Introduction to the Time-of-Flight (ToF) System Design

User's Guide

Literature Number: SBAU219D
December 2013 – Revised May 2014

Contents

List of Figures

List of Tables

Introduction

Time-of-flight techniques have been employed for more than a century for ranging purposes. However, only in the recent past have the speed and size of electronics been able to build small and affordable ToF cameras that provide a complete depth map of a scene. Such cameras enable a myriad of industrial and consumer applications.

The primary purpose of this document is to demystify the ToF camera system design. This document describes the detailed functionality of ToF systems, explains the trade-offs involved in a typical ToF camera, and provides a step-by-step ToF camera design flow.

1.1 Intended Audience

This document is targeted to people who want to:

- Start a new ToF camera design,
- Incorporate a ToF system in their solution,
- Determine if the ToF technique is suitable for their application, and
- Learn about ToF systems in detail.

1.2 Preliminary Study

- Technical White Paper, *Time-of-Flight Camera – An Introduction* (SLOA190)
- Wikipedia

Time-of-Flight Basics

The core of an optical time-of-flight system consists of a light transmitter and a receiver. The transmitter sends out a modulated signal. The transmitted signal bounces off objects in the scene and part of the reflected signal comes back to the receiver. The round-trip time from the transmitter to the receiver is an indicator of the distance of the object that the signal bounced back from. If the signal is periodic, the phase difference between the transmitted and received signal is an indicator of the round-trip time.

2.1 Single-Pixel ToF System

One of the simplest ToF systems is a single-pixel ToF system (also referred to as *ranger* in rest of this document). Typically, these systems employ a modulated collimated laser as a transmitter and a single photodiode as a receiver, as shown in Figure 2-1.

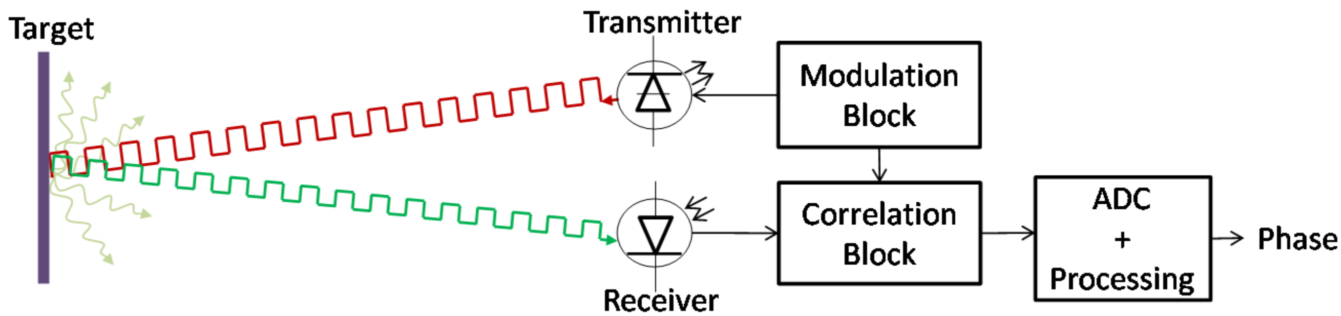


Figure 2-1. Single-Pixel ToF

A ranger provides distance information of a single spot. For the ranger to be able to provide the depth map of an entire scene, some form of scanning must be performed. Such systems are called *scanning ToF systems* and a detailed explanation about scanning ToF systems is beyond the scope of this document. A lens is strictly not necessary as long as the modulated illumination is focused only on the region of interest because depth information of a single spot is measured in a ranger. Even if a lens is used, the only purpose for the lens is to focus light on the receiver diode, rather than for image formation.

2.2 ToF Camera

A ToF camera obtains the depth map of an entire scene. The transmitter consists of an illumination block that illuminates the region of interest with modulated light and the sensor consists of a pixel array that collects light from the same region of interest, as shown in Figure 2-2. The TI ToF sensors belong to a class of ToF sensors that have in-pixel demodulation. That is, each pixel develops a charge that represents the correlation between transmitted and received light. A lens is required for image formation while maintaining a reasonable light collection area because individual pixels must collect light from distinct parts of the scene.

