

# Technical Note

## MT9V022

### High Dynamic Range

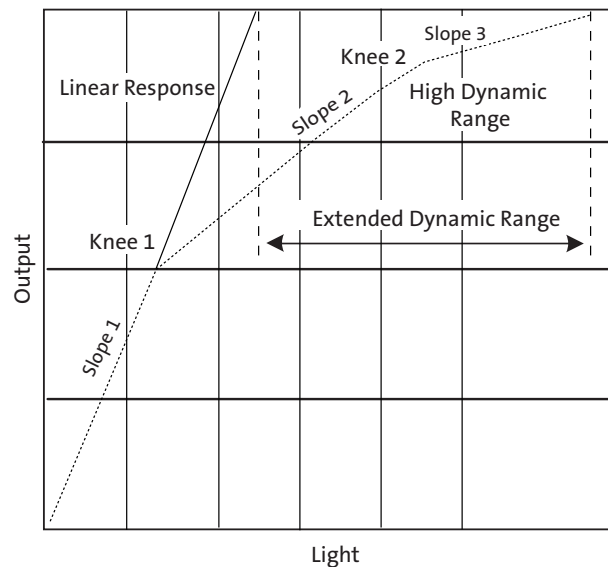
#### Introduction

This technical note addresses the Aptina<sup>®</sup> MT9V022 CMOS image sensor and the flexible high dynamic range (HiDy) feature. Different scenes or applications require different distributions of the intrascene dynamic range of the MT9V022. This technical note assists system designers in achieving a desired dynamic range and pixel response.

#### High Dynamic Range Theory

The MT9V022 has a linear-pixel-response dynamic range of approximately 68dB. A higher dynamic range can be achieved by using a piecewise linear response, as illustrated in Figure 1. By lowering the slope of the response, or contrast, in the higher luminance ranges, the pixels in the MT9V022 can be used to quantize a much greater luminance range before saturation. Progressively lower response slopes allow the MT9V022 to simultaneously maintain good low signal contrast (shadow detail) and significantly extend the range of quantifiable luminance levels.

**Figure 1:** High Dynamic Range with Three-Segment Response



## Background

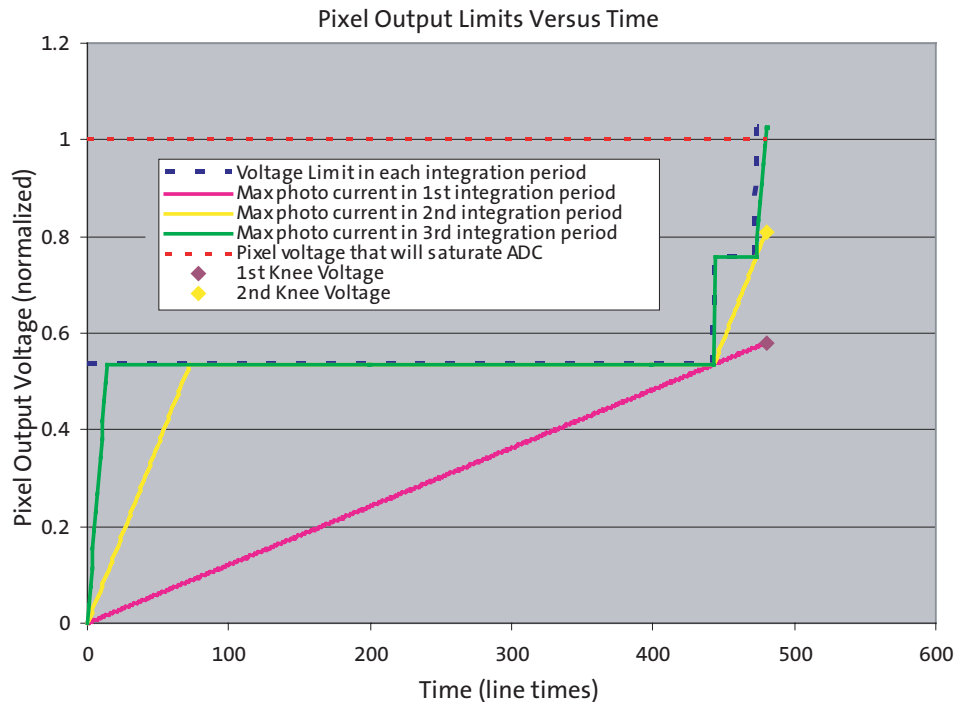
The high dynamic range response of the MT9V022 can be tailored to the designer's required response by adjusting slope of the three response segments and the position of "knee points" between them. Required response is built through register parameters, as explained in this technical note.

