EMCCD Gain and the Ageing Solution

RealGain™, Anti-Ageing & EMCAL™

INTRODUCTION

A note of caution is needed with regard to the gain components in back-illuminated **EMCCD** (Electron Multiplying CCD) technology. The EM register of the EMCCD suffers from gain ageing effects. Fortunately with due care and attention, on behalf of both camera manufacturer and user, these ultrasensitive platforms can deliver many years of quantitative operation.

Here we provide an overview of the proprietary innovations that Andor have developed and integrated into our pioneering and world-leading EMCCD products, designed to get the absolute best in quantitative performance and durability from this exceptionally light-sensitive technology.

Andor's latest revolutionary developments in EMCCD technology include:

- **RealGain™** - Select actual EM gain direct from a linear and quantitative software scale. No more arbitrary EM gain units. The gain you ask for is the gain you get!
- **Anti-Ageing** - internally configured to significantly inhibit saturation-induced decay of EMCCD gain.
- **EMCAL™** - innovative user-initiated self-recalibration of EM gain, based on Andor's unique Linear and Real gain implementation.

Voltage Dependence

When the user applies gain through the software, it is the EM voltage in the gain register that is varied. As can be seen from Figure 1, the dependence of EM gain on EM voltage is sharp. This arises because the signal electrons gain energy as they are accelerated through the EM field, and once this field strength reaches the threshold needed to overcome the band-gap energy, the impact ionization rate rises rapidly. This sharp dependence has meant that the software control of EM gain in EMCCD cameras to date has been via a non-linear scale, with most of the amplification occurring within a relatively small portion at the top of the overall scale. This has required considerable fine tuning by the user to determine an optimal gain setting, and even then the actual gain is determined only through measurement of a stable light source, with and without gain applied.

Temperature Dependence

Figure 2 shows how the EM gain varies with temperature, this dependence arising primarily from phonon scattering. The scattering causes a loss of energy, which increases with temperature. To make up this loss and maintain EM gain, a larger EM electric field (EM voltage) must be used at higher temperatures.

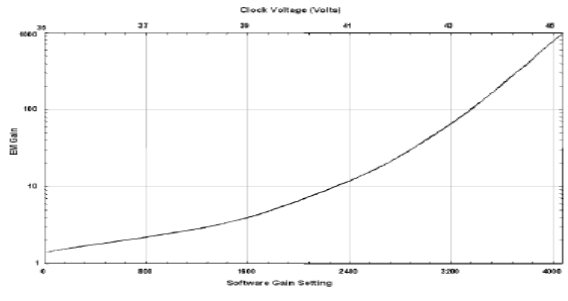

Figure 1 Typical data of EM Gain versus Software Gain, showing a non-linear relationship. Data taken at -50°C.

The Andor Solution (1)

RealGain™ - Real and Linear gain:

Linear

In response to considerable demand from our customers, Andor have set about a detailed analysis of the EM voltage dependence, and have successfully converted the relationship between EM gain and the EM software setting into a linear one.

Real

Importantly, the true EM gain (i.e. the absolute signal multiplication factor) is selected directly from the linear gain scale, as shown in Figure 3. No more guesswork with arbitrary gain units across a non-linear scale - the gain you ask for is the gain you get. Select the best gain to overcome noise and maximize dynamic range.

Temperature Compensated

Although EM gain is temperature dependent, Andor's real/linear gain calibration extends to any EMCCD cooling temperature. Selecting x300 gain software setting @ -50 ºC, or at -100 ºC gives the same x300 true EM gain.

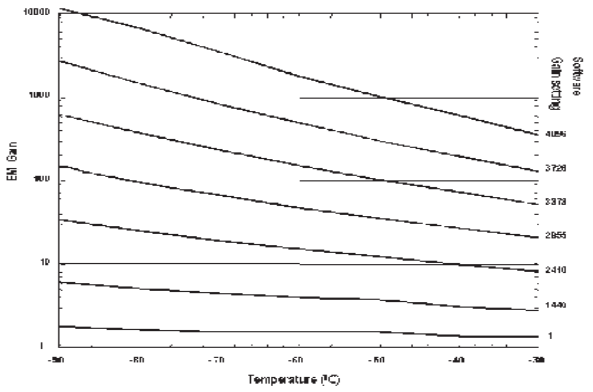

Figure 2 A family of curves showing how EM Gain changes with Temperature for different software gain settings.

