5.21.3 Measurement Conditions

- Uniform illumination (or a spot covering several pixels).
- Irradiance measured in sensor plane, and over a surface area where the incident illumination is uniform with respect to the illuminated area of the CCD.
- Average signal = $V_{SAT}/2$ (unless otherwise specified in the Detail Specification).
- Number of pixels to be averaged to be specified in the Detail Specification.
- Number of locations on the CCD to be specified in the Detail Specification.
- Wavelength range, spectral resolution and bandwidth to be specified in the Detail Specification.

5.22 AVERAGE DARK SIGNAL (V_{DS})

5.22.1 Definition

Dark signal is the output signal in the absence of any illumination on the device, under specified operating conditions (temperature, integration time and bias supplies etc.).

Depending on the sensor type, several elements can contribute to the overall dark signal:

- Image area pixels (photodiode, photoMOS).
- Storage area pixels (for frame transfer arrays).
- Readout register.
- Readout diode.

Dark signal has a time dependant component and therefore the timings for the CCD operation are critical to dark signal analysis. Attention should be paid to whether a certain region of the device has been flushed of all dark signal before acquisition of an image frame. This is particularly relevant for pre-scan or storage area pixels e.g. in frame transfer devices.

Dark signal is highly dependent on whether the surface is inverted (or 'pinned') such that hole recombination can occur. Certain device structures allow multiple image (and storage) area phases to be inverted at the same time i.e. during integration (called multi-phase pinned, MPP, or inverted-mode operation, IMO). The inversion voltage where the dark signal falls steeply, and the ratio of the dark signal for non-inverted and inverted conditions (at a specified substrate voltage) may be required.

Dark signal variation with temperature to be measured as specified in the Detail Specification.

NOTES:

1. Various units can be used for expressing dark signal e.g. nA/cm^2, e$^-$/pixel/s, e$^-$/pixel, mV. Assumptions should be stated when converting between units, e.g. CVF, pixel area definition.
2. When dark signal is very low, binning techniques may be used to measure the average dark signal.

5.22.2 Measurement Principles

5.22.2.1 Measurement Principle 1 – Pixel Dark Signal

An initial zero image (zero integration time) image is acquired with the device in darkness. The mean value of the zero image is subtracted from all subsequent frames to subtract the reference level. Where a zero image is not applicable, pre or post scan pixels can be used as the reference level.

An image with an increased integration time (T_i) is then acquired such that contributions from regions other than the pixel become insignificant and the accuracy is improved. The dark signal V_D is determined from this extended integration time frame after subtraction of the reference level (as above).

Where the integration time of measurement is different to the integration time specified in the Detail Specification, a linear correction can be made.

The corrected dark signal, V_{DS}, is defined as follows:

$$V_{DS} = V_D \cdot \frac{T_i \; specified}{T_i \; of \; measurement}$$ (assuming the detector and electronics are linear over this range of signal level/integration time).

An alternative approach is to take the average of frames at various integration times and determine the slope of the line (according to integration time). This will give a measure of the dark signal per unit time.

The CVF (µV/e$^-$) can be used to express the dark signal in e$^-$/pixel/s.

NOTES:

1. When possible at least 2 integration times should be tested such that a slope per unit time can be calculated, improving accuracy.
2. The number of pixels used to calculate the average V_D needs to be specified.
3. The mean of the zero image can be subtracted as reference level or on a pixel by pixel case, as specified in the Detail Specification.
4. Any non-linearity in the detector or electronics should be considered.

5. The method of straight line fitting to the multiple integration time plot should be clearly defined in the Detail Specification.
6. This method is applicable to image and store (memory) pixels. They may be treated combined or separately (via special timing if necessary).

5.22.2.2 Measurement Principle 2 – Readout Register Dark Signal

The readout register component of dark signal can be measured by integrating for a period of time in the register before readout.

(a) Image clocks stopped

Typical timings are applied to the CCD, except the register clocks are stopped for a (or several) given integration time(s). To avoid parasitic charge coming from the image (and storage) area, the vertical transfer clocks are stopped or reverse clocked away from the register and where applicable the anti-blooming is activated.

(b) Delta acquisition

Two (or more) different timing diagrams can be used to measure the register dark signal.

The pixel dark signal is first measured as per Para. 5.22.2.1 where it is assumed that the readout register component is insignificant. A second acquisition is taken with the same timings except the register clocks are stopped during a defined time. The subtraction of the first measurement from the second gives the register dark signal.

A linear correction is made in order to get the register dark signal per unit time using the integration time when the register clocks were stopped.

5.22.3 Measurement Conditions

- Device in darkness.
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.
- Regions of interest to be defined in the Detail Specification.
- Integration times to be defined in the Detail Specification.

NOTES:

1. Dark signal is a strong function of temperature and substrate voltage. The Detail Specification may require measurement as a function of temperature and/or substrate voltage.

5.23 TEMPORAL NOISE

5.23.1 Definition

Temporal noise is the standard deviation of the fluctuation in time from frame to frame of a given signal. Possible noise contributions to the CCD video output waveform are defined below.

5.23.1.1 Dark Current Shot Noise (DCSN)

Dark current shot noise, DCSN, is the temporal fluctuation of the thermally generated dark signal electrons. The shot noise follows Poisson statistics and is defined as:

$$DCSN = \sqrt{V_{DS}} \quad [e^{-}\ \mathrm{rms}]$$

Where V_{DS} is the mean dark signal in e^{-}/pixel.

5.23.1.2 *Spurious Charge or Clock-induced Charge Shot Noise (CIC_SN)*

Spurious charge is the parasitic signal due to hole impact ionisation at the CCD surface, particularly when the surface is clocked in and out of inversion. The spurious charge causes a fixed dark signal floor for given operating conditions. The temporal fluctuation of this clock induced charge follows Poisson statistics and its shot noise is defined as:

$$CIC\_SN = \sqrt{CIC} \text{ [e}^{-}\text{ rms]}$$

Where CIC is the mean clock-induced charge in e^-/pixel.

The spurious charge is typically measured as part of the dark signal and its associated noise included in the measurement of DCSN, however the CIC component does not scale with integration time or temperature as for the thermally generated dark signal.

5.23.1.3 *Output Amplifier Read Noise*

Output amplifier read noise is a combination of the thermal ‘white’ noise and the flicker noise.

The thermal ‘white’ noise, also called Johnson noise, is defined as:

$$V_w(F) = \sqrt{4kTR} \text{ [V.Hz}^{-1/2}\text{]}$$

Where:

V_W: Thermal ‘white’ noise [V.Hz$^{-1/2}$].
F: Frequency [Hz].
k: Boltzmann’s constant (1.38 × 10^{-23} J/K).
T: Absolute temperature [K].
R: Reset transistor channel resistance [Ω].