For more detailed information regarding the MT9V022 pixel operation in HiDy mode, refer to the Aptina Imaging technical note TN-09-18, "High Dynamic Range Feature."

## Pixel Response across Three Integration Periods

In HiDy mode, the MT9V022 divides the total integration time, or total shutter width, into three periods:  $t_1$ ,  $t_2$ , and  $t_3$ . During each integration period, there is a different potential barrier applied to the pixels that limits the maximum photo current that can be quantized during that period. The potentials applied are  $v_1$ ,  $v_2$ , and  $v_3$ , respectively. This concept is illustrated in Figure 2.

Figure 2: Photo Current Limits in Each Integration Period



### Integration Periods: $t_1$ , $t_2$ , and $t_3$ (Manual Control)

The three integration periods end at shutter width 1 (R0x08), shutter width 2 (R0x09), and total shutter width (R0x0B) lines of integration, respectively. The relationship between the shutter width register settings and the length of each integration period is as follows:

$$t_1 = SW_1(R0x08) \quad (\text{EQ 1})$$

$$t_2 = SW_2(R0x09) - SW_1(R0x08) \quad (\text{EQ 2})$$

$$t_3 = SW_{TOTAL}(R0x0B) - SW_2(R0x09) \quad (\text{EQ 3})$$

In Figure 2 on page 2, the MT9V022 is programmed for 480 lines of total shutter width (R0x0B = 480); shutter width 1 is set to 443 lines (R0x08 = 443) and shutter width 2 is set at 473 lines (R0x09 = 473). With these settings, the integration periods are:  $t_1 = 443$  lines,  $t_2 = 30$  lines and  $t_3 = 7$  lines.

### Integration Periods: $t_1$ , $t_2$ , and $t_3$ (Automatic Control)

Alternatively, the integration periods can be specified using the exposure knee point auto adjust feature (R0x0A[bit8]=1). When this feature is enabled, the image sensor automatically calculates the correct number of lines of exposure given the current exposure time. The relationship between the shutter width register settings and the length of each integration period is as follows:

$$t_3 = SW_{TOTAL}(R0x0B) \cdot \left(\frac{1}{2}\right)^{t3\_ratio(R0x0A[7:4])} \quad (\text{EQ 4})$$

$$t_2 = SW_{TOTAL}(R0x0B) \cdot \left(\frac{1}{2}\right)^{t2\_ratio(R0x0A[3:0])} \quad (\text{EQ 5})$$

$$t_1 = SW_{TOTAL}(R0x0B) - t_2 - t_3 \quad (\text{EQ 6})$$

In this mode, each integration period is truncated to an integer number of lines of integration. For example, when  $SW_{TOTAL} = 480$  lines and  $t3\_ratio = 8$ ,  $t_3$  returns a value of 1 line of exposure. Importantly, when  $SW_{TOTAL} = 480$  lines and  $t3\_ratio = 9$ ,  $t_3$  returns a value of 0 lines (no  $t_3$  exposure happens).



### Potential Barrier Limits: $v_1$ , $v_2$ , and $v_3$

The potential barrier limiting pixel integration during each integration period is controlled by the  $V_1$ ,  $V_2$ , and  $V_3$  control voltage registers: R0x31, R0x32, and R0x33, respectively. Control voltage  $V_4$  (R0x34) is used as a “parking” voltage for the pixel and can generally be left at the default value of “4” and will not affect the high dynamic range pixel response.

### Maximum Photo Current during Each Integration Period

The integration voltage limit and the integration period of  $t_1$ ,  $t_2$ , or  $t_3$  determine the maximum photo current that will not saturate during that period. In a plot of pixel output versus time (Figure 2 on page 2), photo current response is represented as a line with a slope of volts per second. The maximum photo currents that will not saturate in  $t_1$ ,  $t_2$ , and  $t_3$  are represented by magenta, yellow and green lines, respectively.

