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ELECTRO-OPTICAL TEST METHODS

FOR CHARGE COUPLED DEVICES

ESA/SCC Basic Specification No. 25000

SCC

space components
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FIGURES

1. SCOPE

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) shall be given in the Detail Specification.

2. APPLICABLE DOCUMENTS

None.

3. TERMS, DEFINITIONS, ABBREVIATIONS, SYMBOLS AND UNITS

The terms, definitions, abbreviations, symbols and units as specified in ESA/SCC Basic Specification No. 21300 shall apply. Other symbols and abbreviations are defined, as applicable, within the text of this document. For the purpose of this specification the CCD case temperature shall be monitored and held within the limits specified in each test method.

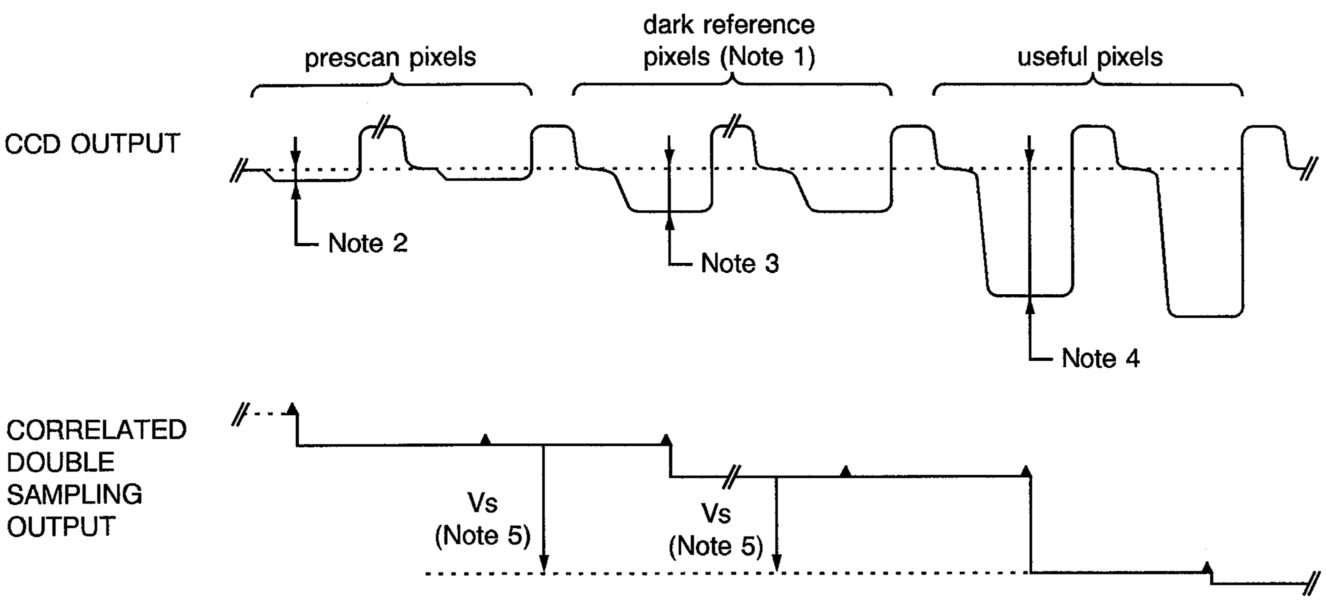
In this specification all CCD output signals are to be measured as the difference between the reference and signal levels of a given pixel, less the difference between the reference and signal levels of pre- (or post-) scan pixels (the offset voltage), shown in Figure 1. The useful signal is defined as the output signal arising from the CCD illumination (and excluding dark signal).

4. TEST EQUIPMENT

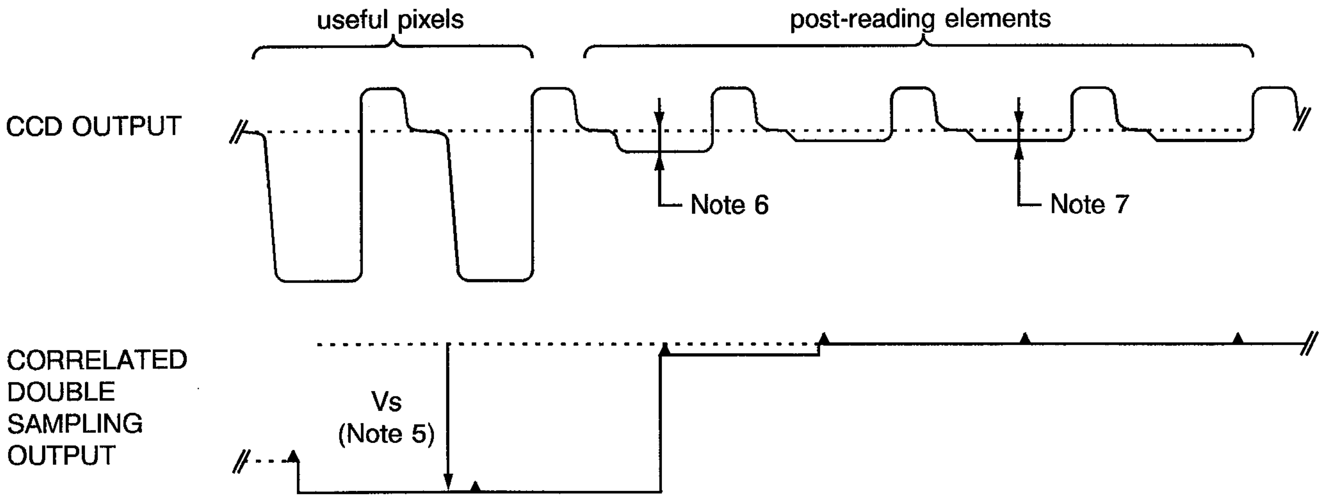
Test equipment applicable to electrical measurements on CCDs is described in Section 5. Test equipment applicable to electro-optical measurements (given in Section 6) would typically consist of a buffer amplifier, a correlated double sampling amplifier and analogue to digital converter, together with a data logging and analysis system (such as a video framestore and computer). For some measurements (particularly charge transfer efficiency, linearity and full well capacity) the results are dependent on the exact form of the clock waveforms (rise and fall times and shape, crossover of clocks). These (or the driver circuits) shall be specified in the Detail Specification.

FIGURE I(a) - TYPICAL LINE TIMING DIAGRAM OF CCD OUTPUT SIGNAL

BEGINNING OF LINE READOUT



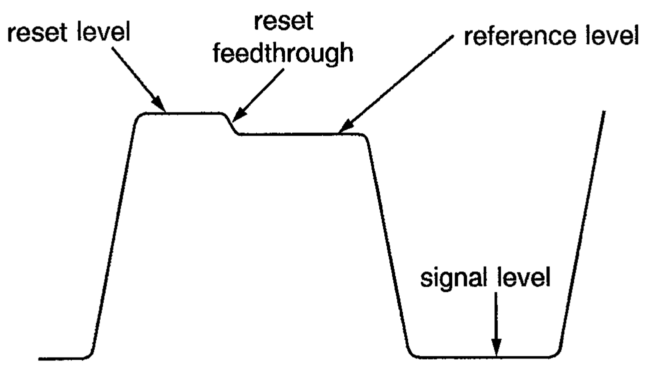
END OF LINE READOUT



NOTES

1. In some CCDs the dark reference pixels appear after the useful pixels.
2. Voltage comprises clock feedthrough (offset voltage) plus register dark signal.
3. Voltage comprises clock feedthrough (offset voltage) plus register dark signal plus photoelement dark signal.
4. Voltage comprises clock feedthrough (offset voltage) plus register dark signal plus photoelement dark signal plus useful photoelement signal.
5. V_S = signal voltage.
6. Voltage comprises clock feedthrough (offset voltage) plus register dark signal plus HCTI signal.
7. Voltage comprises clock feedthrough (offset voltage) plus register dark signal.

FIGURE I(b) - IDEAL CCD SIGNAL OUTPUT WAVEFORM



5. ELECTRICAL TEST METHODS

5.1 LEAKAGE CURRENT ON INPUT GATES (I_L)

5.1.1 Definition

Total leakage current on gates 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 as given in the Detail Specification (corresponding to the value commonly used for the clock high level). V_{SS} and all other pins (including pins which are both gates and diodes) are connected together.

The sum of leakage currents is read by a picoammeter connected between the V_{SS} pins and ground.

5.1.3 Measurement Conditions

- Device in darkness.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).

The device test support is specific to the device type (electrodes connected together; V_{SS} and V_{RD} connected to ground via the picoammeter; see Figure II).

5.2 INSULATION LEAKAGE CURRENT BETWEEN PINS (I_E)

5.2.1 Definition

Leakage current is measured between each pin of the CCD sensor and the other pins connected together.

5.2.2 Measurement Principle

The pin under test is biased at a positive voltage as specified in the Detail Specification. The other pins are connected to ground.