The flicker noise, also called 1/F noise, is defined as:

$$V_F(F) \propto \sqrt{\frac{1}{W.L.Cox.F}} \text{ [V.Hz}^{-1/2}\text{]}$$

Where:

V_F: Flicker noise [V.Hz$^{-1/2}$].
W: Transistor width [µm].
L: Transistor length [µm].
Cox: Transistor Gate oxide capacitance [µm].

5.23.1.4 *Reset Noise*

Reset noise is the temporal fluctuation of the reset level from pixel to pixel. The reset noise is defined as:

$$Vreset = \sqrt{\frac{kT}{C}} \text{ [V rms]}$$

Where C is the sense node capacitance in F.

The reset noise is mainly eliminated by using correlated double sampling of the CCD output waveform.

5.23.1.5 *Photon Shot Noise (PSN)*

Photon shot noise, PSN, is the temporal fluctuation of the arrival of photons on the CCD. The shot noise follows Poisson statistics and is defined as:

$$PSN = \sqrt{Vp} \text{ [e}^{-}\text{ rms]}$$

Where Vp is the mean photon generated signal in e^-/pixel.

5.23.1.6 *Random Telegraph Signal (RTS)*

Random telegraph signal (RTS) is the bistable or multi-stable state of atomic defects, leading to bi- or multi-levels of the dark signal over time. RTS is a noise that can be present in CCD detectors, especially after proton irradiation. The time constant of the dark signal level change is long and can reach several minutes. RTS is temperature dependant.

An RTS pixel has a dark signal modulation greater than a certain threshold, as defined by the Detail Specification, given over a specified period of time and at specified intervals.

5.23.2 Measurement Principle – General

The above defined noise sources all combine to give a temporal fluctuation of the signal at the CCD output for a given input photon flux. The total noise distribution can be measured, under illumination and/or darkness. Where specified in the Detail Specification certain components of the temporal noise can be measured individually. The separation of noise components by addition/subtraction in quadrature assumes each component has a simple Gaussian distribution.

For any measurement of noise the number of data points must be large so as to be statistically significant (typically > 1000). Once a distribution of noise values is measured, the noise is typically given by the standard deviation or rms value of the distribution.

For the majority of temporal noise measurements, the results must be corrected for the system noise contribution (provided the system noise standard deviation is smaller than the CCD noise under test, otherwise the total noise must be measured).

5.23.2.1 *Measurement Principle – System Noise*

The noise of the detection electronics is measured by replacing the CCD by a low-noise DC voltage supply (for example an available CCD bias or a battery) in series with a resistor. The voltage should be representative of the CCD DC output voltage and the resistor value representative of the CCD output impedance.

The CCD clock voltages and timing files are applied as specified in the Detail Specification. The signal as detected at the end of the digital video chain for multiple ‘pixel’ acquisitions, is analysed for the system rms noise, σ_0.

5.23.2.2 Measurement Principles – Total CCD Temporal Noise In Darkness

When measuring the total CCD temporal noise, the measurement principle must remove any spatial contributions to the signal level variance. This is achieved based on measuring either (1) multiple acquisitions of a signal pixel or (2) the difference in signal for each pixel.

(a) Principle 1

Many consecutive frames are acquired in darkness (typically 100, depending on sensor size) and each pixel, i, is analysed for its signal standard deviation over time, σ_i.

$$\sigma i_{i\,i}{}^{2} = \sigma^{2} - \sigma_{0}{}^{2}$$

Where:

σ: Total signal standard deviation for pixel i.
σ_0: System noise (rms).
σ_i: Pixel i noise (rms).

The mean standard deviation of all pixels, $\overline{\sigma_i}$, gives the total CCD temporal noise.

(b) Principle 2

Assuming the number of CCD pixels is large and that there is no low frequency noise component, two consecutive frames are acquired in darkness. The second image is subtracted from the first on a pixel by pixel basis. The resultant image is analysed for its standard deviation and the value is then divided by √2.

5.23.2.3 Measurement Principles – Output Amplifier Read Noise

(a) Principle 1 (applicable in the case of a single stage amplifier)

The noise power spectrum of the output amplifier transistor can be measured directly using a spectrum analyser if the CCD design allows access to the amplifier connections (e.g. as for a single stage amplifier). The reset transistor is biased permanently on and the output amplifier is biased as for normal operation (as specified in the Detail Specification). A spectrum analyser is used to record the noise spectrum at the drain (or source) of the amplifier MOSFET. The gain of the amplifier shall be determined (e.g. by injecting test pulses into the reset drain line) in order to refer noise voltages to the gate of the on-chip MOSFET.

N.B.:

The high frequency component (the white noise) will have a contribution from the effective channel resistance of the reset FET in the 'on' state which does not normally occur. This gives a Johnson noise component which must be taken into account (the channel resistance is typically 104Ω).

(b) Principle 2 (applicable if the output can be isolated)

The read noise generated in the output amplifier(s) can be separated from the overall noise if the design structure enables the output to be isolated by reverse clocking, where the order of clock high pulses is reversed so as to conduct the dark signal away from the output circuit. The CCD is otherwise operated as defined in the Detail Specification and multiple ‘pixel’ acquisitions are analysed for rms read noise.

(c) Principle 3: total noise analysed for read noise

If the output cannot be isolated from the pixels, the total CCD noise is measured (and corrected for system noise) and the amplifier read noise is deduced by subtracting the theoretical dark current shot noise in quadrature (calculated from a previous dark signal measurement).

5.23.2.4 Measurement Principle – DCSN

The dark current shot noise is not measured unless specified in the Detail Specification. It can only be separated from the total CCD noise if the output amplifier read noise can be isolated by measurement (see Para. 5.23.2.3, Principles 1 and 2). If this is the case then it is assumed that the remaining noise source is the shot noise from the pixel and register dark signal.

5.23.2.5 Measurement Conditions for DCSN

- Device in darkness.
- If required by design, the appropriate load has to be connected to the output pin.
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.
- Noise components to be measured as specified in the Detail Specification.

5.23.2.6 Measurement Principle – PSN

The total CCD temporal noise under illumination can be tested in a similar way to the total noise in darkness, but for a uniform illumination. The resultant noise is typically provided for signal to noise ratio measurements.

The total CCD temporal noise under illumination can be assumed to equal the sum in quadrature of the total temporal noise in darkness and the photon shot noise. If the total temporal noise in darkness has previously been measured then the remaining photon shot noise contribution can be calculated.

5.23.2.7 Measurement Conditions for PSN

- Uniform illumination.
- Average signal = $V_{SAT}/2$ (unless otherwise specified in the Detail Specification).
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.
- Noise components to be measured as specified in the Detail Specification.

NOTES:

1. The CVF optical measurement principle (Para. 5.20.3) uses the fact that the photon shot noise obeys Poisson statistics and measures the photon shot noise over different signal levels. Each column of data read in continuous scan mode (e.g. 1000 rows) contains the photon shot noise (PSN) and the variance, or (PSN [e^- rms])^2, and any increase in noise for increasing signal level e.g. from column to column, is due to the photons and not the equivalent noise in darkness.