### Two-Knee-Point Voltages

Photo currents resulting from illumination levels that are lower than the maximum photo current during  $t_1$  (the magenta line in Figure 2 on page 2) integrate without saturating throughout the total shutter width [R0x0B]. The voltage that is reached at the end of the integration period (480 lines in Figure 2) due to this maximum photo current corresponds directly to the first knee of the output response curve (Figure 1 on page 1). All of the photo currents below this limit will result in an output code versus illumination slope that is equivalent to that of the MT9V022 linear mode response slope (for example, Slope 1 in Figure 1 on page 1).

### Response Slopes

The three segments of the pixel response curve (Figure 1 on page 1) each have a different slope. The slope of the first segment is dependent only on the total shutter width and is the same as the slope in linear operation mode with the same total shutter width setting. Slope 2 has a lower slope than Slope 1, and Slope 2 has a lower slope than Slope 3.

Figure 2 on page 2 shows that the maximum photo current that will not saturate during  $t_2$  (the yellow line) is significantly larger than the maximum photo current that will not saturate during  $t_1$  (the magenta line). The range of photo currents between these two limits represent the illumination levels that will integrate to voltages between the first two knee-point voltages, VKnee1 and VKnee2.

The ratio of the Slope 1 to Slope 2 in the response curve is determined by the ratios of their exposure times. The Slope 1 response is due to photo current integration for the total integration time, or  $SW_1$ , and the Slope 2 response is due to photo current integration during  $t_2$  and  $t_3$ . Therefore, the ratio between Slope 1 and Slope 2 in the response curve can be determined from:

$$\text{Slope 1 / Slope 2} = SW_{TOTAL} / (t_2 + t_3) = SW_{TOTAL} / (SW_{TOTAL} - SW_1) \quad (\text{EQ 7})$$

where  $t_2, t_3$  = the second and third integration periods

**Note:**  $(t_2 + t_3)$  is equal to  $SW_{TOTAL} - SW_1$ , which means that the slope of the second segment of the response curve is dependent only on  $SW_1$  (R0x08), assuming a fixed total integration period.

In the third segment of the response curve, photo currents between the maximum photo currents of integration periods  $t_2$  and  $t_3$  (the yellow and green lines of Figure 2) integrate to voltages between the second knee voltage and the maximum voltage reached at the end of the total shutter width.

The ratio of *Slope 2* to *Slope 3* in the response curve is determined by the ratios of their exposure times. The *Slope 2* response is due to photo current integration for periods  $t_2$  and  $t_3$ ; the *Slope 3* response is due to photo current integration during  $t_3$ . Therefore, the ratio between *Slope 2* and *Slope 3* in the response curve can be determined from:

$$\text{Slope 1 / Slope 2} = (t_2 + t_3) / t_3 = (SW_{TOTAL} - SW_1) / (SW_{TOTAL} - SW_2) \quad (\text{EQ 8})$$

where  $t_2, t_3$  = the second and third integration periods

**Note:**  $t_3$  is equal to  $SW_{TOTAL} - SW_2$ , which means that the slope of the third segment of the response curve is dependent only on  $SW_2$  (R0x09).

### Pixel Response Equation Summary and Required Conditions

Table 1 on page 6 summarizes the high dynamic range pixel response equations defined in the previous sections (reference Figure 2 on page 2). For these equations to accurately predict the behavior of the MT9V022, several conditions must be met:

- $SW_{TOTAL} (R0x0B) > SW_2 (R0x09) > SW_1 (R0x08)$
- For simultaneous exposure mode, vertical blanking  $(R0x06) > SW_{TOTAL} - SW_1$ . The MT9V022 switches the pixel threshold voltage from  $V_1$  to  $V_2$  and from  $V_2$  to  $V_3$  during the vertical blanking period, so the interval must be longer than  $t_2 + t_3$  for HiDy mode to function properly.
- $V_1 (R0x31) > V_2 (R0x32) > V_3 (R0x33) \rightarrow v_1 < v_2 < v_3$