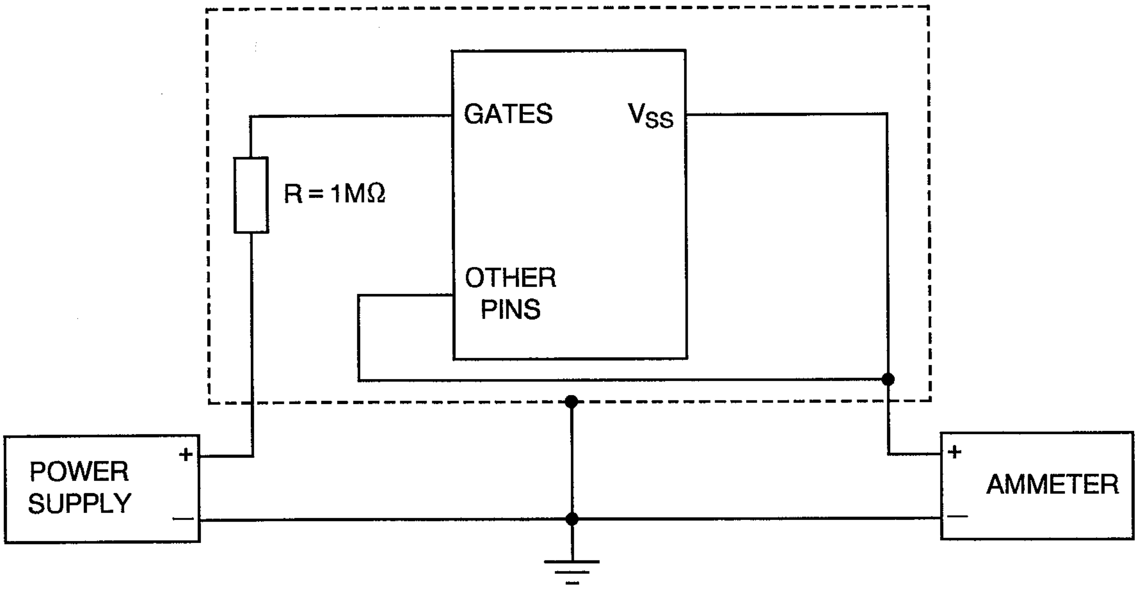
NOTES

1. If the pin under test is a diode, the other diodes must be disconnected from ground.

5.2.3 Measurement Conditions

- Device in darkness.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Each pin is successively addressed (other pins ground connected).

FIGURE II - LEAKAGE CURRENT MEASUREMENT ON INPUT GATES



5.3 POWER SUPPLY CURRENT

5.3.1 Definition

I_{DD} : supply current of the CCD output amplifier(s).

I_H : supply current of the internal driver circuits (if applicable).

5.3.2 Measurement Principle

Current measurement with an ammeter in the output amplifier (or internal clock driver) circuit(s).

5.3.3 Measurement Conditions

- Device in darkness.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification) (1).
- CCD operating biases can be dynamic or static (as specified in the Detail Specification).

NOTES

1. This parameter can be temperature sensitive and so measurements at more than one temperature may be specified in the Detail Specification.

5.4 DC OUTPUT LEVEL (V_{REF})

5.4.1 Definition

DC output voltage corresponding to the reference level of the output amplifier with respect to ground.

5.4.2 Measurement Principle

In order to protect the CCD and to have a good impedance matching the output voltage is sensed (e.g. using an oscilloscope) after a DC coupler buffer amplifier. The voltage difference between the input and output of the buffer amplifier shall be subtracted in the measurement.

5.4.3 Measurement Conditions

- Device in darkness.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).

5.5 AMPLITUDE OF RESET FEEDTHROUGH (V_{RESET})

5.5.1 Definition

When a pulse is applied to the gate of the reset transistor in order to recharge the output floating diode there is a capacitative feedthrough of this pulse onto the output video waveform. The amplitude of this feedthrough defined as the difference between the reset level and the reference level (as shown in Figure I) is the value to be measured.

5.5.2 Measurement Principle

Measurement of the output waveform using a digital oscilloscope.

5.5.3 Measurement Conditions

- Bias and clock voltages as given in the Detail Specification.
- CCD temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).

6. ELECTRO-OPTICAL TEST METHODS

6.1 OUTPUT IMPEDANCE (Z_S)

6.1.1 Definition

Dynamic output impedance of the CCD output amplifier.

6.1.2 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 output pin and ground, the average signal is then V2 (Figure III).

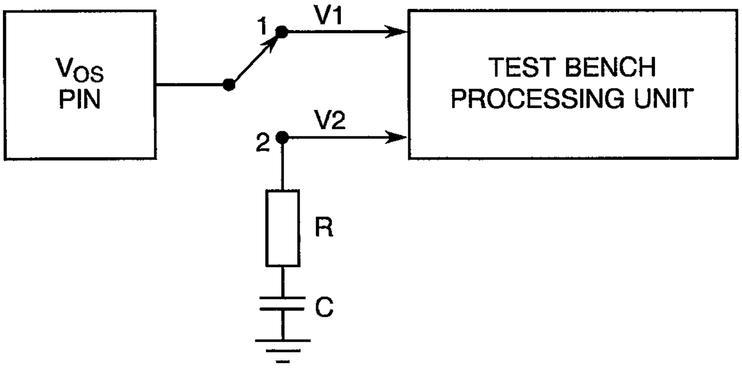
Measuring V1, V2 and knowing R enables the calculation of the output dynamic impedance:

$$V2 = V1 \times \frac{R}{R + Z_S} \Rightarrow Z_S = R \left[\frac{V1 - V2}{V2}\right]$$

6.1.3 Measurement Conditions

- Light source: halogen lamp + infrared filter (unless otherwise stated in the Detail Specification).
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).

FIGURE III - OUTPUT IMPEDANCE MEASUREMENT SETUP



NOTES
1. R and C shall be as specified in the Detail Specification.

6.2 ELECTRODE CAPACITANCE

6.2.1 Definition

This is the capacitative load experienced by an external TTL-MOS driver circuit when connected to a given clock input pin.

The capacitance is made up of three components: the capacitances of the gate dielectric, the depletion region and the inter-electrode oxide isolation(s). Since the depletion region capacitance depends on the stored charge the total electrode capacitance will vary with illumination level.

6.2.2 Measurement Principle

This measurement method takes the total capacitance into account. The capacitor under test is loaded at a DC voltage with an AC signal superimposed. The reset drain is biased at its typical operating value, V_{RD} (as given in the Detail Specification). The pin under test is connected to the input 'high' of a capacitance bridge. The gates which are not under test are connected to a voltage of 15Vdc (unless otherwise specified in the Detail Specification). V_S and V_{SS} are connected to the input 'low' of the capacitance bridge.

6.2.3 Measurement Conditions

- Illumination level as given in the Detail Specification (typically in darkness but the capacitance can also be specified for uniform saturation conditions or for a uniform illumination level in between).
- Load voltage: 10Vdc plus 50mV, 1.0MHz (unless otherwise stated in the Detail Specification).
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).

6.2.4 Electrode Capacitance with Respect to Another Clock

The method is identical to the one specified in Para's 6.2.2 and 6.2.3 with the following modification:

Some clock pins (as specified in the Detail Specification) are connected together with respect to others in order to get equations according to the overlapping capacitances to be measured.

6.3 OUTPUT SIGNAL WAVEFORM FEATURES

6.3.1 Definition

Output signal waveform measurements include the settling time and duration of both the reset level and the signal level.

6.3.2 Measurement Principle

The CCD output signal is sensed directly at the output of a buffer amplifier with a digital oscilloscope. The serial register transfer clocks are used for time reference of signal level measurement. The reset clock ΦR is used for time reference of the reset level measurement.

Operating frequency and drive circuits shall be as specified in the Detail Specification. 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.

The settling time and level duration are defined as follows:

- Settling Time: time elapsed from reference clock falling edge (taken at 10%, unless otherwise stated in the Detail Specification) to the start of the error band (1).
- Duration: duration of the signal within the error band (1).

NOTES

1. The error band consists of two limits defined in the Detail Specification either as voltages or percentages of the output signal (see Figure IV).
2. The bandpass of the oscilloscope must be at least 5 times the readout frequency.