5.23.2.8 Measurement Principle – RTS

The dark signal of each pixel is measured at multiple time intervals over a long duration defined as T_{range} (typically several minutes to a few hours). An acquisition of a burst of frames is taken every ΔT in time (and the number of acquired bursts = $T_{range}/\Delta T$). The dark signal is measured for all pixels. A burst of multiple images can be acquired and the median value found at each ΔT, so that any temporal noise becomes insignificant.

The number and position of the RTS pixels are given. The dark signal modulation threshold, above which the pixel is defined as having RTS, is given in the Detail Specification.

The RTS results can also be specified as follows:

- Peak to peak dark signal (for each RTS pixel, for the whole frame or for all pixels).
- A graph of signal versus time of RTS pixels which shows any bi- or multi-level signal.

- The difference between levels is defined as a step and the largest step is provided; MaxStep per RTS pixel.
- Distribution of values of the MaxSteps over the pixels.
- Position co-ordinates of the RTS pixels (pixels with a MaxStep greater than the defined threshold).

5.23.2.9 *Measurement Conditons for RTS*

- Device in darkness.
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.
- Integration times to be defined in the Detail Specification.
- Period between acquisitions, ΔT, to be defined in the Detail Specification.
- Total time range, T_{range}, to be defined in the Detail Specification.
- MaxStep threshold limit to be specified in the Detail Specification.

NOTES:

1. RTS may vary strongly as a function of temperature. The Detail Specification may require measurement as a function of temperature.

5.24 SPATIAL NON-UNIFORMITY

5.24.1 Definition – General

Spatial non-uniformity is the dispersion of performance from pixel to pixel that does not vary over time. Contributions to the CCD spatial non-uniformity are defined as follows:

- Pixel offset dispersion (also called Fixed Pattern Noise, FPN).
- Dark signal non-uniformity, DSNU.
- Photo-response non-uniformity, PRNU.
- Spectral photo-response non-uniformity, SPRNU.

5.24.2 Measurement Principle – General

For any spatial non-uniformity measurement, multiple image acquisitions should be acquired and averaged so that any temporal noise becomes insignificant.

The image reference level(s) should be carefully specified so as to correctly include the spatial dispersion under test.

5.24.3 Definition of Pixel Offset Dispersion (PFN)

Pixel offset dispersion is the variation of offset level from pixel to pixel in darkness and that is independent of integration time. The measurement gives the spatial variation of the dark signal 'floor' and measures any artefacts (defects not included) inherent to every image taken by the CCD. A fixed pattern noise can occur due to the structure of the CCD (e.g. diode glow, mask edges) or due to repeatable clock coupling onto the output signal.

The FPN will be present in all images and calculations of DSNU and PRNU and the Detail Specification should clearly state if FPN is subtracted.

5.24.4 Measurement Principle – FPN

A mean image is acquired in darkness with the minimum integration time. The resulting image can be subtracted on a pixel by pixel basis to correct for the offset dispersion.

There are several ways to specify the FPN:

- Peak to peak FPN: Max(FPNi) and Min(FPNi).
- Zero to peak FPN: Max|FPNi|.
- Standard deviation of the FPN: $[1/N\ \mathrm{SUM}(FPNi^2)]^{1/2}$.

5.24.5 Measurement Conditions for FPN

- Device in darkness.
- Minimum integration time.
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.

5.24.6 Definition of Dark Signal Non-Uniformity (DSNU)

Dark signal non-uniformity, DSNU, is the difference in signal output from one pixel to another in darkness. The DSNU represents the difference between the signal of each pixel and the average signal.

5.24.7 Measurement Principle – DSNU

An initial zero image (zero integration time) image is acquired with the device in darkness. The zero image is subtracted on a pixel by pixel basis from all subsequent frames to subtract the reference level and Fixed Pattern Noise. Where a zero image is not applicable, pre or post scan pixels can be used as the reference level in which case FPN is not subtracted.

An image with an increased integration time (T_i) is then acquired as per the average dark signal (Para. 5.22).

For each pixel i, a DSNUi is defined as a percentage of the average signal as:

$$DSNUi = [(V_{si} - V_a)/V_a] \times 100\ [\%]$$

Where:

V_{si} = Pixel signal.
N = Number of considered pixels.
V_a = Average signal = $[\mathrm{SUM}(V_{si})]/N$.

NOTES:

1. The DSNU can also be measured by considering the ‘local’ DSNU of blocks of p×p pixels.
2. DSNU can also be presented as an absolute value.

Where the integration time of measurement is different to the integration time specified in the Detail Specification, a linear correction can be made. The corrected dark signal, DSNU(T_i), is defined as:

$$DSNUi(Ti) = DSNU_i \cdot \frac{T_i\ specified}{T_i\ of\ \ measurement}$$

Where:

$DSNU_i$: DSNUi measured for the extended T_i.
i: Pixel index.

There are several ways to specify the DSNU:

- Peak to peak DSNU: Max(DSNUi) and Min(DSNUi).

- Zero to peak DSNU: Max|DSNUi|.
- Standard deviation of the DSNU: [1/N SUM(DSNUi^2)]$^{1/2}$.
- DSNU defect pixels (spikes and dips) beyond a threshold level [-a; +a].

Typically a = 3 times the maximum allowed standard deviation. The maximum allowed standard deviation is as specified in the Detail Specification.

The Detail Specification may require all DSNUi data in an appropriate format e.g. image, linear curve(s), histogram, defect mapping.

5.24.7.1 *Image Sensors Designed with Several Video Outputs*

DSNU calculations are made separately on each video output. Due to a gain mismatch between the different outputs, a dark signal imbalance may occur.

For each output, k, a DSNU$_{output\_k}$ is defined as:

DSNU$_{output\_k}$ = [Max(Vak) - Min(Vak)] / [SUM(Vak)/n] × 100 [%]

Where:

Vak = Average signal of output k.
n = Number of outputs.

The global DSNU of a multi-output device when expressed as a standard deviation is defined as:

$$Global\ DSNU = \sqrt{DSNU_\sigma(VOS1)^2 + DSNU_\sigma(VOS2)^2 + \dots\ + DSNU_\sigma(VOSk)^2 + \dots\ + DSNU_\sigma(VOSn)^2}$$

5.24.8 Measurement Conditions for DSNU

- Device in darkness.
- Operating conditions, clock waveforms and drive circuits to be specified in the Detail Specification.
- Regions of interest to be defined in the Detail Specification.
- Number of pixels (in a square block p×p) to be used for DSNU determination to be specified in the Detail Specification.
- Integration times to be defined in the Detail Specification.
- DSNU defect pixel threshold limit to be specified in the Detail Specification.