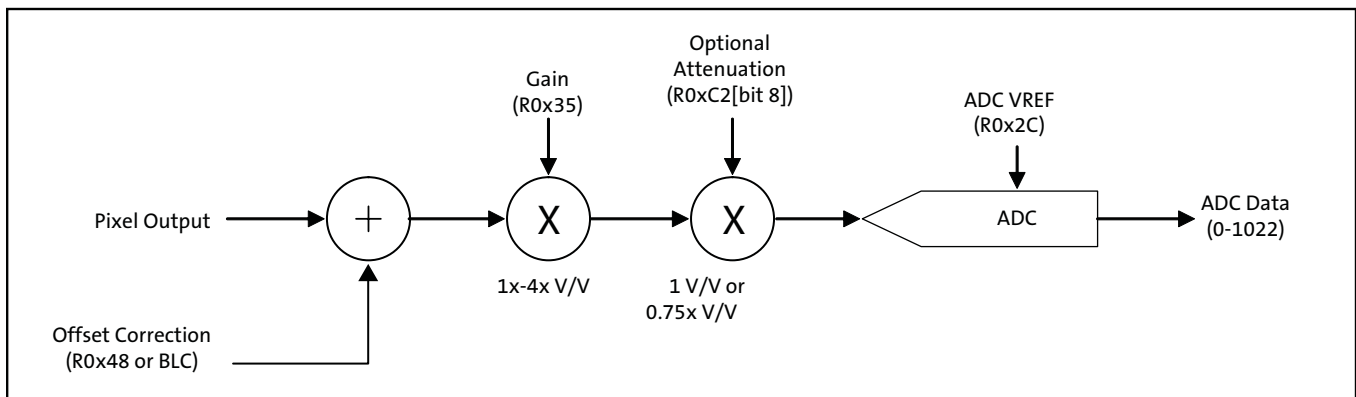
**Table 1: Summary of Pixel Response Equations**

$t_1 = SW_1 (R0x08)$	$v_1$ : determined by R0x31 value
$t_2 = SW_2 (R0x09) - SW_1 (R0x08)$	$v_2$ : determined by R0x32 value
$t_3 = SW_{TOTAL} (R0x0B) - SW_2$	$v_3$ : determined by R0x33 value
Slope 1 = same slope as linear response with same $SW_{TOTAL}$ setting	
Slope 1/Slope 2 = $SW_{TOTAL} / (t_2 + t_3) = SW_{TOTAL} / (SW_{TOTAL} - SW_1)$	
Slope 2/Slope 3 = $(t_2 + t_3) / t_3 = (SW_{TOTAL} - SW_1) / (SW_{TOTAL} - SW_2)$	

### Mapping the Pixel Response to Output Codes

The MT9V022 ADC converts the analog output from the pixel, after offset correction and analog gain, into a digital output code ranging from 0 through 1022. To achieve the maximum dynamic range from the MT9V022, the output range of the pixel must be matched as closely as possible to the input range of the ADC.

**Figure 3: Gain**



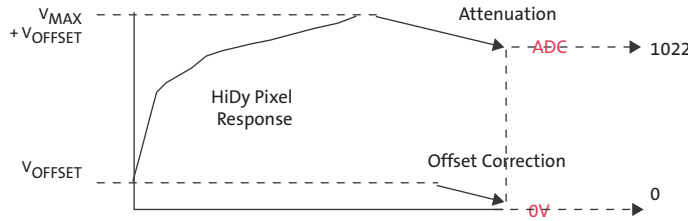
If the ADC is operating in 10-bit linear mode, the output code can be predicted by the following equation:

$$\text{ADC output code} = V_{\text{Pixel}} * \text{Gain} * \text{Attenuation} * 1022 / \text{ADC\_VREF} \tag{EQ 9}$$

where  $V_{\text{Pixel}}$  is the sampled pixel output voltage.

ADC Input Range

Figure 4: ADC Input Range



By default, the pixel output range is considerably larger than the default ADC input range. This is typical of default image sensor configurations because it is often desirable to match the most linear region of the response of the pixel to the input range of the ADC. In high dynamic range applications, the output response of the pixel is intentionally nonlinear and the goal is to monotonically quantize as much of the output range of the pixel as possible.