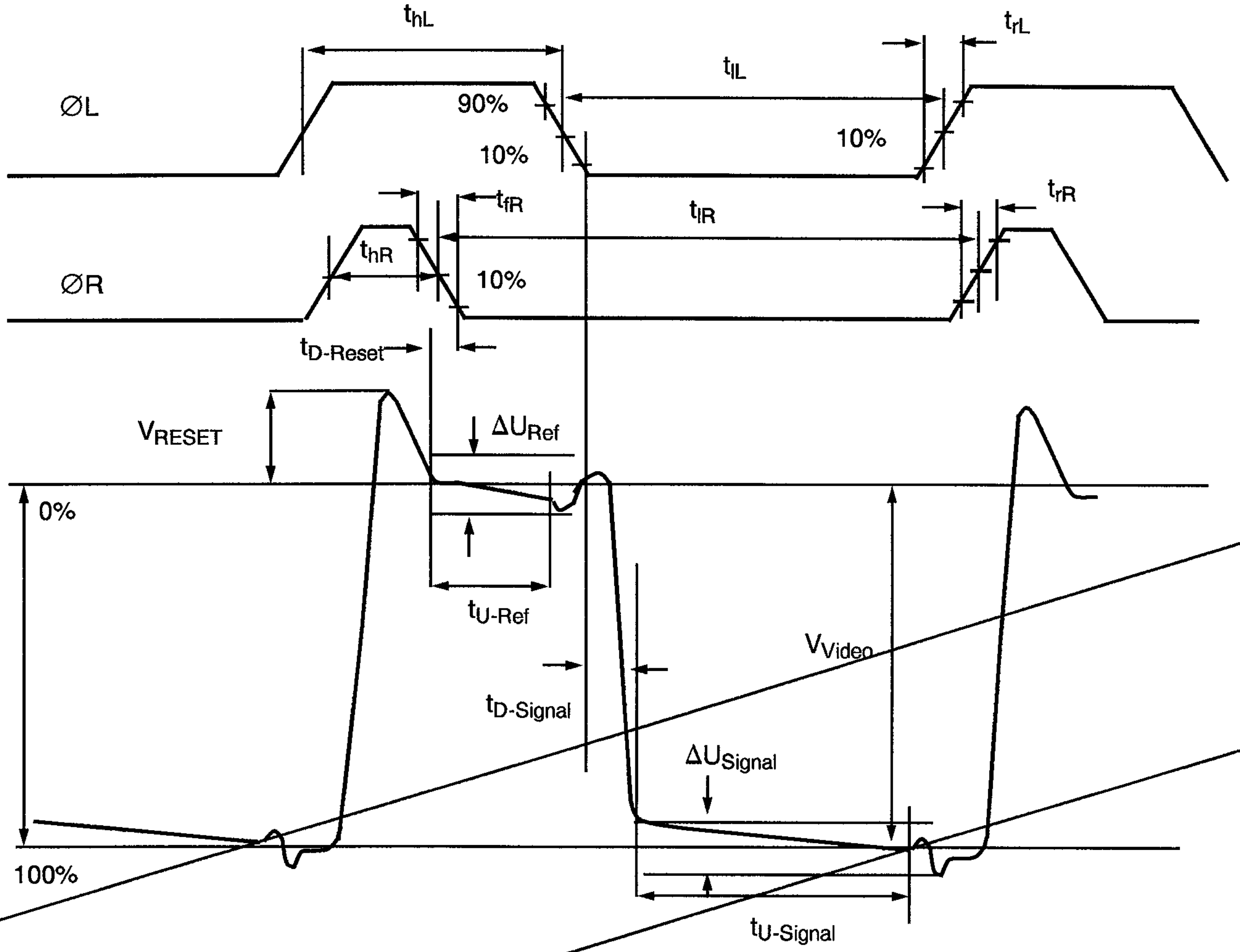
6.3.3 Measurement Conditions

- Light source: halogen lamp + infrared filter (or as stated in the Detail Specification).
- Uniform illumination ($V_{SAT/2}$) (or as stated in the Detail Specification (1)).
- Temperature: 25 ± 3°C (or as stated in the Detail Specification).
- Clock waveforms and drive circuits as specified in the Detail Specification.

NOTES

1. A measurement in darkness gives a convenient record of system-induced ripple on the output waveform.

FIGURE IV - TIMING RELATIONS USED FOR OUTPUT SIGNAL WAVEFORM MEASUREMENTS



6.4 TEMPORAL NOISE

6.4.1 Definition

The temporal noise on the CCD output waveform arises from the following sources:

(i) Noise associated with the CCD output amplifier stage.

(ii) Reset noise associated with the resetting of the output stage.

(iii) Shot noise on any signal (arising either from illumination or thermal dark current).

(iv) Noise due to external (off-chip) electronics and to on-chip feedthrough from clock and bias lines.

It is assumed that the test system electronics is such that (iv) is small in comparison to the total CCD temporal noise, in which case the total rms output noise will be the root sum square of the above components.

6.4.2 Measurement Principle

Methods of measuring CCD temporal noise can be grouped as follows:

(a) Measurements of the noise power spectrum of the output amplifier. These can be made if the CCD design allows access to the amplifier connections (e.g. as for a single stage amplifier). If there is an off-chip load this must be specified in the Detail Specification. The reset transistor is biased permanently on and the output amplifier is biased as for normal operation (as given 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.

Note that the high frequency component (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 allowed for (the channel resistance is typically $10^4\Omega$).

(b) - Forming the rms of N successive pixel values, X_i, for a single pixel

The noise σ_m is given by

$$\sigma_m = \frac{1}{G} \left[\frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X}_i)^2 \right]^{\frac{1}{2}}$$

where G = gain of the off-chip signal processing unit.

The total number of individual pixel measurements (= N) should be at least 1000.

- If necessary, the average over a group of pixels can be made (assuming the noise is the same for every pixel in the group).

$$\sigma_m^2 = \frac{1}{n} \sum_{j=1}^{n} \sigma_{m,j}^2$$

The measurement shall be made in darkness either for valid or for pre- (or post-) scan pixels (as specified in the Detail Specification). In the former case the measurement will include the shot noise on the dark current.

(c) If the noise on successive pixels (in a row or column) is not correlated - i.e. if a correlated double sampling amplifier is used to remove low frequency noise, then the following procedure can be used (if specified in the Detail Specification).

Two successive acquisitions of the same row (or area) are made.

L1 = First acquisition (containing N pixels) x_1, x_2.....x_N.

L'1 = Second acquisition (containing N pixels) x'_1, x'_2.....x'_N.

With spatial non-uniformity elimination, it is equivalent to 2 x N acquisitions of a single pixel, and it is possible to derive the noise σ_m:

$$\sigma_m = \frac{1}{G} \left[\frac{(x_1 - x'_1)^2 \quad + (x_2 - x'_2)^2 \quad + \dots \ (x_N - x'_N)^2}{2N} \right]^{\frac{1}{2}}$$

where G = gain of the off chip signal processing unit.

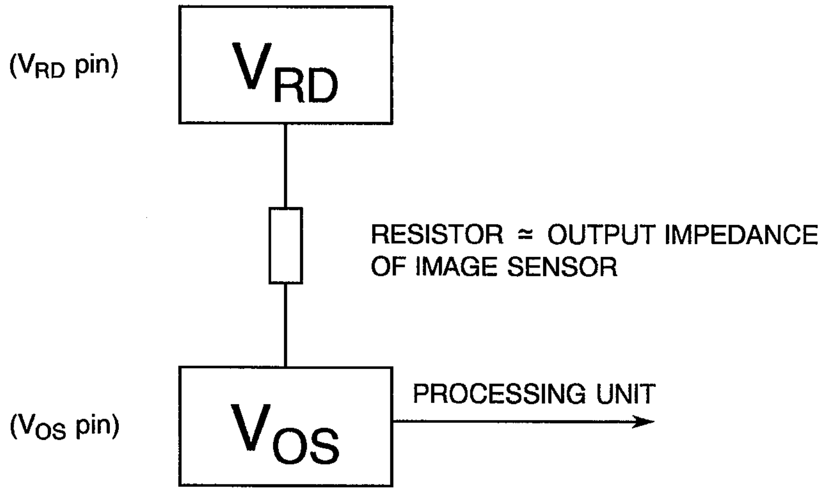
In cases (b) and (c), σ_m is the RMS noise of both the processing unit and the image sensor under measurement.

Knowing the processing unit noise, σ_o, the image sensor noise is defined as:

$$V_N = (\sigma_m{}^2 - \sigma_o{}^2)^{\frac{1}{2}}$$

σ_o is measured by replacing the image sensor by a specific noise calibrator in order to input, into the processing unit, a DC signal equivalent to the image sensor DC output voltage (Figure V).

FIGURE V - PROCESSING UNIT NOISE MEASUREMENT



6.4.3 Measurement Conditions

- Device in darkness.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Pixel frequency as given in the Detail Specification.

6.5 OFFSET VOLTAGE (V_{offset})

6.5.1 Definition

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 signal charge or thermal dark current. It arises from the clock feedthrough of readout register clocks onto the output node.

6.5.2 Measurement Principle

Measurement of the voltage difference between the reference and signal levels for pre- (or post-) scan elements, averaged over several such elements.

NOTES

1. The difference between the reference level and the signal level contains the clock feedthrough and the register average signal.

6.5.3 Measurement Conditions

- Temperature: $25 \pm 3°C$ (unless otherwise stated in the Detail Specification (1)).
- Bias voltages as given in the Detail Specification (2).
- Clock waveforms as given in the Detail Specification (2).

NOTES

1. This parameter can be temperature sensitive and the Detail Specification may require measurement at several temperatures.
2. This parameter can be sensitive to some operating biases and the Detail Specification may require measurement at several bias or clock voltages.