NOTES:

1. The mean value of several image acquisitions can be used so that the temporal noise is negligible.
2. DSNU is a strong function of temperature and substrate voltage, as for dark signal. The Detail Specification may require DSNU measurement as a function of temperature and/or substrate voltage.
3. If the FPN (and defect pixels) is subtracted in the DSNU measurement, the Detail Specification may require the FPN data separately (see Para. 5.24.3).

5.24.9 Definition of Photo-Response Non-Uniformity (PRNU)

Photo-response non-uniformity, PRNU, is the difference in signal output from one pixel to another for a uniform illumination. The PRNU represents the difference between the signal of each pixel and the average signal from a window of surrounding pixels or the entire image.

5.24.10 Measurement Principle – PRNU

The PRNU is measured at the specified wavelength using uniform illumination, typically set to a signal level around $V_{SAT}/2$. The mean value of several image acquisitions can be used so that the temporal noise is negligible.

With the same integration time, a mean dark image is acquired. The value of this dark image is subtracted on a pixel by pixel basis from the mean image under illumination.

For each pixel, i, a PRNUi is defined as:

$PRNUi = [(V_{si} - V_a)/V_a] \times 100$ [%]

Where:

V_{si} = Pixel signal.
N = Number of considered pixels.
V_a = Average signal = $[SUM(V_{si})]/N$.

The V_a value may correspond to a specified area of the CCD, such as the central $1cm^2$ area.

The PRNU can also be measured by considering the ‘local’ PRNU of blocks of p×p pixels, also called High Frequency PRNU.

There are several ways to specify the PRNU:

- Peak to peak PRNU: Max(PRNUi) and Min(PRNUi).
- Zero to peak PRNU: Max |PRNUi|.
- Standard deviation of the PRNU: $[1/N\ SUM(PRNUi^2)]^{1/2}$.
- PRNU defect pixels (spikes and dips) beyond a threshold level [-a; +a].

Typically a = 3 times the maximum allowed standard deviation. The maximum allowed standard deviation is as specified in the Detail Specification.

The Detail Specification may require all PRNUi data in an appropriate format e.g. image, linear curve(s), histogram, defect mapping.

NOTES:

1. The measured PRNU may depend on the cone angle and wavelength of the light beam used to form the uniform illumination, large cone angles (such as provided by a diffuser close to the CCD) shall not be used.
2. A diffuser can be used when testing specifically for pixel defects.

5.24.10.1 *Image Sensors Designed with Several Video Outputs*

PRNU calculations are made separately on each video output. Due to a gain mismatch between the different outputs, a responsivity imbalance may occur.

For each output, k, a $PRNU_{output\_k}$ is defined as:

$PRNU_{output\_k}$ = [Max(Vak) - Min(Vak)] / [SUM(Vak)/n] × 100 [%]

Where:

Vak = Average signal of output k.
n = Number of outputs.

The global PRNU of a multi-output device when expressed as a standard deviation is defined as:

$$Global\ PRNU = \sqrt{PRNU_{\sigma}(VOS1)^2 + PRNU_{\sigma}(VOS2)^2 + \ldots\ + PRNU_{\sigma}(VOSk)^2 + \ldots\ + PRNU_{\sigma}(VOSn)^2}$$

5.24.11 Measurement Conditions for PRNU

- Wavelength (and bandwidth) of illumination to be specified in the Detail Specification.
- Uniformity of illumination to be better than ±2.5% over the area of interest or uniformity correction shall be used.
- Cone angle of the illumination beam to be specified in the Detail Specification.
- Average signal = $V_{SAT}/2$ (unless otherwise specified in the Detail Specification).
- Number of pixels (in a square block p×p) to be used for PRNU determination to be specified in the Detail Specification.
- PRNU defect pixel threshold limit to be specified in the Detail Specification.

5.24.12 Definition of Spectral Photo-Response Non-Uniformity (SPRNU)

Spectral Photo-Response Non-Uniformity (SPRNU) is the spectral variation of responsivity in the photosensitive area, for a given narrow spectral band.

Usually, it is obtained by the difference of PRNU between a broad band reference spectrum and several spectral bands.

5.24.13 Measurement Principle – SPRNU

Non-uniformity due to spectral responsivity can be measured by a comparison of photo-response per pixel between different spectral bands.

For each pixel, i, in a given spectral band, the output signal is measured giving PRNUi.

For different specified spectral bands, B0 to Bk:

PRNU with B0 = PRNUi (B0)

PRNU with B1 = PRNUi (B1)

…

PRNU with Bk = PRNUi (Bk)

B0 is typically a broad spectral band containing the other narrower bands, B1 – Bk.

For each spectral band, an SPRNU(i) is defined (for each pixel i) by:

SPRNUi B1/B0 = PRNUi(B1) - PRNUi(B0)

SPRNUi B2/B0 = PRNUi(B2) - PRNUi(B0) etc.

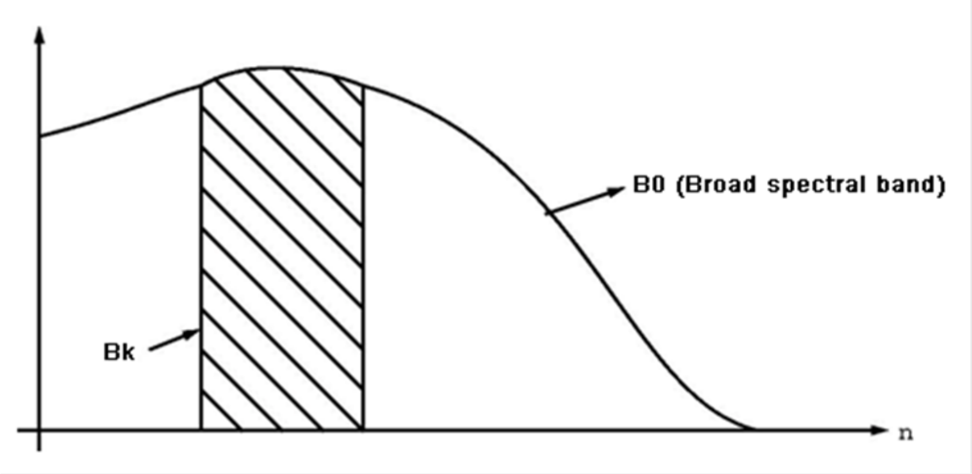
As for PRNU, the SPRNU for one band with respect to another can be specified as follows:

- Peak to peak SPRNU: Max(SPRNUi Bk/B0) - Min(SPRNUi Bk/B0).
- Zero to peak SPRNU: Max |SPRNUi Bk/B0|.
- Standard deviation of the SPRNU: $[1/N \text{ SUM}(\text{SPRNUi Bk/B0}^2)]^{1/2}$.

The Detail Specification may require all SPRNUi data in an appropriate format e.g. image, linear curve(s), histogram, defect mapping.