To ensure the maximum amount of dynamic range, care must be taken to adjust the output range of the pixel to match the input range of the sensor. The output range of the pixel can be matched to the input range of the ADC by one of the following methods:

- Using attenuation (set R0xC2[bit 8] = 1)
- Adjusting the ADC reference voltage (VREF\_ADC Control, R0x2C)
- Adjusting the maximum output voltage (V<sub>3</sub>, R0x33)

Of these three options, the best way to match the pixel response range to the ADC range is to employ the optional signal attenuation by setting R0xC2[bit 8] = 1. Attenuation provides an optional 0.75x V/V analog gain applied after the programmable gain amplifier controlled by R0x35.

The ADC input reference range can also be adjusted by changing the value of the VREF\_ADC Control, R0x2C. Changing the VREF\_ADC Control changes the ADC input range according to the values in Table 2. Of the eight possible values for VREF\_ADC, 4, 5, and 6 are the only reasonable options to use to help match the pixel output range (usually > 1.0V) to the ADC input range. Seven is not a reasonable setting for the ADC reference voltage because 1.5V is beyond the typical pixel output range and attenuation can more effectively be used to reduce the ADC signal input signal range to close to 1.0V.

Table 2: ADC Reference Settings

VREF_ADC (R0x2C)	ADC Input Range
0	0.71V
1	0.79V
2	0.86V
3	0.93V
4	1.0V
5	1.07V
6	1.14V
7	1.5V

To avoid capturing pixel-to-pixel saturation mismatches, it is best if the output range of the pixel (v<sub>3</sub>) is slightly larger (by at least 25mV) than the input range of the ADC.

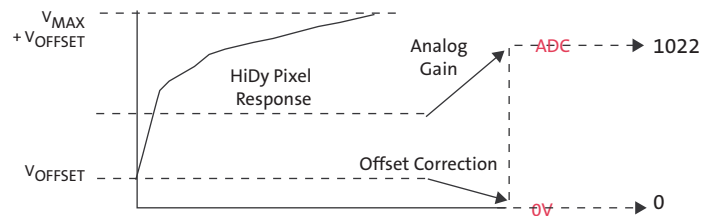
## Offset Correction

Offset correction is the first analog process applied to the sampled pixel response output. Achieving a wide dynamic range is impossible if the offset calibration is not properly calibrated. The offset correction parameters should be programmed such that the minimum detectable signal from the pixel produces an output code slightly above zero codes—perhaps with a mean of 6–8 10-bit ADC codes. Failure to properly set the offset correction will result in either loss of low- light signal details (a crushed black level) or a loss of high signal dynamic range. All the pixel response equations used in this technical note assume that an accurate black level correction was applied to the pixel output of the MT9V022.

The offset correction in the MT9V022 has an offset correction DAC that can either be programmed to a manual offset level, or be automatically adjusted by an adjustable black level calibration algorithm. Refer to the MT9V022 image sensor data sheet for further details regarding the black level calibration settings.

## Using Analog Gain with High Dynamic Range Mode Enabled

Figure 5: High Dynamic Range Pixel Response



Analog gain is applied to the pixel response after it has been sampled, and therefore does not change the equations that predict the ratios of Slope 1/Slope 2 or Slope 2/Slope 3. But it does directly affect what range of the signal will be quantized by the ADC. When the analog gain is set to anything greater than 1 V/V, and a multi-segment high dynamic range response is still desired, care should be taken to check that knee-points 1 and 2 are still within the quantifiable range of the ADC.

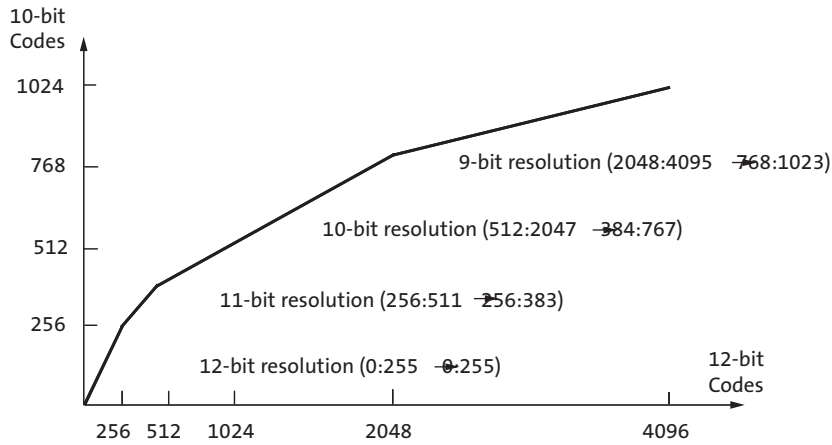
Any analog gain setting of greater than 1 V/V causes a smaller portion of the well capacity of the pixel to be quantized by the ADC, so the loss in dynamic range must be weighed against the gain in sensitivity.