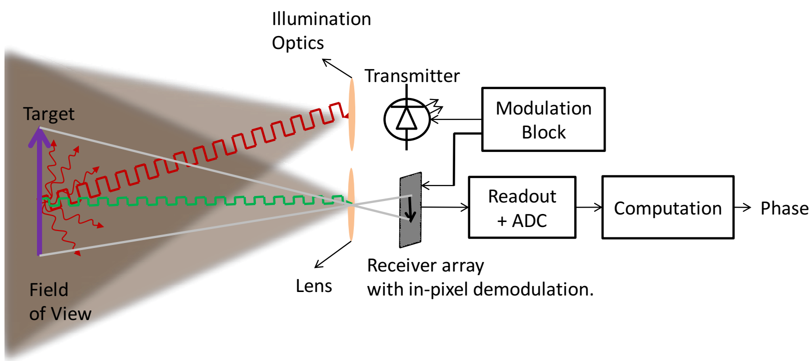


Figure 2-2. ToF Camera

A typical ToF camera sensor does not have a dedicated analog-to-digital converter (ADC) and processing block for each pixel. The analog data in the pixel array must be readout and then processed. Therefore, unlike the single-pixel ToF system, data acquisition the data processing occur at separate instances of time. The duration of data acquisition is called *integration time* and the duration of data readout is called *readout time*.

ToF Camera Sensor: The Pixel

All pixels in the sensor are controlled by a common demodulation input that comes from the modulation block. The demodulation input to the pixels is synchronous with the illumination block modulation. In the simplest form, each pixel can be approximated by the model shown in Figure 3-1.

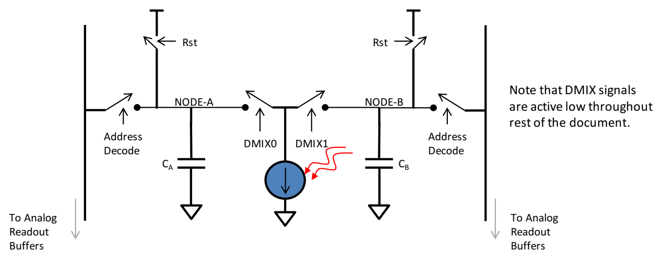


Figure 3-1. Simplest Pixel Form

Each measurement is split into four phases: reset, integration, readout, and dead time, as shown in Figure 3-2.

Figure 3-2. Phases

During reset time, the pixel is reset with the Rst signal to a known voltage value (V_R). During integration time, the photocurrent is directed towards Node-A or Node-B by driving the demodulation signals DMIX0 and DMIX1 in the opposite phase. If DMIX0 is active, Node-A discharges and conversely (if DMIX1 is active), Node-B discharges. During readout time, demodulation is stopped and the address decode signals are activated to readout the entire array in a programmed sequence.

3.1 Ideal Pixel: Scene With No Ambient Light

With the pixel structure previously discussed, if there are no mismatches between capacitances C_A and C_B and if the reset voltages of both capacitors are the same, a simple timing scheme as suggested Figure 3-3 can be used to measure the distance.

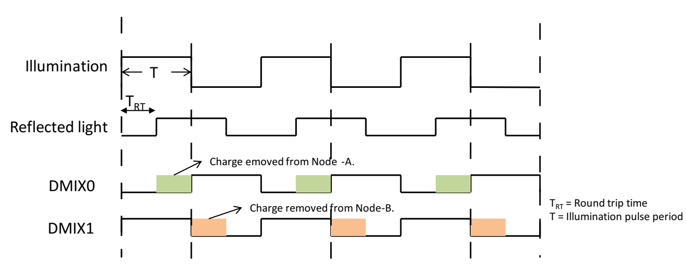


Figure 3-3. Simple Timing Scheme

If A and B are respectively defined as the voltages on Node-A and Node-B, and with T_{RT} less than or equal to T, A and B can be calculated by Equation 1 and Equation 2:

$$A = V_R - (T - T_{RT}) \times K \quad (1)$$

$$B = V_R - T_{RT} \times K \quad (2)$$

Distance can be calculated with Equation 3. The unambiguous range is defined by Equation 4.