NOTES:

1. The different spectral bands B1 – Bk must all be situated inside the large band B0. To take the weighting factor of the broad band B0 into account, when measuring SPRNU in band Bk, the Bk filter must be superimposed on B0:



5.24.14 Measurement Conditions for SPRNU

- Wavelength bands to be specified in the Detail Specification.
- Uniformity of illumination to be better than ±2.5% over the area of interest or uniformity correction shall be used.
- Cone angle of the illumination beam to be specified in the Detail Specification.
- Average signal = $V_{SAT}/2$ (unless otherwise specified in the Detail Specification).

5.25 PHOTOSITE TO SHIFT REGISTER CROSSTALK

5.25.1 Definition

Photosite to shift register crosstalk is the ratio of charge generated in the shift register to the useful signal generated in the photosensitive area, for a given output signal.

5.25.2 Measurement Principle

Four images are acquired such that the ratio of photo-generated charge can be calculated.

An image under nominal operating conditions is acquired in darkness and a second image is acquired under illumination. The dark image is subtracted on a pixel by pixel basis and the average signal in the resultant image gives the useful signal coming from the photosensitive area.

A dedicated timing diagram is used to measure the charge detected uniquely in the shift register. To stop charge coming from the image area, the vertical transfer clocks are stopped, or reverse clocked away from the register, and where applicable the anti-blooming is activated.

An image with the dedicated timings is acquired in darkness and a second image is acquired under illumination. The dark image is subtracted on a pixel by pixel basis and the average signal in the resultant image gives the crosstalk signal being generated in the shift register.

The crosstalk is expressed as a percentage of the useful signal.

$$\text{Photosite to register crosstalk} = \frac{\sum_{i=1}^{N}(Vi_{light} - Vi_{dark})_{vertical\,clocks\,stopped} \Big/ N}{\sum_{i=1}^{N}(Vi_{light} - Vi_{dark}) \Big/ N} \times 100 \quad [\%]$$

Where:

V: Output signal.
i: Pixel index.
N: Number of active pixels.

NOTES:

1. The dark signal must be removed from the signals measured.
2. The integration time may be extended to increase measurement accuracy.
3. The register clocks may be stopped as well as the vertical transfer clocks, in order to increase the measurement accuracy. In this case the integration time for crosstalk detection differs from the integration time for useful signal detection and the ratio should be adjusted accordingly.
4. The crosstalk into each register element can also be provided, to include spatial information.
5. A similar method can be applied to measure the photosite to storage area crosstalk in a frame transfer device.
6. Any electrical crosstalk is not detected by this method due to subtraction of the dark signal.

5.25.3 Measurement Conditions

- Uniform illumination (wavelength as per Detail Specification).
- Average signal = $V_{SAT}/2$ (unless otherwise specified in the Detail Specification).
- Dedicated timing for crosstalk signal measurement.

5.26 LAG EFFECT

5.26.1 Definition

In a linear array, lag is the amount of residual photocharge left in a photodiode after a transfer operation from photosite to shift register. In a 2D array, lag is the amount of residual photocharge left in a pixel after multiple readouts.

The lag is defined as:

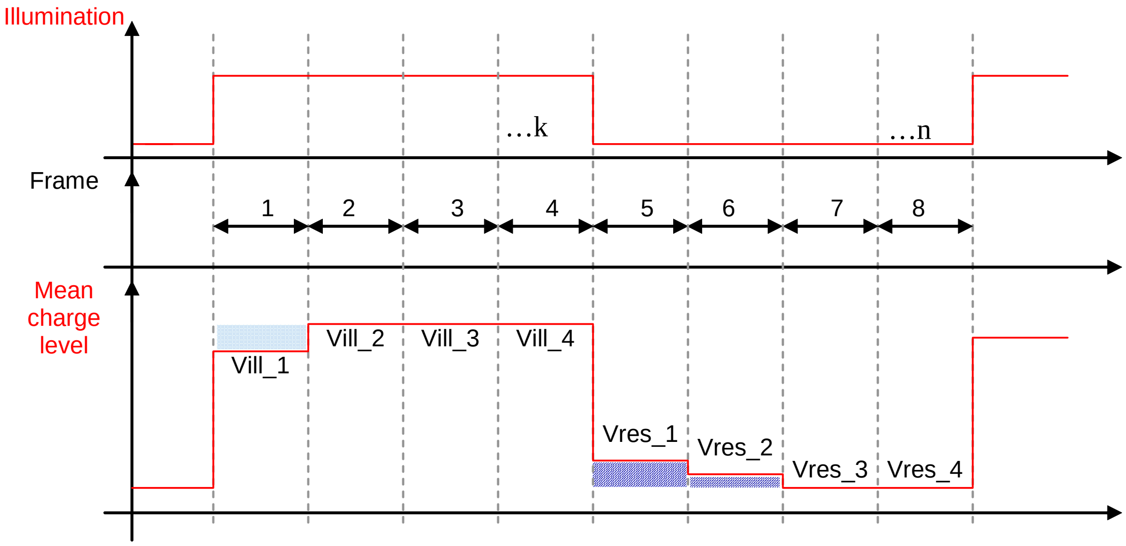
$$\text{Lag}(\%) = 100 \times \left[\frac{\text{Residual signal}}{\text{Useful signal}}\right]$$

5.26.2 Measurement Principles

The lag is measured after emptying the photodiode or pixels. This is typically done using pulsed illumination, such as an LED source.

For a linear array, the illumination period is synchronised to the vertical transfer clock so it is possible to read either the output signal due to incident illumination or the output signal due to the lag effect when the LED source is switched off (see timing chart below). The number of frames is chosen such that enough frames are read out in darkness to detect all deferred charge due to lag. The last frames contain only dark signal and system offsets and are used as reference. The number of illuminated frames must be large enough to be sure to obtain a stabilised signal.

SPECIFIC TIMING FOR LAG EFFECT MEASUREMENT IN LINEAR IMAGE SENSORS



For a 2D array, the principle of pulsed illumination is the same, except that the time constants are generally much longer. The image area should be continually readout to remove any charge transfer residue. The residual signal over the whole array (i.e. the lag) may be measured several minutes after stopping the illumination. The reference image should be taken after a sufficiently long time in darkness.

5.26.2.1 *Measurement Principle 1 – Extended Pixel Edge Response*

The residual signal can be detected in one or several images in darkness after the illumination period.

Due to the lag phenomenon, the output level of the first frame under illumination is lower than the established level so it is not used to calculate the useful signal. The useful signal is calculated from the last illuminated frame.

$$\text{Lag }(\%) = 100 \times \left[\frac{\text{Residual signal}}{\text{Useful signal}} \right]$$

$$= 100 \times \left[\frac{\sum_{m=1}^{n} Vres\_m \quad - n \cdot Vres\_n}{Vill\_k - Vres\_n} \right] \qquad \textit{for a linear array}$$

Where:

m: Frame integer.
k: Number of frames under illumination.
n: Number of frames in darkness.