6.6 LINEARITY ERROR (LE)

6.6.1 Definition

The linearity error of the output signal voltage versus input exposure (= irradiance × exposure time, T_E) is defined as the maximum discrepancy between the output signal and the ideal (straight line) behaviour. Departures from linearity become large as saturation is approached (i.e. for signals comparable with the CCD full well capacity, V_{SAT}). Thus specification of a maximum allowed linearity error also defines the useful full well capacity. The non-linearity at saturation is a symptom of charge coming into contact with surface states. This contact also results in a reduction in charge transfer efficiency. Hence the maximum non-linearity is also linked to the worst-case charge transfer efficiency. Below saturation, non-linearity can be caused by readout capacitance non-linearity, output amplifier non-linearity and charge transfer efficiency effects.

Unless otherwise stated in the Detail Specification, the linearity error is defined as a percentage of the output signal at any time. However, if specified in the Detail Specification, linearity error can be expressed as a percentage of the full scale signal. Full scale shall normally be defined as CCD full well capacity but the Detail Specification may call for a smaller value of full scale voltage (e.g. in a case where linearity for small signals is important).

6.6.2 Measurement Principle

Several methods of linearity measurement are possible but these can be classified into two groups according to the method of illumination:

(i) uniform illumination.

(ii) spot illumination.

The results obtained for these two types of illumination will not necessarily be the same because of the characteristics of the surface traps involved.

The principle of the measurement is to increase the incident exposure (TE × E) by acting either on Ti or the incident illumination. Integration time can be measured with a better accuracy and a large range of different Ti can be obtained. So it is recommended that the variations of incident exposure are made by varying Ti, keeping the irradiance constant (using a stabilised light source) (Figure VI). At least 10 measurement steps shall be used.

The straight line fit to the data shall be found by the method of least squares. Below saturation (i.e. on the straight line part of the linearity plot), it can normally be arranged that the fit is over a range of data points such that the correlation coefficient between the data and the fitted line should normally be 0.995.

For spot measurements on a single pixel, the diameter of the spot (first Airy ring) shall be less than 5.0μm (unless otherwise stated in the Detail Specification).

For each exposure step E_i, the average signal V_j is calculated (averaged over N pixels for uniform illumination or N frames for spot illumination): $V_j = SUM[Vs_i]/N$, where i is the pixel index. The dark signal (averaged over the same pixels) is then subtracted so as to give signal values S_j:

$$S_j = V_j - VDS_j$$

In the case where LE is expressed as a percentage of the signal at any time a discrepancy can be calculated for each measured point by comparison with the straight line:

$$\text{Discrepancy (j)} = \left[\frac{S_j / E_j}{\text{straight line slope}} - 1 \right] \times 100\ (\%)$$

The linearity error LE is defined by:

$$LE = MAX\ [\ \text{Discrepancy (j)}\ ]$$

In the case where LE is expressed as a percentage of full scale (corresponding to full scale exposure $E_{\text{full scale}}$), we have:

$$\text{Discrepancy (j)} = \left[\frac{S_j / E_{\text{full scale}}}{\text{straight line slope}} - \frac{E_j}{E_{\text{full scale}}} \right] \times 100\ (\%)$$

6.6.3 Measurement Conditions

- Clocking waveforms and drive circuits as given in the Detail Specification.
- Status of antiblooming control, if applicable (i.e. ON or OFF) to be defined in the Detail Specification.
- Method of illumination (spot or uniform) as given in the Detail Specification.
- CCD temperature 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Spot size (diameter of first Airy ring) <5.0μm (unless otherwise stated in the Detail Specification).

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

6.7.1 Definition

As stated in Para. 6.6, linearity deteriorates rapidly on approaching saturation either due to the approach to pixel full well capacity (degradation of transfer efficiency) or to the onset of large non-linearities in the output amplifier. V_{SAT-IM} is defined as the output voltage below which the linearity is within a specified error.

6.7.2 Measurement Principle

Coarse methods for determining the full well capacity on a global scale (for the whole CCD) can be used to determine regions of the CCD which will have a low full well capacity, whilst other methods can accurately determine the behaviour for a small number of pixels:

(a) Global method: use a steadily increasing line illumination and monitor the signal in the first overscanned line (the line immediately following the last useful line). At saturation the signal in the first overscanned line starts to increase.

(b) Measurement of the output signal from a single pixel (or group of pixels) as a function of exposure (= irradiance, E × Ti) as in Para. 6.6.

V_{SAT-IM} is then the output voltage corresponding to a maximum value of linearity error LE_{SAT}.

6.7.3 Measurement Conditions

- Clocking waveforms and drive circuits as given in the Detail Specification.
- Method of illumination (spot or uniform) as given in the Detail Specification.
- CCD temperature 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Maximum allowed linearity error for definition of V_{SAT} (LE_{SAT}) = 3.0% (unless otherwise stated in the Detail Specification).
- Spot size (diameter of first Airy ring) < 5.0µm (unless otherwise stated in the Detail Specification).

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

6.8.1 Definition

Saturation (V_{SAT}) can be defined for the readout register of an area array in the same way as in Para. 6.7. $V_{SAT-READOUT}$ will normally be higher than for the image (or storage) zone of an area device.

6.8.2 Measurement Principle

Linearity and $V_{SAT-READOUT}$ measurements are performed as in Para's. 6.6 and 6.7 method (b) i.e. with similar illumination level per pixel) but either with line illumination (oriented along a CCD column) or uniform illumination; and with binning of lines into the readout 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 given in the Detail Specification, a typical number being 3 lines). Note that spot illumination of a single pixel is not appropriate, if a small area of the CCD is to be illuminated then there must be uniform illumination of at least N pixels in the column direction.

6.8.3 Measurement Conditions

- Clocking waveforms and drive circuits as given in the Detail Specification.
- Method of illumination (column or uniform) as given in the Detail Specification.
- CCD temperature 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Maximum allowed linearity error for definition of V_{SAT} (LE_{SAT}) = 3.0% (unless otherwise stated in the Detail Specification).
- Width of column illumination < 10µm (unless otherwise stated in the Detail Specification).

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

6.9.1 Definition

Saturation ($V_{SAT-OUTPUT}$) can be defined for the output node (normally a floating diode) in the same way as in Paras. 6.7 and 6.8. V_{SAT} will normally be higher than for the CCD register part(s) of the device.

6.9.2 Measurement Principle

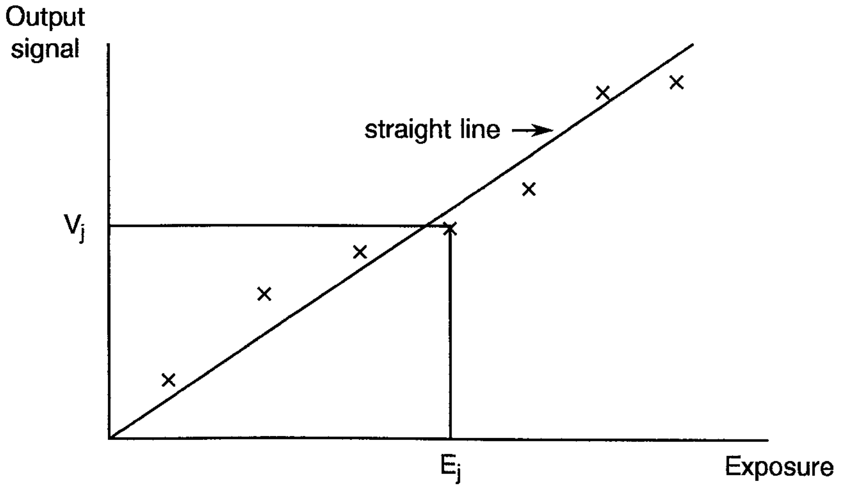
(i) Use uniform illumination and transfer charge from the serial register into the output node without resetting. The output voltage will then increase in a staircase fashion until saturation is reached. If necessary, pixels can be binned into the readout register to improve uniformity.

(ii) A method which does not rely on the uniformity of illumination is an extension of that given in Para. 6.7 (output voltage versus exposure) but to bin a number of pixels (typically 3) into the output node (saturation shall occur in the output node before it occurs in the readout register or image area). Spot illumination shall be used with the spot size being large enough to ensure uniform illumination of the pixels to be binned.

6.9.3 Measurement Conditions

- Clocking waveforms and drive circuits as given in the Detail Specification.
- Method of illumination (spot or uniform) as given in the Detail Specification.
- CCD temperature 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Maximum allowed linearity error for definition of V_{SAT} (LE_{SAT}) = 3.0% (unless otherwise stated in the Detail Specification).

FIGURE VI - DEFINITION OF LINEARITY ERROR (LE)



6.10 BLOOMING CHARACTERISTICS

6.10.1 Definition

When saturation is reached, charge starts to spread from an illuminated pixel into adjacent pixels. This phenomenon is termed blooming.

6.10.2 Measurement Principle

Spot illumination is used (spot size = diameter of first Airy ring $<5\mu m$ unless otherwise stated in the Detail Specification). Signals in the adjacent pixels are plotted as a function of exposure (as well as the illuminated pixel).

6.10.3 Measurement Conditions

- Clocking waveforms and drive circuits as given in the Detail Specification.
- Method of illumination (spot) as given in the Detail Specification.
- Wavelength of illumination as given in the Detail Specification.
- CCD temperature: $25 \pm 3°C$ (unless otherwise stated in the Detail Specification).
- Spot size (diameter of first Airy ring) $<5\mu m$ (unless otherwise stated in the Detail Specification).