## Companding

By default, the MT9V022 ADC has a linear response with 10-bit resolution. The ADC can also be configured to have a 12- to 10-bit companding response as illustrated in Figure 6. This mode allows higher ADC resolution (12-bit) for low level signals (shadow details) and lower ADC resolution (9-bit) for high level signals (highlight details). Companding can be enabled by setting R0x1C = 3.



Figure 6: 12 to 10-Bit ADC Companding Response



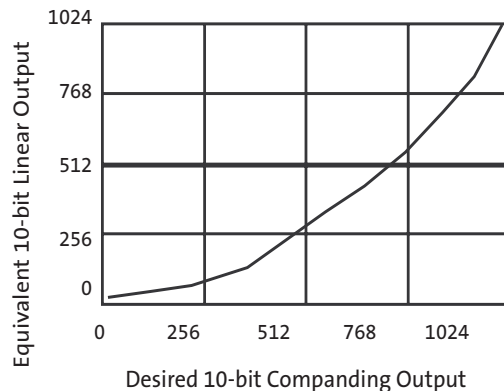
Companding can be effectively used with the high dynamic range mode to enhance shadow detail, but it must be considered when customizing the high dynamic range response curve. Given a desired response curve with ADC companding enabled, the best way to determine the appropriate HiDy parameters is to first apply the inverse of the companding response to the desired response. This results in a curve representing the desired response if a linear 10-bit ADC was used. The appropriate high dynamic range parameters can then be selected using the procedure outlined in the section “Customizing HiDy Response” on page 10 .

The inverse of the companding response can be determined as shown in Table 3.

Table 3: Companding Equation

10-Bit Code with Companding Enabled	10-Bit Code with Companding Disabled
0 through 255	Divide by 4
256 through 383	Subtract 128 then divide by 2
384 through 767	Subtract 256
768 through 1023	Subtract 512 then multiply by 2

Figure 7: Companding to Linear Response



## Customizing HiDy Response

This section defines the steps of a procedure that can be used to customize the MT9V022 high dynamic range pixel response.

### Step 1. Adjust and Verify the Black Level

As mentioned in “Offset Correction” on page 8, accurately adjusting the black level such that the minimum detectable signal from the pixel produces an output code as close to zero as possible without clipping is critical to achieving expected high dynamic range results. The offset correction settings (either manual or automatic) should be optimized with row noise correction disabled (set R0x70[bit5] = 0) since row noise correction adds an additional post-ADC offset to output data.

If you are using Aptina's DevWare application, ensure that “Subtract True Black” is disabled from the data interpretation page of the sensor control dialog box.

### Step 2. Set the Maximum Pixel Output and the ADC Input Range

Set  $V_3$  (R0x33) = 16. This sets the maximum output pixel output voltage ( $V_3$ ) near the full well capacity of the pixel. Since  $V_3$  does not have any effect on the knee points or the slope of any segment of the pixel response, it is best to use the input range of the ADC to limit output response. There is therefore, no reason to use any other setting for  $V_3$ .

Assuming  $V_{MAX}$  is used, it is usually appropriate to enable 0.75X attenuation (set R0xC2[bit8] = 1) so that with a default ADC reference range of 1.0V (R0x2C = 4), the maximum pixel response can be quantized.

If the 0.75X loss in sensitivity that results from attenuation is unacceptable, then the response knee points must be programmed to a larger value and it should be understood that less of the well capacity of the pixel will be quantized by the ADC (see “Mapping the Pixel Response to Output Codes” on page 6 for further details).

### Step 3. Determine the Required Total Shutter Width, $SW_{TOTAL}$

The slope of the first segment of the response curve is dependent on the total integration time and is not affected by any of the other high dynamic range parameters.  $SW_{TOTAL}$  should be selected so that the darkest scene details are detectable with the minimum required signal-to-noise ratio.