$$normalized\ distance = \frac{distance}{range} = phase = \frac{T_{RT}}{T} = \frac{V_R - B}{2V_R - (A + B)} \tag{3}$$

$$range = \frac{T \times c}{2} \tag{4}$$

Note that phase and normalized distance are used interchangeably throughout this document.

3.2 Practical Pixel: Offset, Scene with Ambient Light

With the same timing as in Section 3.1, if the voltages developed resulting from ambient light (V_{AX}) are introduced and the pixel reset voltages (V_{OX}) are different on nodes A and B, the formulae listed in Section 3.1 no longer work. Instead, the voltages on Node-A and Node-B are now defined by Equation 5 and Equation 6.

$$A = V_{AA} + V_{OA} + V_R - (T - T_{RT}) \times K \tag{5}$$

$$B = V_{AB} + V_{OB} + V_R - T_{RT} \times K \tag{6}$$

Now there are four unknowns [($V_{AA} + V_{OA}$), ($V_{AB} + V_{OB}$), K, and T_{RT}] and only two equations. Therefore, to resolve the additional unknowns, one more measurement must be performed. A simple way to run the additional experiment is to run the experiment without illumination. Doing so results in four equations (Equation 7, Equation 8, Equation 9, and Equation 10).

This gives us 4 equations :

$$A_0 = V_{AA} + V_{OA} + V_R - (T - T_{RT}) \times K \tag{7}$$

$$B_0 = V_{AB} + V_{OB} + V_R - T_{RT} \times K \tag{8}$$

$$A_{OFF} = V_{AA} + V_{OA} + V_R \tag{9}$$

$$B_{OFF} = V_{AB} + V_{OB} + V_R \tag{10}$$

A_0 and B_0 are determined with a modulating illumination and A_{OFF} and B_{OFF} are determined with illumination off.

If we use Equation 11 and Equation 12 (again solving for T_{RT}), distance is determined by Equation 13.

$$A = A_0 - A_{OFF} = -(T - T_{RT}) \times K \tag{11}$$

$$B = B_0 - B_{OFF} = -T_{RT} \times K \tag{12}$$

$$phase = B / (A + B) \tag{13}$$

3.3 Practical Pixel: Gain Error

With the same timing as in Section 3.3 , if the capacitances C_A and C_B are different in value or discharge at different rates for the same amount of light, the formulae listed in Section 3.3 no longer work. A and B are now given by Equation 14 and Equation 15:

$$A = -G_A \times (T - T_{RT}) \times K \tag{14}$$

$$B = -G_B \times T_{RT} \times K \tag{15}$$

Now there are four unknowns (G_A, G_B, T_{RT}, and K) and only two equations. Therefore, to determine the additional unknowns, more measurements must be performed, which brings us to the typical 4-quad ToF system. One way to perform the measurements is to delay the illumination modulation phase by 0°, 90°, 180°, and 270° with respect to the sensor demodulation signal phase, as shown in Figure 3-4. Each measurement is called a *quad*.

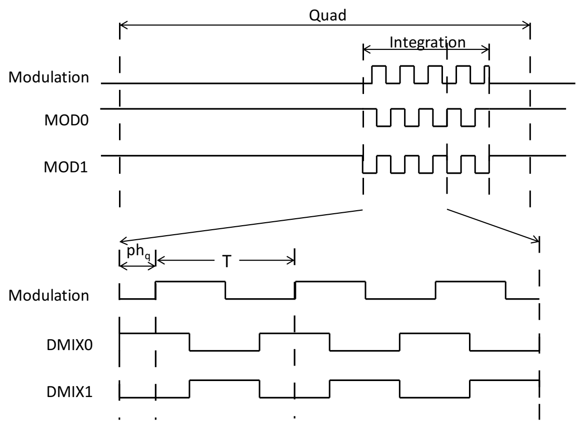


Figure 3-4. Sensor Demodulation Signal Phase

The waveforms in Figure 3-5 and Figure 3-6 show the ideal relationship between A-B and T_{RT}, assuming that the modulation and demodulation waveforms are perfect square waves.