6.11 ANTIBLOOMING OPERATION

6.11.1 Definition

Some CCD architectures have antiblooming structures which drain charge out of an illuminated pixel when saturation is reached. Performance is specified in terms of the optical overload (in multiples of the saturation exposure) that the sensor can experience before blooming occurs.

6.11.2 Measurement Principle

Spot illumination is used (spot size = diameter of first Airy ring $<5\mu m$ unless otherwise stated in the Detail Specification). Signals in the adjacent pixels are plotted as a function of exposure (as well as the illuminated pixel).

6.11.3 Measurement Conditions

- Clocking waveforms and drive circuits as given in the Detail Specification.
- Method of illumination (spot) as given in the Detail Specification.
- Wavelength of illumination as given in the Detail Specification.
- CCD temperature: $25 \pm 3°C$ (unless otherwise stated in the Detail Specification).
- Spot size (diameter of first Airy ring) $<5\mu m$ (unless otherwise stated in the Detail Specification).

6.12 CHARGE TRANSFER EFFICIENCY (CTE)

6.12.1 Definition

CTE measures the proportion of charge transferred from one stage to the next (Note 1).

The percentage of well-transferred charge after N stages is given by:

$(CTE)^N = (1 - \varepsilon)^N \approx 1 - N.\varepsilon$

where ε is the charge transfer inefficiency for one stage .

The CTE can be defined for horizontal (i.e. serial) transfer: HCTE or for vertical (i.e. parallel) transfers: VCTE.

The charge transfer inefficiency CTI = 1-CTE and HCTI, VCTI are defined for horizontal and vertical transfers respectively.

At CCD saturation the CTE is reduced because charge comes into contact with surface states. Hence the minimum CTE is usually defined at V_{SAT}. However CTE can sometimes be reduced for small signals also (and can be a function of signal intensity). Hence the signal level (or levels) must be stated in the Detail Specification.

NOTES

1. A stage is a set of four gates on two phases and four phases CCD design or a set of three gates on three phases design.
2. ε is the charge transfer inefficiency for one stage.

6.12.2 Measurement Principle

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

(i) Methods based on measuring the signal lost from a charge packet as a function of the number of transfers.

(ii) Methods based on measuring the signal deferred into trailing pixels, as a function of the number of transfers.

In general charge lost during a given transfer may be deferred over several pixels so that the two types of measurement will not necessarily give the same results in all circumstances (depending on the exact details of the method and the experimental errors).

Methods of illumination also vary:

(a) Uniform illumination methods. These rely on measuring deferred charge (for the first trailing pixel or a group of pixels). The CCD architecture must give a sharp transition between the last useful line (or column) and the first masked (or overscanned) pixel. This determination can also be called extended pixel edge response.

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

(b) Point illumination methods. Methods of introducing charge into a single pixel 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 given in the Detail Specification.

(ii) Illumination with soft x-rays from a radioactive source (e.g. Cd^{109} or Fe^{55}). 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 (given in electrons by the x-ray energy, in eV, divided by 3.65).

(iii) Electrical injection of charge, the so called periodic pulse technique. This is only applicable if the CCD has an input gate.

(c) Imaging methods. For example, imaging of a grid pattern can be a useful technique for assessing low signal 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. The Detail Specification shall specify the measurement method to be used and also the accuracy of measurement required.

Only the x-ray method, imaging methods and spot illumination methods (with several widely spaced pixels to be measured) are capable of identifying localised regions of poor CTE.

For TV mode sensors, there is smearing in the image zone if the transfer is made under illumination, incident photons add spurious charge to those which have been accumulated during integration time.

The total smearing factor NS is defined by:

$$NS = \frac{T_t \times N}{Ti + (T_t \times N)}$$

where N = number of lines to transfer
T_t = duration of vertical transfer period
Ti = integration time

This smearing information must be subtracted to obtain the level of the transfer inefficiency.

NOTES

1. The smearing can be disabled if a pulsed LED source is used instead of a halogen lamp.

6.12.3 Measurement Conditions

- Clocking waveforms and circuits as given in the Detail Specification.
- Status of antiblooming control, if applicable (i.e. ON or OFF) to be defined in the Detail Specification.
- Method of illumination, pixels to be measured and accuracy of measurement to be given in the Detail Specification.
- CCD temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).

6.13 CAPTURE AND EMISSION TIME CONSTANTS OF TRAPPING STATES

6.13.1 Definition

Trapping states in a CCD buried channel contribute to reduced charge transfer efficiency. The capture and emission time constants of these traps (τ_c and τ_e, respectively) are important parameters for determining the effect of operating conditions (e.g. clocking waveforms, temperature) on CTE performance.

6.13.2 Measurement Principle

Point illumination or periodic pulse techniques can be used. Techniques are specialised and, if required, are to be defined in the Detail Specification.

6.14 PHOTORESPONSE NON-UNIFORMITY

6.14.1 Definition

For a uniform illumination, charge signals will be somewhat different from one pixel to another and there is thus what is termed photoresponse non-uniformity.

The photoresponse non-uniformity, PRNU, represents the difference in % between the signal of each pixel and the average signal of the total photosensitive area (excluding the extreme edge pixels in some cases).

6.14.2 Measurement Principle

Analysis of uniform bright field images in the processing unit, after first subtracting the dark signal.

For each pixel, i, a $PRNU_i$ is defined.

Its analytic expression is: $PRNU_i = [\ (Vs_i - Va)/Va\ ] \times 100$

Where:

Va = Average signal = $[\ SUM(Vs_i)\ ]/N$
Vs_i = Pixel signal
N = Number of considered pixels

If required in the Detail Specification, the PRNU shall also be measured by considering the PRNU of blocks of square pixels.

There are several ways to specify the PRNU:

- The peak to peak PRNU: $Max(PRNU_i)$ and $Min(PRNU_i)$
- Standard deviation of the $PRNU_i$ values: $[\ 1/N\ SUM(PRNU_i^2)\ ]^{\frac{1}{2}}$
- Pixels (spikes and dips) beyond a level $[-a;\ +a]$.
  Usually $a = 3$ times the maximum allowed standard deviation. The maximum allowed standard deviation is defined in the Detail Specification.

For linear sensors a uniformity curve shall be provided.

For area sensors, mapping of spikes and dips and a histogram of PRNU values shall be provided for information.

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.

6.14.2.1 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.

It is defined in % as:

$$100 \times [\ \mathrm{Max}(Va_k) - \mathrm{Min}(Va_k)\ ] / [\mathrm{SUM}(Va_k)/n\ ]$$

With:

Va_k = average signal of output k.
n = number of outputs.

6.14.3 Measurement Conditions

- Wavelength (and bandwidth) of illumination to be given in the Detail Specification.
- Uniformity of illumination to be better than ±2.5% or uniformity correction shall be used.
- Cone angle of the illumination beam to be defined in the Detail Specification.
- Average signal = $\frac{1}{2}V_{SAT}$ (unless otherwise stated in the Detail Specification).
- CCD temperature: 25±3°C (unless otherwise stated in the Detail Specification).
- Number of pixels (in a square block) to be used for PRNU determination shall be given in the Detail Specification (otherwise only one pixel shall be taken).
- Threshold limit as given in the Detail Specification.

6.15 SPECTRAL RESPONSIVITY

6.15.1 Definition

This is the ratio of useful signal voltage (first having subtracted the dark pixel) to incident illumination measured in various spectral bands (responsivity measurement). From these values, a curve can be derived, giving the shape of the responsivity in a broad spectrum containing each elementary spectral band.

6.15.2 Measurement Principle

In a given spectral band Bi, the responsivity is Ri.

The various points Ri make the spectral responsivity curve.

The measurement can be an average of the responsivity for several adjacent pixels.

6.15.3 Measurement Conditions

- Uniform illumination (or a spot covering several pixels).
- Temperature: 25±3°C (unless otherwise stated in the Detail Specification).
- Number of pixels to be averaged given in the Detail Specification.
- Number of locations on the CCD to be given in the Detail Specification.
- Wavelength range and spectral resolution to be defined in the Detail Specification.

6.16 SPECTRAL PHOTORESPONSE NON-UNIFORMITY

6.16.1 Definition

The Spectral Photo-Response Non-Uniformity (SPRNU) represents 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.

6.16.2 Measurement Principle

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

A PRNU measurement gives a chart p_i including each pixel. B0 is a broad spectral band (typically 400-900nm).

B1, B2, B3, ... are different narrower spectral bands with a typical width of 100nm.

PRNU with B0 : chart p_i (B0)
PRNU with B1 : chart p_i (B1)
PRNU with B2 : chart p_i (B2).

For each spectral band, a $SPRNU_{(i)}$ is defined (for each pixel i) by:

$SPRNU_i$ B1/B0 = $p_i(B1)$ - $p_i(B0)$
$SPRNU_i$ B2/B0 = $p_i(B2)$ - $p_i(B0)$ etc.