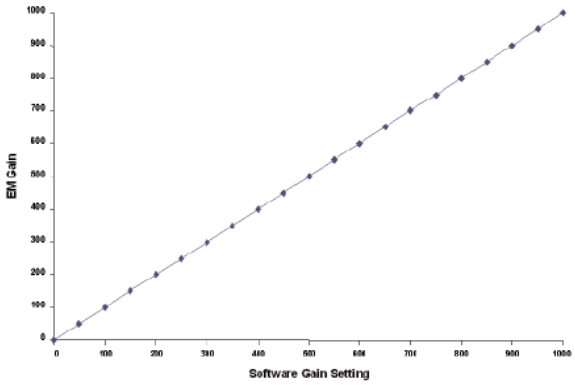

Figure 3 RealGainTM calibration - the same linear relationship holds for all temperatures

RealGain™ delivers to the user a new benchmark of simplicity and ease of operation, and sets a new precedent in what we should expect from EMCCD technology

Gain Ageing

It has been observed that EMCCD sensors, more notably in cameras that incorporate L3Vision sensors from E2V, are susceptible to EM gain fall-off over a period of time.

It is important to note that the ageing effect applies to any EMCCD camera, by any manufacturer, that incorporates these L3Vision sensors. In Andor's iXon^{EM}+ range, this corresponds to DU-897, DU-860 and DU-865 models. In the Newton range, this corresponds to DU-970N and DU-971N models. If left unchecked, this ageing phenomenon has the potential to significantly compromise the long-term quantitative reliability of EMCCD cameras. Fortunately, if these highly sensitive sensors are used with due care and attention, ageing can be minimized and should not present any real problem to the user.

An E2V technical note has been written on this phenomenon, entitled: **'An Overview of the Ageing Characteristics of L3Vision™ Sensors'**. This can be downloaded from: http://www.e2v.com/products/ccd-and-cmos-imaging-and-semiconductors/imaging-l3vision/datasheets-and-technical-papers.cfm

Handy Guidelines

More details of this effect can be found later in the document, but listed below are some guidelines to minimize the EM ageing process:

• **Don't** use EM gains greater than necessary to overcome the read noise. A rule of thumb is that a gain of x4 or x5 the rms read noise (accessible from the spec sheet or performance sheet) is more than sufficient to render this noise source negligible. In practice, this can always be achieved with EM Gain of less than x300 (often much less). Pushing gain beyond this value would give little or no extra S/N benefit and would only reduce dynamic range.

• Only for single photon counting can we justify **extending the scale to x1000** EM gain, provided. The user needs to ensure that signal falling onto the sensor is indeed within the regime of low numbers of photons per pixel.

• **Turn down** the gain when not in use and try **not to over-saturate** the detector.

Fortunately, as will be described, many of these guidelines have been uniquely woven into the Andor EMCCD cameras, to make it difficult for the user to step outside of them and unwaringly cause accelerated sensor ageing.

E2V and Texas Instruments

It is important and fair to note that EMCCD cameras incorporating sensors from Texas Instruments have shown rates of EMCCD saturation-induced ageing that are orders of magnitude slower than those with E2V sensors, exposed to comparable light intensity and gain. In Andor's iXon^{EM}+ range this refers 885 series. Note also that the Luca^{EM} models contain exclusively sensors from Texas Instruments.

The Andor Solution (2)

Andor have recognized the ageing issue and have been busy implementing innovative measures to stabilize the EM gain on these sensors, ensuring that this ground-breaking ultrasensitive technology can deliver a prolonged quantitative service to the user.

This defence is two pronged, and makes heavy use of Andor's linear and quantitative gain calibration scale, a new fundamental standard in day-to-day EMCCD usage.