In practice, the modulation and demodulation waveforms are not as perfectly square as depicted in Figure 3-5. As a result, the A-B versus T_{RT} waveforms resemble sinusoids more than triangular waves. Figure 3-6 depicts the waveforms with sinusoids.

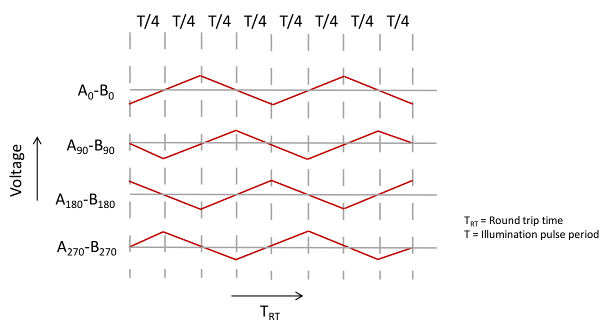


Figure 3-5. Waveform 1

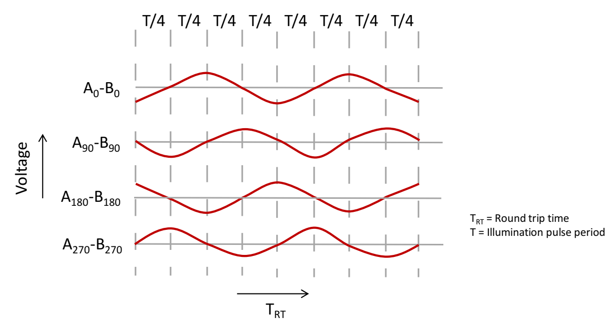


Figure 3-6. Waveform 2

Incidentally, the sinusoids are simpler to work with for rigorous mathematical applications. The formulae for A-B for the quads are listed in Equation 16, Equation 17, Equation 18, and Equation 19.

$$A_0 - B_0 = (V_{AA} + V_{OA} + V_R) - (V_{AB} + V_{OB} + V_R) - (G_A + G_B) \times 2\cos(T_{RT} / T) \tag{16}$$

$$A_{180} - B_{180} = (V_{AA} + V_{OA} + V_R) - (V_{AB} + V_{OB} + V_R) + (G_A + G_B) \times 2\cos(T_{RT} / T) \tag{17}$$

$$A_{90} - B_{90} = (V_{AA} + V_{OA} + V_R) - (V_{AB} + V_{OB} + V_R) - (G_A + G_B) \times 2\sin(T_{RT} / T) \tag{18}$$

$$A_{270} - B_{270} = (V_{AA} + V_{OA} + V_R) - (V_{AB} + V_{OB} + V_R) + (G_A + G_B) \times 2\sin(T_{RT} / T) \tag{19}$$

The in-phase component can be calculated as I (Equation 20) and Q (Equation 21).

$$I = (A_0 - B_0) - (A_{180} - B_{180}) = -(G_A + G_B) \times 4\cos(T_{RT} / T) \tag{20}$$

$$Q = (A_{90} - B_{90}) - (A_{270} - B_{270}) = -(G_A + G_B) \times 4\sin(T_{RT} / T) \tag{21}$$

Finally, the formula for phase is determined by Equation 22:

$$\text{Phase} = \tan^{-1}(Q / I) \tag{22}$$

This theory can be generalized for an N-quad system. The I/Q computation for a generic N-Quad system can be generalized to Equation 23 and Equation 24.