It is possible to define the maximum $SPRNU_i$ in a given band:
Max [$SPRNU_i$ Bi/B0]

NOTES

1. The different spectral bands used for this measurement 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 Bi, the Bi filter must be superimposed on B0 (Figure VII).

NOTES

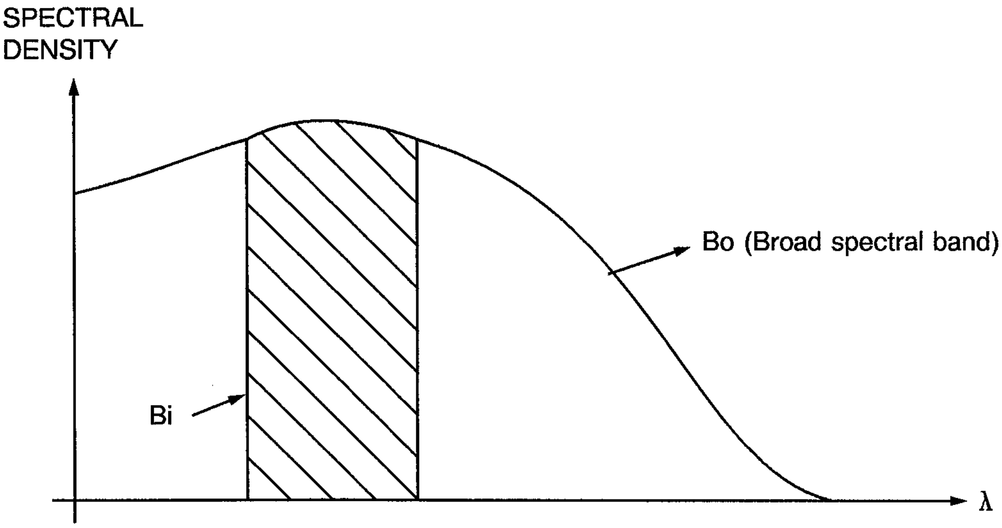
1. For linear image sensors, the SPRNU shall be given as a chart providing the SPRNU for each pixel.

For area sensors, a SPRNU mapping can be given, indicating only the pixels beyond a $\pm 3\sigma$ max. limit.

6.16.3 Measurement Conditions

- Cone angle of uniform illumination to be given in the Detail Specification.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Average signal in each band = $\frac{1}{2}V_{SAT}$ (unless otherwise stated in the Detail Specification).
- Wavelength range and spectral resolution to be defined in the Detail Specification.

FIGURE VII - SUPERIMPOSITION OF Bi FILTER ON B0 BROAD BAND FILTER



6.17 RESPONSIVITY (R)

6.17.1 Definition

Responsivity, R, is the ratio of useful signal voltage (i.e. excluding dark charge) to exposure (in J/m^2) for a given wavelength band of illumination.

It is a function of two parameters : photo-element sensitivity and charge-to-voltage conversion factor.

6.17.2 Measurement Principle

In a given spectral band, for a given incident irradiation, the average output signal is Va (mV).

The incident irradiation is measured : E (mW/m^2).
Ti = Integration time (ms).

$$R\ (V/\mu J/cm^2) = \frac{10 \times Va}{Ti \times E}$$

6.17.3 Measurement Conditions

- Uniform illumination (or a spot covering several pixels).
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Number of pixels to be averaged given in the Detail Specification.
- Number of locations on the CCD to be given in the Detail Specification.
- Wavelength range and spectral resolution to be defined in the Detail Specification.

6.18 CHARGE TO VOLTAGE CONVERSION FACTOR (CVF)

6.18.1 Definition

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

6.18.2 Measurement Principle

(a) $$\mathrm{CVF}\ (\mu V/e) = \frac{Va}{n} = \frac{Va}{I_{RD} \times Ti} \times q \times N \times 10^{15}$$

Where:

Va(mV) = Average output signal under illumination.
n = Number of electrons in the readout diode.
I_{RD}(nA) = Average signal current read in V_{RD} electrode.
Ti(ms) = Integration time.
N = Total number of useful pixels.
q = 1.6×10^{-19} coulomb (electron charge).

(b) The same result can be performed with a differential method : measurements of Va and I_{RD} variations obtained by an illumination change.

$$\mathrm{CVF}\ (\mu V/e) = \frac{(Va_2 - Va_1)}{(I_{RD2} - I_{RD1}) \times Ti} \times q \times N \times 10^{15}$$

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.

6.18.3 Measurement Conditions

- Light source: halogen lamp + infrared filter.
- Uniform illumination.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).

6.19 QUANTUM EFFICIENCY (QE)

6.19.1 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.

6.19.2 Measurement Principle

The quantum efficiency is deduced from the responsivity R at a given wavelength

(a) $$QE = \frac{h.c.R}{q.\lambda} \times 10^9$$

Where:

λ (nm) = Centre wavelength of the spectral band used for measurement.
R(A/W) = Responsivity at wavelength λ.
q = 1.6×10^{-19} C.
h = Planck constant = 6.62×10^{-34} J.s.
c = Light velocity = 3×10^8 m/s.

(b) If responsivity is not available in A/W the formula becomes:

$$QE = \frac{h.c.R}{A.CVF.\lambda} \times 10^{29}$$

Where:

$R(V/\mu J/cm^2)$ = Responsivity at wavelength λ.
$A(\mu m^2)$ = Pixel area.
$CVF(\mu V/e^-)$ = Conversion factor.

6.19.3 Measurement Conditions

- Uniform illumination (or a spot covering several pixels).
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Number of pixels to be averaged as given in the Detail Specification.
- Number of locations on the CCD to be given in the Detail Specification.
- Wavelength range and spectral resolution to be defined in the Detail Specification.

6.20 AVERAGE DARK SIGNAL

6.20.1 Definitions

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

For a frame transfer area array the signal in a dark image varies with line number because of the progressively more time that charge spends in the storage region before readout.

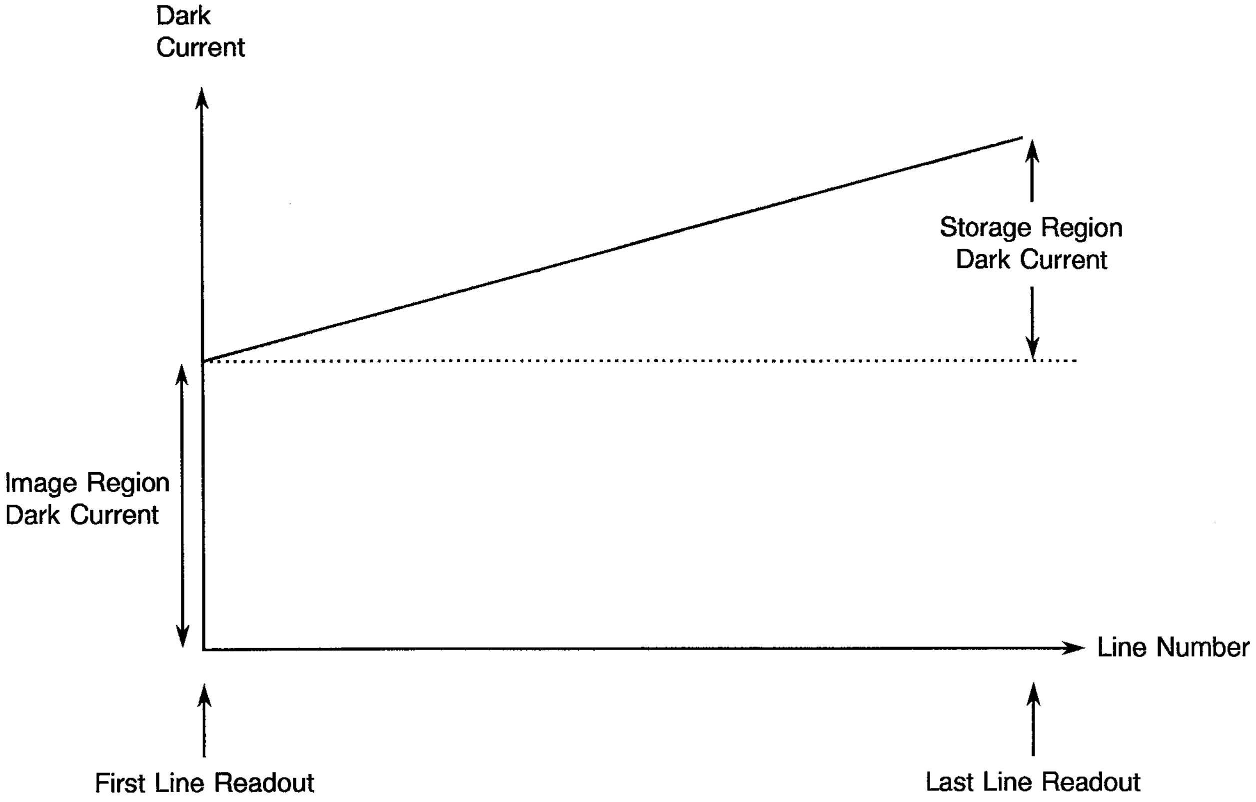
The average dark signal in the first few lines readout (excluding pixels subject to edge effects) gives the average dark signal from the image area. The average dark signal in the last few lines readout (excluding pixels subject to edge effects) is the sum of the average dark currents from the image and storage regions (Figure 8). The average dark currents from the first and last lines of a frame transfer array shall be measured separately (unless otherwise stated in the Detail Specification).