5.26.2.2 *Measurement Principle 2 – First Pixel Edge Response (Only for Linear Arrays)*

As for CTE, the lag can be calculated using the extended pixel edge response or the first pixel edge response. Since the lag can depend on the signal level, the two types of measurement will not necessarily give the same results.

$$\text{Lag }(\%) = 100 \times \left[\frac{\text{Residual signal}}{\text{Useful signal}} \right] = 100 \times \left[\frac{Vill\_k - Vill\_1}{Vill\_k - Vres\_n} \right]$$

Due to the lag effect being a characteristic of the photodiode intrinsic structure, the measurement is performed on all pixels along the line.

NOTES:

1. The exact timing of the LED illumination has to be carefully designed in order to avoid illumination during transfer from the image area to the register. For 2D arrays the illumination timings may be controlled by a mechanical shutter.

5.26.3 Measurement Conditions

- Uniform illumination.
- Average signal = $V_{SAT}/2$ and $V_{SAT}/10$ (unless otherwise specified in the Detail Specification).
- LED wavelength to be specified in the Detail Specification.
- For a 2D array, time of frame acquisition after illumination has been stopped to be specified in the Detail Specification.

5.27 MODULATION TRANSFER FUNCTION (MTF)

5.27.1 Definition

Modulation Transfer Function, MTF, represents the spatial resolution capability of an image sensor.

The pixelated nature of CCDs means measuring MTF in terms of the continuous response to a sinusoidal input is not possible. Instead an ‘operational’ 1-dimensional MTF can be calculated by analysing the line spread function or edge spread function for a single pixel or a group of pixels.

The line spread function is defined as the relative response to an infinitesimally narrow line imaged on the pixel, measured at various distances from the centre of the pixel.

The edge spread function is defined as the relative response to a perfect black to white transition, imaged on the pixel, measured at various distances from the centre pixel. The derivative of the edge spread function gives an equivalent line spread function.

The Modulation Transfer Function for a given spatial frequency, v, is defined as the modulus of the Fourier transform of the line spread function. For zero spatial frequency, i.e. a constant mean input irradiance, v = 0 and MTF = 1. The measured MTF at a spatial frequency, v, is normalised to the MTF for zero spatial frequency.

Usually the resolution limit is taken at half the spatial sampling frequency of the CCD (the Nyquist frequency) and the MTF is typically specified at this particular spatial frequency:

$$v_0 = \frac{1}{2.p} \text{ [cycles/mm]}$$

Where:

v_0: Nyquist frequency.
p: Pixel pitch.

If the spatial frequency is equal to [1/pixel geometrical aperture] then the MTF is zero.

In all cases the MTF of the optical projection system must be measured and corrected for in the calculation of the CCD MTF. The optical system MTF must be obtained with the same wavelength band and optical configuration (aperture and magnification) as for the measurement of the detector.

$$MTF_{CCD} = \frac{MTF_{measured}}{MTF_{optics}}$$

5.27.2 Measurement Principles

Different measurement methods are:

1. Knife-edge or line scanning method.
2. Imaging of a slanted edge pattern or slit (applicable to area array devices only).

5.27.2.1 *Measurement Principle 1 – MTF Knife-edge or Line Scanning (Slit) method*

Through a lens or imaging optics, a “knife-edge” (or slit image), projected onto the sensitive area, is scanned in front of the device along a given direction. The CCD output voltage at each position gives one point of the edge spread function (or line spread function for a slit) of the analysed pixel. The mean dark signal is subtracted from each pixel output voltage.

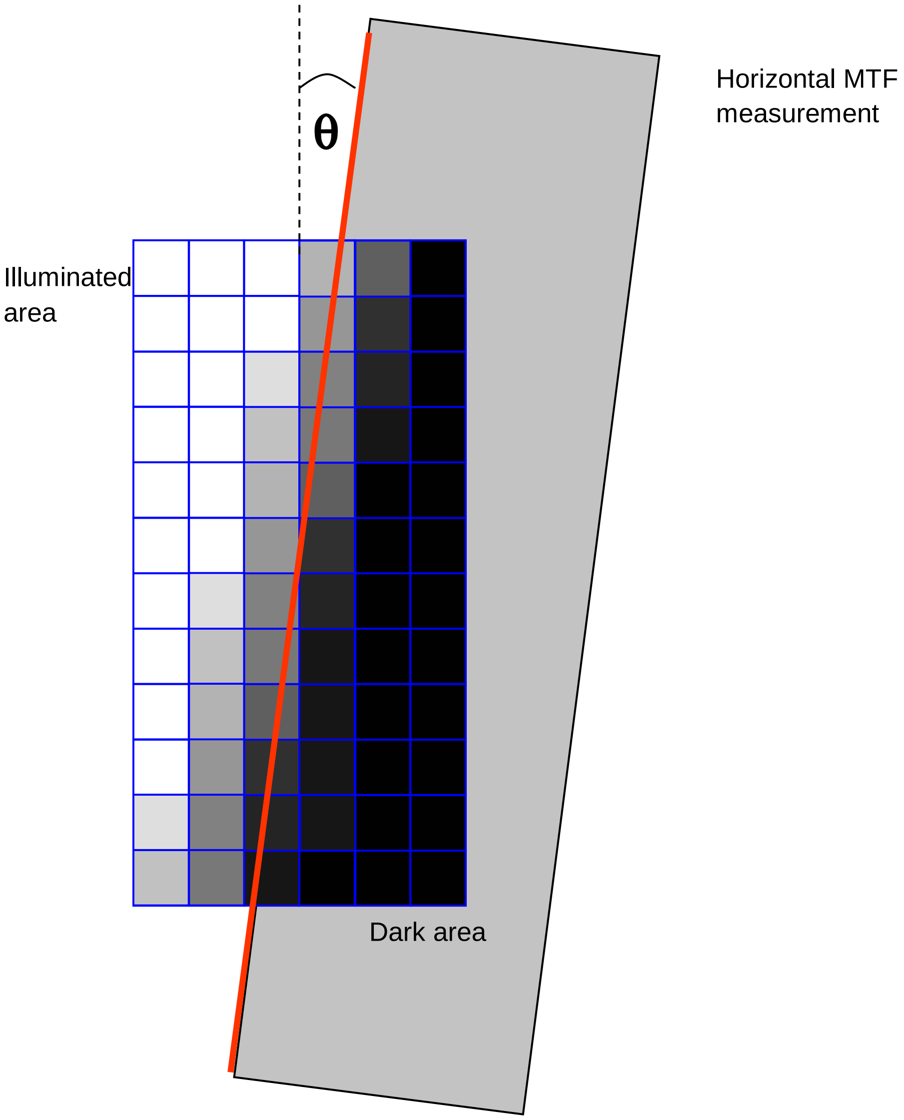
The line spread function is given by the derivative of the edge spread function (or is measured directly in the case of the image of a slit).