### Step 4. Set the Second Segment Slope Using $SW_1$

The second segment slope is dependent on the  $SW_1/SW_{TOTAL}$  ratio. Assuming that the total shutter width,  $SW_{TOTAL}$ , has been selected for the desired first segment response, the desired second segment slope should be selected using  $SW_1$  (R0x08) according to the following:

$$\text{Slope 1} / \text{Slope 2} = SW_{TOTAL} / (SW_{TOTAL} - SW_1) \quad (\text{EQ 10})$$

or

$$SW_1 = SW_{TOTAL} \times (1 - \text{Slope 2} / \text{Slope 1}) \quad (\text{EQ 11})$$

For example, if  $SW_{TOTAL} = 480$  and a second segment slope that is  $1/8$  the slope of the first segment slope is desired, then:

$$SW_1 = 480(1 - 1/8) = 420 \quad (\text{EQ 12})$$

### Step 5. Set the First Knee Point Using $V_1$

The first knee point can be adjusted by setting  $V_1$  (R0x31).

The actual response transition of the MT9V022 from one linear segment to the next is not a sharp knee but a rounded transition. Therefore, one should choose to more accurately control the slope of the segments using  $SW_1$  and  $SW_2$ , rather than trying to exactly pinpoint the knee codes.

In the typical case where  $ADC_{VREF} = 1.0V$  and attenuation is enabled, the minimum possible code for the first knee is when  $V_1 = 31$  and it is dependent on the  $SW_{TOTAL} : SW_1$  ratio.

### Step 6. Set the Third Segment Slope Using $SW_2$

Using the  $SW_{TOTAL}$ , and  $SW_1$  values from the previous steps, the slope of the third segment can be set using  $SW_2$  (R0x09):

$$\text{Slope 2/Slope 3} = (SW_{TOTAL} - SW_1) / (SW_{TOTAL} - SW_2) \quad (\text{EQ 13})$$

or

$$SW_2 = SW_{TOTAL} - (SW_{TOTAL} - SW_1) \times \text{Slope 3/Slope 2} \quad (\text{EQ 14})$$

For example, if  $SW_{TOTAL} = 480$  and  $SW_1 = 424$ , and a Slope 2/Slope 3 ratio of 12:1 is desired then:

$$SW_2 = 480 - (480 - 424) * 1/12 = 475.3$$

which, when rounded to 475 would result in the closest possible Slope 2/Slope 3 ratio of 11.2.

### Step 7. Set the Second Knee Point Using $V_2$

The second knee point can be adjusted by setting  $V_2$  (R0x32).

If the knee point of transition between the second and the third segment of the response curve must be more accurate than the slope of the third segment, then  $SW_2$  may be adjusted to get a more accurate knee point code at the expense of the accuracy of the third segment slope.



## Customizing the HiDy Response—Procedure Summary

Table 4: Procedure Summary

Step	Procedure
1	Adjust and verify the black level.
2	Set the maximum pixel output and the ADC input range. Set $V_3$ (R0x33) = 16. Enable attenuation: Set R0xC2[bit8] = 1.
3	Determine the required total shutter width, $SW_{TOTAL}$ (R0x0B). Set according to minimum required detectable illumination.
4	Set the second segment slope using $SW_1$ (R0x08). $SW_1 = SW_{TOTAL} * (1 - \text{Slope } 2 / \text{Slope } 1)$ .
5	Set the first knee point using $V_1$ (R0x31).
6	Set the third segment slope using $SW_2$ (R0x09). $SW_2 = SW_{TOTAL} - (SW_{TOTAL} - SW_1) * \text{Slope } 3 / \text{Slope } 2$ .
7	Set the second knee point using $V_2$ (R0x32).

## Conclusion

For more information on this and other features, refer to the MT9V022 data sheet on Aptina's Web site at [www.aptna.com](http://www.aptna.com).



## Revision History

Rev. C .....	9/10
• Updated to Aptina template	
Rev. B .....	8/06
• Minor edits and format updates.	
Rev. A .....	5/06
• Initial release.	

10 Eunos Road 8 13-40, Singapore Post Center, Singapore 408600 prodmtg@aptina.com www.apina.com  
Aptina, Aptina Imaging, and the Aptina logo are the property of Aptina Imaging Corporation  
All other trademarks are the property of their respective owners.