Associated parameters which are defined are the temperature coefficients of the image and storage area dark currents, the inversion voltage (voltage at which the surface becomes inverted and dark current falls steeply) and the ratio of the dark current components (image or storage) for non-inverted and inverted conditions (at specified substrate voltages).

6.20.2 Measurement Principle

Analysis of dark images in the data processing unit.

FIGURE VIII - DEFINITION OF THE IMAGE AND STORAGE REGIONS AVERAGE DARK SIGNAL COMPONENTS



6.20.3 Measurement Conditions

- CCD case temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification) (1) (2).
- Applied biases as given in the Detail Specification (2).

NOTES

1. The case temperature shall be measured with an accuracy of 0.5°C.
2. Dark current is a strong function of temperature and substrate bias (relative to the clock low bias of the integration zone). The Detail Specification may require measurement as a function of temperature and/or substrate bias.

6.21 Dark Signal Non-Uniformity (DSNU)

6.21.1 Definition

For devices in darkness, charge signals will be somewhat different from one pixel to another. The DSNU is the non-uniformity of dark images (after allowing for the slope in average dark charge arising for frame transfer devices - see Para. 6.20).

6.21.2 Measurement Principle

Analysis of dark images in the processing unit.

For each pixel i, a $DSNU_i$ is defined as:

$DSNU_i = (Vs_i - Va)/Va$

Where:

Va = Average signal = $[SUM(Vs_i)]/N$
Vs_i = Pixel signal.
N = Number of considered pixels.

There are several ways to specify the DSNU.

- The peak to peak DSNU: $Max(DSNU_i)$ and $Min(DSNU_i)$.
- Standard deviation of the $DSNU_i$ values: $[1/N\ SUM(DSNU_i^2)]^{\frac{1}{2}}$.
- Pixels (spikes and dips) beyond a level $[-a; +a]$.
  Usually $a=3$ times the maximum allowed standard deviation. The maximum allowed standard deviation is defined in the Detail Specification.

  For linear sensors a uniformity curve shall be provided.

  For area sensors, mapping of spikes and dips and a histogram of DSNU values shall be provided.

If required in the Detail Specification the DSNU shall also be measured by considering the DSNU of blocks of $p \times p$ pixels.

6.21.3 Measurement Conditions

- CCD case temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification) (1) (2).
- Applied biases as given in the Detail Specification (2).
- Number of pixels in a block ($p \times p$) to be defined in the Detail Specification, otherwise assume $p=1$.
- Threshold level (a) to be defined in the Detail Specification.

NOTES

1. The case temperature shall be measured with an accuracy of 0.5°C.
2. DSNU is a strong function of temperature and substrate voltage. The Detail Specification may require measurement as a function of temperature and substrate voltage.

6.22 THRESHOLD VOLTAGES

6.22.1 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:

$V_{RD\ threshold}$: The V_{RD} voltage below which charge is no longer attracted to the output stage and I_{RD} falls.

$V_{antiblooming\ threshold}$: The antiblooming voltage (if applicable) below which charge flows from the antiblooming drain into the device and I_{RD} increases.

$V_{reset\ pulse\ turn\ on/off}$: The values of ΦR below/above respectively which the reset transistor is turned OFF/ON respectively.

$V_{inversion}$: The substrate voltage (relative to the clock low voltage) at which surface inversion occurs and dark signal falls.

6.22.2 Measurement Principle

The relevant parameter (usually I_{RD}) is measured as a function of the bias voltage and the switching point determined.

6.22.3 Measurement Conditions

- Temperature: 25 ± 3°C (unless otherwise defined in the Detail Specification).
- Illumination conditions as specified in the Detail Specification.

6.23 PHOTOSITE TO SHIFT REGISTER CROSSTALK (ONLY FOR LINEAR SENSORS)

6.23.1 Definition

The photosite to shift register crosstalk is the ratio of charge generated in the shift register (not coming from the photosensitive area) to the useful signal (charge coming from the photosensitive area), for a given integration time and output signal.

6.23.2 Measurement Principle

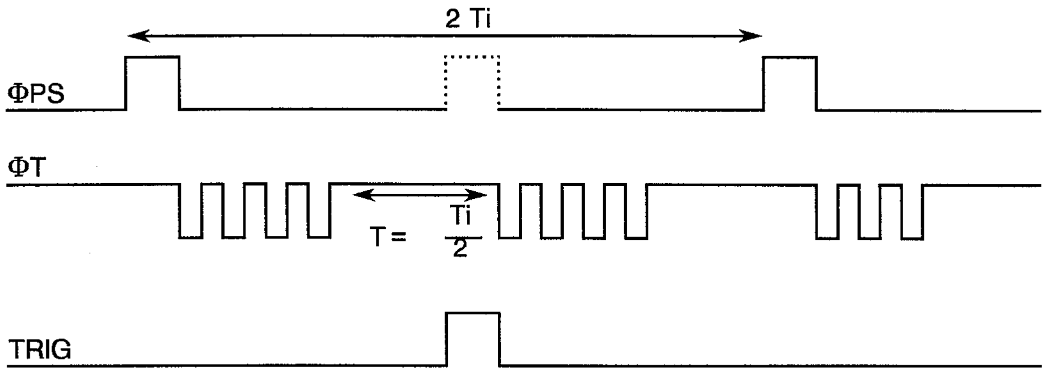
Specific timing diagram (Figure IX):

- Charge is accumulated inside the shift register under illumination, during a time T (ΦT is inhibited during T).
- ΦPS clock (photosite to shift register transfer clock) is inhibited in order to acquire only the charge coming from the shift register (TRIG signal) and not the charge generated in the photosites.
- The signal contribution of each shift register stage is calculated for a duration of one ΦT clock period. The total photosite to shift register crosstalk is obtained by summation of each single contribution and computed as a percentage of average output signal (measured under the same incident illumination with a typical standard timing diagram).

NOTES

1. The dark signal is removed from the crosstalk signal.

FIGURE IX - SPECIFIC TIMING DIAGRAM FOR PHOTOSITE TO SHIFT REGISTER CROSSTALK MEASUREMENT (LINEAR IMAGE SENSORS ONLY)



6.23.3 Measurement Conditions

- Light source: halogen lamp + infrared filter.
- Optical filter: BG 38 (thickness = 2mm) or equivalent (unless otherwise stated in the Detail Specification).
- Uniform illumination.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Typical timing diagram for average signal measurement at a given Ti (Illuminance adjustment to get $V_{SAT}/4$).
- Specific timing diagram (transport clock ΦT inhibited during $T = Ti/2$).

6.24 LAG EFFECT (ONLY FOR LINEAR SENSORS)

6.24.1 Definition

The lag effect is the image trailing effect caused by residual photocharge left in a photodiode after a transfer operation from photosite to shift register.

6.24.2 Measurement Principle

A specific timing diagram enables the synchronisation of the ΦPS transfer clock with illumination from an LED source. 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 off (Figure X).

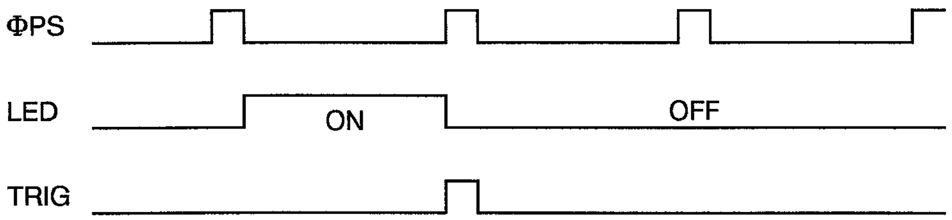
The lag effect being a characteristic of the photodiode intrinsic structure, the measurement is performed on a single pixel.

6.24.3 Measurement Conditions

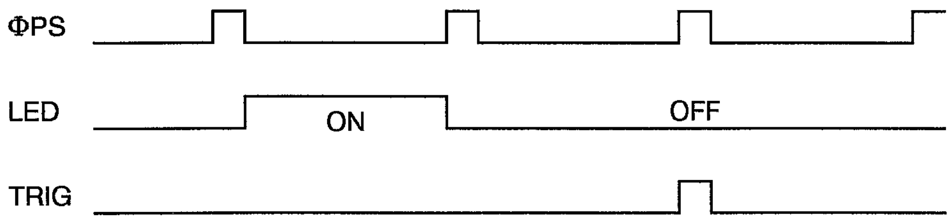
- LED wavelength to be defined in the Detail Specification.
- Temperature: 25 ± 3°C (unless otherwise defined in the Detail Specification).