Gain and Signal restrictions

Andor EMCCDs have been internally configured to ensure that the rate of gain fall off is significantly reduced under standard operation. Part of the measures taken has been to invoke real gain limits, coupled with signal intensity feedback warnings (after EM amplification) to ensure that the user is more restricted in his/her ability to apply excessive gain and/or signal. The scales offered are more than sufficient to render the read noise floor as negligible for a given signal intensity and readout speed . These controls significantly reduce the rate of gain fall off.

EMCAL™

Andor have developed, a unique and patented method of user-initiated **EM gain self-recalibration**. Even after exercising due care during usage and availing of the above internal restrictions, the EM gain may deplete over an extended period of time. The EMCAL™ self-recalibration process is very easily initiated by the user. At the touch of a button, a routine is triggered that measures EM gain and uses the iXon^{EM}+ in-built temperature compensated linear gain scales to reset the EM gain calibration (if required), to deliver the true values requested on the software scale. EMCAL™ aims to markedly prolonged operational lifetime and quantitative reliability of the technology, and circumvent the need to return to the factory for recalibration.

1. What technologies suffer from gain ageing?

A note of caution is needed with regard to the gain components in both ICCD and EMCCD technology i.e. both the MCP of the ICCD and the EM register of EMCCD suffer from gain ageing effects. For a given applied voltage to the gain components you would expect the gain to remain constant. However the gain components suffer from parasitic effects that lower their gain as a function of the total charge that passes through them.
Therefore, for either technology, if you measure the gain over a period of time at a fixed voltage and temperature the gain will fall off, and the fall off will be more pronounced the more charge that passes though the gain component.

A secondary effect must also be borne in mind for ICCDs. Under conditions of intense illumination they can suffer from an irretrievable damage to the photocathode QE performance, due to a process of positive ion feedback. While photocathodes are these days generally better protected against this effect, it must not be overlooked completely.

2. What causes the ageing effect in EMCCDs, and how is it countered?

The ageing effect in EMCCDs appears to be dependent on the amount of charge that is passed through the gain register, combined with the EM field strength that it is transferred through. It appears to be very strongly dependent on the EM field strength, therefore when operated at high EM gains the ageing rate can be disproportionately greater.

Fortunately it has been observed that this ageing effect itself decreases with time, meaning that with proper use the device should remain useful for many years. As part of Andor's EMCCD production process, we expose the sensors 'short-term ageing', prior to calibration and setting of the gain.

The explanation for the ageing effect is not fully understood, but it is assumed that accelerating charge through the high electric fields is causing a tiny fraction of that charge to become permanently embedded in the insulator (typically silicon dioxide) between the EM electrode and the active silicon.

This slow build-up of charge effectively reduces the field strength produced by the electrode. Independent of the mechanism involved, this reduction in field strength can be easily compensated for by measuring the EM gain and increasing the EM voltage accordingly.

A proprietary method for doing this has been incorporated into the iXon^{EM}+ - EMCAL™. This is a user-initiated self-recalibration, enabling the user to carry out this correction without return to the factory, by running a simple routine! To minimize the ageing and keep the time between adjustments as long as possible, iXon^{EM}+ uses preventative technology to protect the camera from excessive conditions. To the user, this means optimal signal to noise ratio, maximum dynamic range and prolonged system longevity.

3. Longevity - How extensively can Andor's back-illuminated EMCCDs be used before they can no longer be recalibrated (EMCAL™) to factory EM gain settings?

Andor have ran extensive testing in order to project the service lifetime of the back-illuminated EMCCDs. Under the quite aggressive test conditions employed it was projected that even after 7 years of round the clock operation, the test camera would be expected only to reach ~ 65% of the available voltage range required to maintain EM calibration, with the rate of ageing steadily decreasing under continued usage. As such, under reasonable usage and taking due care and attention to stay within recommended operating conditions and applying EMCAL™ as required, the gain ageing phenomenon is not considered to ever impose a restriction on the quantitative reliability of your camera. More complete description of this longevity test is given in the Andor tech note entitled: **'Longevity in EMCCDs'**

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