5.27.2.2 *Measurement Conditions for MTF Knife-edge or Line Scanning (Slit) Method*

- Uniform illumination.
- $V_{MAX} = V_{SAT}/2$ (unless otherwise specified in the Detail Specification).
- Knife-edge mask image or slit (negligible non-uniformity with respect to pixel pitch).
- MTF micro bench using micro-displacement units.
- Displacement Step to be specified in the Detail Specification (typically minimum 6 points per pixel pitch).
- Scanning direction to be specified in the Detail Specification.
- Scanning distance to be carefully chosen (more than one pixel pitch away but this shall depend on the specified wavelength and pixel size).
- Position of pixel(s) under test to be specified in the Detail Specification.
- Wavelength band and optics aperture to be specified in the Detail Specification.
- Optical MTF correction by measurement or analysis.

5.27.2.3 *Measurement Principle 2 – MTF Slanted Edge or Slit method*

Through a lens a “knife-edge” (or narrow slit) is projected onto the sensitive area array at an angle that is not parallel to the pixel edges:



With the same integration time, a dark image is acquired. The value of this dark image is subtracted on a pixel by pixel basis from the image under illumination.

In the resulting image, the position of the edge (or centre of the slit) within each row (or column) is determined. The signal in the row is normalised and the edge or slit position for that row is defined as the column in which the maximum of the derivative of the edge, or the maximum signal of the slit, is detected. A best-line fit to a plot of this column number for each line (or the inverse for vertical MTF) gives the gradient and therefore angle θ of the edge or slit.

Then for each pixel, the distance in x (or y), due to the gradient, is calculated with regards to the chosen reference pixel (the point where the edge or slit passes through the 'centre' of a pixel).

The composite edge spread function (or line spread function in the case of a slit image) of the device can then be constructed from a plot of each pixel's signal versus its distance from the centre of the reference pixel, with all rows (or columns) superposed on the same graph.

For the knife-edge, the line spread function is given by the derivative of the final construction of the edge spread function.

5.27.2.4 Measurement Conditions for MTF Slanted Edge or Slit Method

- Uniform illumination in the illuminated area.
- $V_{MAX} = V_{SAT}/2$ (unless otherwise specified in the Detail Specification).
- Device operated in full frame ('matrix' or 'staring' mode) or frame transfer mode.
- Knife-edge mask image or slit (negligible non-uniformity with respect to pixel pitch).
- MTF micro bench using micro-displacement units to position the edge with the specified gradient.
- Position of pixel(s) under test to be specified in the Detail Specification.
- Wavelength band and optics aperture to be specified in the Detail Specification.
- Angle of the edge or slit to be specified in the Detail Specification, typically for an MTF measurement in the x axis (called across track for scanning devices) the edge gradient is set to cross approximately 1 horizontal pixel for every 8 vertical pixel rows. For an MTF measurement in the y axis (called along track for scanning devices) the edge gradient is set to cross approximately 1 row for every 8 columns.
- Number of pixels either side of the edge (or slit) to be carefully chosen (more than one).
- Optical MTF correction by measurement or analysis.

NOTES (APPLICABLE TO PRINCIPLES 1 AND 2 UNLESS OTHERWISE SPECIFIED):

1. MTF is strongly dependant on wavelength.
2. In order not to degrade the MTF measurement, the edge or slit image has to be perfectly focused onto the CCD.
3. The fact that MTF=0 at a spatial frequency of 1/[pixel geometrical aperture] may be used as a criteria to check good measurement set-up. Displacement step, scanning distance, angle and number of pixels, must be chosen in order to satisfy this requirement.
4. The two methods to measure MTF only measure the static MTF of the CCD.
5. For matrix array sensors a pulsed light source may be used to eliminate transfer smearing.
6. If a slit is used to produce a line image on the CCD, the slit image width must be significantly less than the pixel pitch.
7. If significant PRNU is present, this should be corrected for in the image analysis (slanted edge/slit principle only).
8. To improve the accuracy of the Fourier Transform, a hamming window can be applied to the line spread function.
9. Reference documents:
    - ISO 15529, Optics and Photonics – Optical transfer function – Principles of measurement of modulation transfer function (MTF) of sampled imaging systems.
    - ISO 12233, Photography – Electronic still-picture cameras – Resolution measurements.
    - ISO 9334, Optics and Photonics – Optical transfer function – Definitions and mathematical relationships.
    - ISO 9335, Optics and Photonics – Optical transfer function – Principles and procedures of measurement.
    - ISO 11421, Optics and Optical Instruments – Accuracy Of Optical transfer function measurement.

5.27.3 Definition of Spectrally Weighted Modulation Transfer Function

Spectrally Weighted Modulation Transfer Function, MTF_W, is the MTF analysed and spectrally weighted over the range of spectral bands as required by the Detail Specification.

The MTF_w is defined as:

$$MTF_w = \frac{\sum_{\lambda=\lambda_1,\lambda_2....\lambda_n} \lambda \cdot QE(\lambda) \cdot I(\lambda) \cdot T(\lambda) \cdot MTF(\lambda)}{\sum_{\lambda=\lambda_1,\lambda_2....\lambda_n} \lambda \cdot QE(\lambda) \cdot I(\lambda) \cdot T(\lambda)}$$

Where:

λ_1, λ_2….λ_n are the centre wavelengths of the narrow band filters used to measure QE and MTF e.g. 500nm, 600nm etc.,
I(λ) is the spectral irradiance at the entrance of the objective imaging the edge, and
T(λ) is the spectral transmittance of the objective imaging the edge.

5.28 CONTRAST TRANSFER FUNCTION (CTF)

5.28.1 Definition

Contrast Transfer Function, CTF, represents the spatial resolution capability of the image sensor.

CTF is the CCD spatial frequency response to an input illumination (I) with a bar pattern spatial variation in the vertical (or horizontal) direction of the form

I = Io for 0 < x < (1/2v)n

I = 0 for (1/2v)n < x < (1/v)n

Where:

x: The distance across the CCD.
v: Spatial frequency of the pattern (cycles/mm).
n: Integer.

The bar pattern input will induce an output signal whose maximum (V_{max}) and minimum (V_{min}) can be found, and compared to the maximum (V_{MAX}) and minimum (V_{MIN}) signals that would be detected with ideal resolution.

The CTF is given by:

$$CTF = \frac{V_{\max} - V_{\min} \big/ V_{\max} + V_{\min}}{V_{MAX} - V_{MIN} \big/ V_{MAX} + V_{MIN}}$$

Usually the resolution limit is taken at half the spatial sampling frequency of the CCD called the Nyquist frequency and the CTF is typically specified at this particular spatial frequency:

$$v_0 = \frac{1}{2.p} \text{ [cycles/mm]}$$

Where p: Pixel pitch.