FIGURE X - SPECIFIC TIMING DIAGRAMS FOR LAG EFFECT MEASUREMENT (LINEAR IMAGE SENSORS ONLY)

ACQUISITION OF OUTPUT SIGNAL (DUE TO INCIDENT ILLUMINATION)



ACQUISITION OF LAG SIGNAL



LED : Pulsed Light Emitting Diodes
TRIG : Signal for acquisition start

6.25 PIXEL CROSSTALK (VERTICAL OR HORIZONTAL) - SPOT METHOD

6.25.1 Definition

For spot illumination on a single pixel this is defined as the signal in an adjacent pixel (in the vertical or horizontal direction). The crosstalk is defined as a percentage of the signal in the illuminated pixel.

6.25.2 Measurement Principle

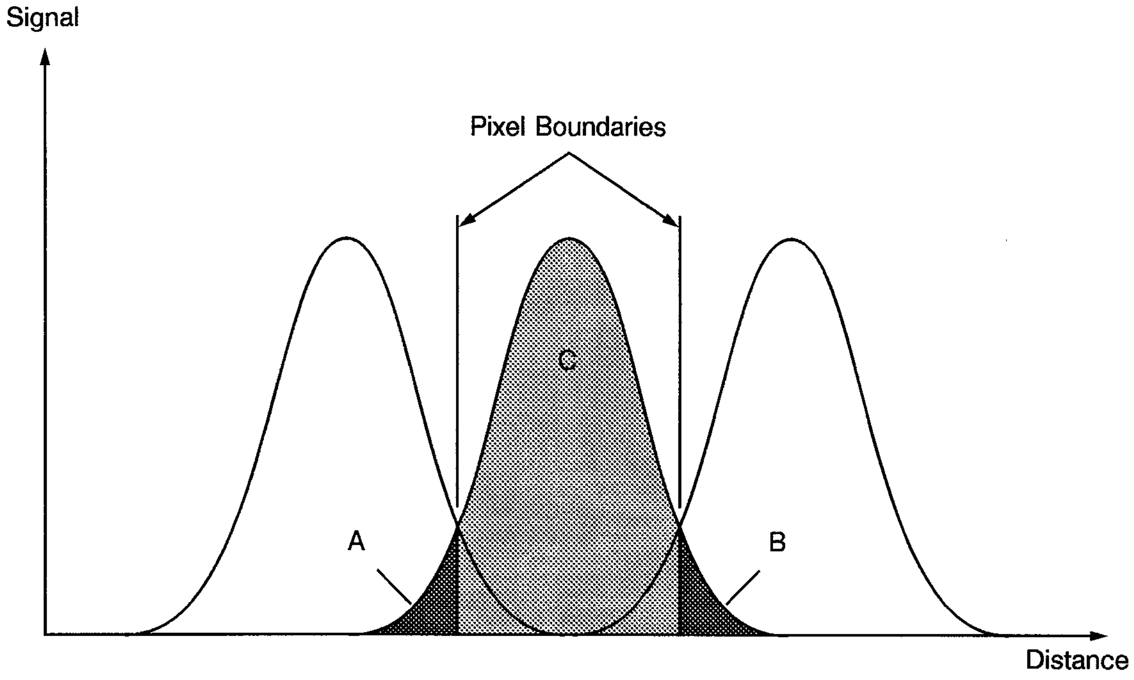
Spot illumination is used with a spot size (diameter of the first Airy disk) <5µm (unless otherwise specified in the Detail Specification). The spot is scanned across several pixels (in the vertical or horizontal direction) and the crosstalk is defined as in Figure XI.

6.25.3 Measurement Conditions

- Wavelength of illumination as defined in the Detail Specification.
- Temperature: 25 ± 3°C (unless otherwise stated in the Detail Specification).
- Spot size as given in the Detail Specification.

FIGURE XI - DEFINITION OF PIXEL CROSSTALK

$$\text{Crosstalk (\%)} = \frac{\text{Area A} + \text{Area B}}{\text{Area A} + \text{Area B} + \text{Area C}} \times 100$$



6.26 PIXEL CROSSTALK (VERTICAL OR HORIZONTAL) - EDGE METHOD

6.26.1 Definition

The pixel responsivity is usually spread over an area greater than its geometrical aperture, a phenomenon called crosstalk.

The crosstalk is defined as a percentage of the signal as follows:-

- Q0 = Signal coming from a pixel which area corresponding to its goemetrical aperture is under illumination and the rest in darkness.
- Q1 = Signal coming from the same pixel when the area corresponding to its geometrical aperture is in darkness and the rest is under illumination.

Crosstalk (%) = Q1 / (Q0 + Q1)

NOTES

1. Q0 + Q1 = Total signal under uniform illumination (pixel responsivity).
   If Q1 = 0 then crosstalk = 0 (there is no crosstalk).

6.26.2 Measurement Principle

MTF measurement with edge scanning (see Para. 6.28).

Differentiation and Fourier transform will yield the MTF curve and pixel responsivity shape (in spatial coordinates).

The crosstalk is obtained by analysis of the pixel responsivity shape by comparison to the geometrical aperture of the pixel.

6.26.3 Measurement Conditions

- Electro-optical bench with MTF micro bench using micro-displacement units.
- Wavelength and aperture used to be defined in the Detail Specification.
- Temperature = 25 ± 3 °C.

6.27 MODULATION TRANSFER FUNCTION (MTF) IN THE VERTICAL AND HORIZONTAL DIRECTIONS - GENERAL METHODS

6.27.1 Definition

MTF is defined for an input illumination (I) with a spatial variation in the vertical (or horizontal) direction of the form

$$I = I_o\ (1 + \cos(x))$$

where x is the distance across the CCD.

The sinusoidal input pattern will induce an output signal whose maximum (V_{MAX}) and minimum (V_{MIN}) can be found, and:

$$MTF = \frac{V_{MAX} - V_{MIN}}{V_{MAX} + V_{MIN}}$$

For a CCD, V_{MAX} and V_{MIN} will be taken as the output of two specific pixels.

6.27.2 Measurement Principles

Measurement methods fall into two types:

(i) Spot and line scanning methods (as in Para. 6.25). The MTF is the Fourier transform of the response across a pixel.

(ii) Imaging of a bar pattern. The bar pattern shall have a sinusoidal profile at the detector plane.

In either case the MTF of the optical projection system must be measured and allowed for in the calculation.

6.27.3 Measurement Conditions

- Method used to be defined in the Detail Specification.
- Wavelength and cone angle used to be defined in the Detail Specification.
- Temperature: 25 ± 3 °C (unless otherwise defined in the Detail Specification).

6.28 MODULATION TRANSFER FUNCTION (MTF) - EDGE METHOD

6.28.1 Definition

The modulation transfer function (MTF) is the curve of modulation depth versus spatial frequency of sinusoidal irradiance.

The MTF represents the capacity of spatial resolution of the image sensor, for a given analysed pixel.

Usually the resolution limit is taken at half spatial sampling frequency called the Nyquist frequency 1/2p), where p is the pixel pitch; the modulation depth is generally given at this particular frequency.

6.28.2 Measurement Principle

Through a lens, a “knife-edge” image, projected onto the sensitive area, is scanned in front of the device along a given direction.

The electrical response stemmed from the device under test gives, through the recording system, the image of the integrated Line Spread Function of the analysed pixel.

A specific data processing applied to this result allows to get the system MTF, including the lens MTF too.

The MTF values for all spatial frequency are obtained.

A correction is made, due to the intrinsic modulation transfer function of the optical system.

6.28.3 Measurement Conditions

- Electro-optical bench with MTF micro bench using micro-displacement units.
- Wavelength and aperture used to be defined in the Detail Specification.
- Temperature = 25 ± 3°C.

6.29 CONTRAST TRANSFER FUNCTION (CTF)

6.29.1 Definition

The CTF is the curve of modulation depth versus spatial frequency of a bar pattern image focused on the photosensitive area. The CTF represents the capacity of spatial resolution of the image sensor, for a given analysed pixel. Usually the resolution limit is taken at half the spatial sampling frequency called the Nyquist frequency (1/2p), where p is the pixel pitch; the modulation depth is calculated at this particular frequency.

6.29.2 Measurement Principles

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

$$\text{CTF (f)} = \frac{(4)}{\pi} \left(\text{MTF (f)} + \frac{(\text{MTF (3f)}}{3} - \frac{(\text{MTF (5f)}}{5} + \ldots\ldots\ldots \right)$$

(b) A bar pattern at Nyquist frequency is focused on the CCD through a microscope objective and a lens.

The bar pattern image is scanned with a single pixel over a distance greater than one period in order to detect minimum and maximum values of the modulation.

The reference Vr (for modulation calculation) is measured on the black area of the pattern (near the network of lines pairs).

$$\text{Modulation depth} = \frac{\text{Vmax - Vmin}}{\text{Vmax + Vmin - 2Vr}}$$

A correction is made, due to the intrinsic modulation transfer function of the optical system. With a first order approximation, the measured modulation depth is divided by the optical system modulation transfer at Nyquist frequency.

6.29.3 Measurement Conditions

- CTF micro bench with micro-displacement units.
- Wavelength and aperture used to be defined in the Detail Specification.
- Temperature = 25 ± 3°C.