$$I = \sum_{i=0}^{i=N} D_i \cos\left(\frac{2\pi}{N}\right) \tag{23}$$

$$Q = \sum_{i=0}^{i=N} D_i \sin\left(\frac{2\pi}{N}\right) \tag{24}$$

The parametric relationship between I, Q, and phase is given in Equation 25 and Equation 26.

$$\text{Phase} = \tan^{-1} (Q / I) \tag{25}$$

$$\text{Distance} = (\text{Phase} \times \text{Range}) / 2\pi \tag{26}$$

In the parametric form, I and Q can be plotted against phase as in Figure 3-7:

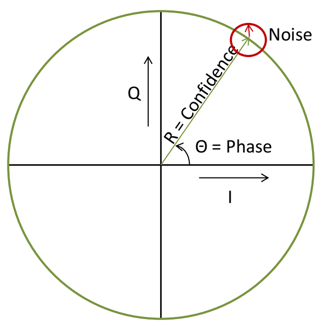


Figure 3-7. Parametric: I and Q versus Phase

As shown in Figure 3-7, phase is the distance information and confidence is the indicator of amplitude of the signal. If confidence is higher, the radius of the circle in Figure 3-7 is higher and, therefore, the phase distortion caused by noise is lower. Additionally, if confidence is higher, the signal-to-noise ratio (SNR) is higher. The formula for confidence is given by Equation 27:

$$confidence = \sqrt{I^2 + Q^2} \tag{27}$$

3.4 Practical Pixel: Non-Idealities in the Conversion of Photons to Voltage

To understand the tradeoffs involved in a ToF system, the non-idealities of a ToF pixel must be understood. In this section, the following non-idealities are introduced:

- Fill factor,
- Responsivity, and
- Demodulation contrast.

3.4.1 Fill Factor

Apart from the active light collection area, a ToF pixel contains other circuitry related to demodulation, reset, and readout. Therefore, all this circuitry reduces the light collection efficiency. Fill factor is defined as Equation 28. Therefore, the useful power at the pixel is determined by Equation 29.

$$F_F = \frac{\text{Active Pixel Area}}{\text{Total Pixel Area}} \tag{28}$$

$$\text{Useful Power at Pixel} = p = \text{Incident Power} \times F_F = p_i \times F_F \tag{29}$$

3.4.2 Responsivity

The conversion of photons to electrons is a quantum process and is governed by probability. Thus, not all the light that hits the pixel is converted to electrons. This non-ideality is called *quantum efficiency*. Quantum efficiency is a function of wavelength and, for a particular wavelength, is defined as by Equation 30:

$$quantum\ efficiency = \eta(\lambda) = \frac{no.of\ electrons\ generated}{no.of\ photons\ hitting\ the\ active\ pixel\ area} = \frac{n_e}{n_p} \tag{30}$$

The total generated electrons (n_e) consist of two components, as shown by Equation 31:

$$n_e = n_m + n_a \tag{31}$$

n_m represents the number of electrons generated resulting from the modulation signal light and n_a represents the number of electrons generated resulting from ambient light.

Responsivity is another term used to indicate efficiency and is closely related to quantum efficiency. Responsivity is defined by Equation 32:

$$responsivity = \frac{current\ generated}{power\ incident\ on\ the\ active\ pixel\ area} = \frac{i}{p} = \frac{\lambda \times q_e \times n_e}{hc \times n_p} = \frac{\lambda \times q_e}{hc} \times \eta(\lambda)$$

where:

- h is the plank's constant,
- c is the speed of light in the medium,
- λ is wavelength of the light used, and
- q_e is the charge of a single electron. (32)

From Equation 32, i and q can be derived by Equation 33 and Equation 34. Therefore, v is calculated by Equation 35.

$$i = \text{Responsivity} \times p \tag{33}$$

$$q = i \times t_I = \text{Responsivity} \times p \times t_I \tag{34}$$

$$v = \frac{q}{c} = \frac{responsivity\ \times p \times t_I}{c}$$

where:

- q is the charge collected,
- t_I is the integration time, and
- v is the voltage developed on each node of the pixel. (35)

Therefore, confidence can be derived with Equation 36:

$$confidence \propto \frac{responsivity \times p_I \times F_F \times t_I}{c}$$

where:

- p_I is the incident-modulated power on each pixel during integration time. (36)

In summary, if any fill factor, responsivity, illumination power, or integration time increases, confidence increases and SNR thus increases. Although decreasing the capacitance of the pixel seems to increase the confidence, doing so also increases the noise voltage because the input noise current is scaled by the same factor. Therefore, decreasing capacitance does not lead to a proportional increase in SNR.