5.28.2 Measurement Principles

5.28.2.1 Measurement Principle 1 – Derivation from MTF

The CTF can be derived from the MTF measurement using the Coltman algorithm:

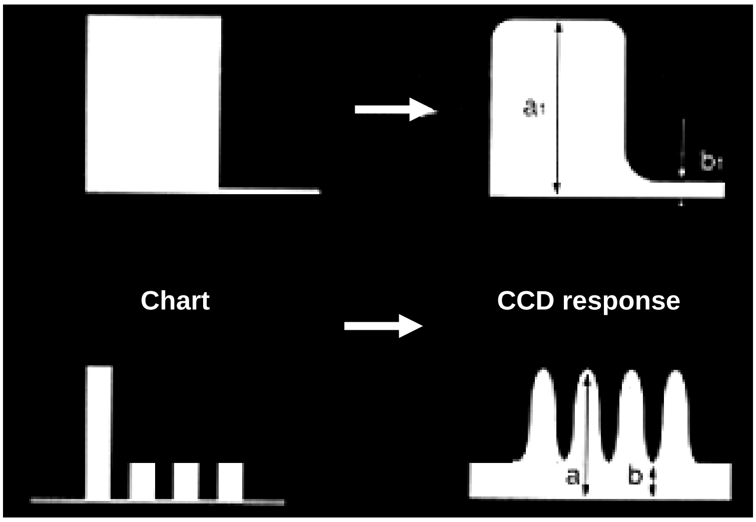
$$CTF(\upsilon)=\frac{4}{\pi}\times\left(MTF(\upsilon)+\frac{1}{3}MTF(3\upsilon)-\frac{1}{5}MTF(5\upsilon)+...\right)\cong\frac{4}{\pi}\times MTF(\upsilon)$$

5.28.2.2 Measurement Principle 2 – CTF Bar Pattern Method

Through a lens a test chart image of an ideal bar pattern is projected and focused onto the sensitive area array perpendicular to the measurement axis x or y (for linear devices only the x axis can be measured).

The bar pattern shall have a delta function profile of black and white at the detector plane. The period of the bar pattern should be equal to twice the pixel pitch i.e. the Nyquist frequency, or the specified spatial frequency.

The minimum and maximum values of the modulation are detected and compared to the minimum and maximum signals that would be detected with ideal resolution. The reference zero is measured on the black area of the pattern or chart.



NOTES:

1. a_1: Output signal under chart illumination, no spatial frequency ($V_{MAX}\theta$).
2. b_1: Output signal in black area of chart, no spatial frequency = zero reference.
3. a: Output signal maximum (V_{max}) under bar chart illumination.
4. b: Output signal minimum (V_{min}) under bar chart illumination.

The CTF is given by:

$$C = \frac{(a-b)}{(a+b)}, \quad C_1 = \frac{(a_1-b_1)}{(a_1+b_1)}, \quad CTF(\%) = \frac{C}{C_1}\times 100$$

The MTF of the optical projection system must be measured and corrected for in the CTF calculation. To a first order approximation the lens MTF can be used.

5.28.3 Measurement Conditions for CTF Bar Pattern Method

- Uniform illumination in the illuminated area.
- Bar pattern test chart (negligible non-uniformity with respect to pixel pitch).
- Bar pattern period at the CCD image plane to be specified in the Detail Specification (taking into account the optics magnification).
- The bar pattern image has to be strictly aligned with the pixels, in order to eliminate any low frequency modulation due to aliasing.
- Position of pixel(s) under test to be specified in the Detail Specification.
- Wavelength band and optics aperture to be specified in the Detail Specification.
- Optical MTF correction by measurement or analysis.

NOTES:

1. The bar pattern measurement of CTF only measures the static CTF of the CCD.
2. For matrix array sensors a pulsed light source may be used to eliminate transfer smearing.

5.29 THRESHOLD VOLTAGES

5.29.1 Definitions

The threshold voltage for a given bias or clock supply is the voltage below which (or in some cases above which) correct operation of the CCD no longer occurs.

5.29.1.1 Reset Drain threshold

The V_{RD} voltage below which charge is no longer transferred to the output node and the charge handling capacity of the output node is reduced.

5.29.1.2 Reset threshold

The $V_{\varnothing R}$ voltage below which the reset transistor is incorrectly turned ‘on’ such that charge remains on the output node after reset.

5.29.1.3 Antiblooming threshold (if applicable)

The antiblooming drain voltage below which charge flows from the antiblooming drain into the device. Alternatively for gated antiblooming structures the antiblooming gate voltage above which charge flows from the antiblooming drain into the device may be given.

5.29.1.4 Inversion threshold (if applicable)

The substrate voltage (relative to the clock low voltage) above which surface inversion occurs and dark signal is reduced.

5.29.2 Measurement Principles

All operating voltages must be set to nominal. The relevant parameter (often I_{RD}) is measured as a function of the bias voltage under test and the switching point determined.

5.29.2.1 *Measurement Principle 1 – Reset Drain threshold*

Uniform illumination is set such that the CCD output signal is as defined in the Detail Specification. The V_{RD} voltage is gradually decreased until a reduction in output signal and/or average Reset Drain current is detected. As the reduction in output signal occurs, an increase in horizontal transfer inefficiency may also occur.

5.29.2.2 *Measurement Principle 2 – Reset threshold*

When the Reset transistor does not correctly evacuate all charge and reset the output node to the V_{RD} potential, the measured reset level will vary depending on the signal level in the CCD. Uniform illumination is set such that the CCD output signal is as defined in the Detail Specification. An oscilloscope is used to analyse the output video waveform before the CDS and the reset level of an active pixel (typically the last active register pixel) is compared to a dark reference pixel. The $V_{ØR\_high}$ voltage is gradually decreased until a difference in reset level is detected between the two pixels. A reduction in output signal and an increase in horizontal transfer inefficiency may also occur.

5.29.2.3 *Measurement Principle 3 – Antiblooming threshold*

The CCD is operated in darkness. The antiblooming drain voltage is gradually decreased until an increase in dark signal (measured at the CCD output or as a reset drain current) is detected due to the injected charge.

Alternatively the antiblooming gate voltage is gradually increased until an increase in dark signal is detected due to the injected charge.

5.29.2.4 *Measurement Principle 4 – Inversion threshold*

The CCD is operated in darkness. The substrate voltage (relative to the clock low voltage) is gradually increased until a decrease in dark signal (measured at the CCD output or as a reset drain current) is detected due to the surface inversion and electron-hole recombination.

5.29.3 Measurement Conditions

- Uniform illumination (signal levels to be specified in the Detail Specification).
- Threshold switching point criteria to be specified in the Detail Specification.