Note that when the pixel is chosen, responsivity, fill factor, and pixel capacitance are fixed. Therefore, in a given system, Equation 36 reduces to Equation 37.

Confidence $\propto p_I \times t_I$ (37)

3.4.3 Demodulation Contrast

Thus far, demodulation is assumed to be perfect. That is, when DMIX0 is low and DMIX1 is high, all generated electrons are collected by Node-A and none are collected by Node-B. Conversely, when DMIX1 is low and DMIX0 is high, all generated electrons are assumed to be collected by Node-B and none by Node-A. In practice, this collection ratio is rarely the case. The non-ideality that represents this phenomenon is called *demodulation contrast*.

For example, assume that DMIX0 is out-of-phase with illumination and DMIX1 is in-phase for certain durations. During this time, if the number of electrons collected by Node-A is n_{ea} and the number of electrons collected by Node-B is n_{eb}, the demodulation contrast is defined by Equation 38.

$$demodulation\ contrast = C_d = \frac{n_{ea} - n_{eb}}{n_{ea} + n_{eb}} \tag{38}$$

The ideal value of demodulation contrast is 1. If C_d is lower, the amplitude of the differential signal A-B reduces and thus confidence reduces. Demodulation contrast is a function of frequency. Typically, demodulation contrast is highest at zero frequency (dc) and decreases with increases in frequency.

3.5 Practical Pixel: Modulation Voltage

So far, the demodulation controls are assumed to be ideal switches. The TI ToF sensors use a current assisted photonic demodulator (CAPD) pixel. For a CAPD pixel, the correct representation is not a switch but an electrical field that is setup to move the electrons to preferentially Node-A or Node-B as shown in Figure 3-8 .

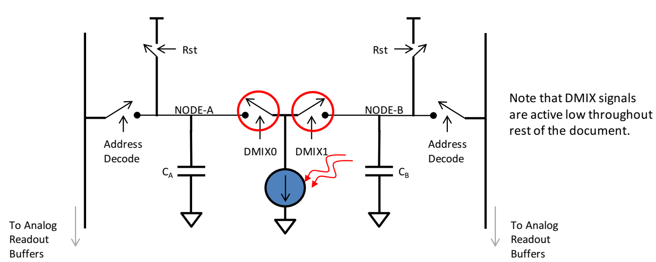


Figure 3-8. Practical Pixel

Node A and Node B consist of reverse biased diodes. Modulation is achieved by alternatively changing the direction of the voltage applied between the DMIX0 and DMIX1 nodes. The typical pixel structure is as shown in Figure 3-9.

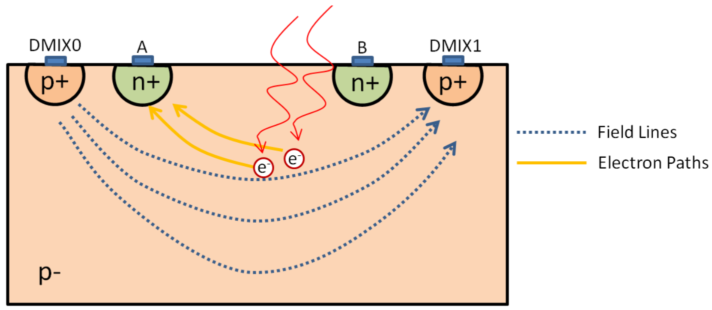


Figure 3-9. Pixel Structure

Due to this modulating field applied within the substrate, electrons that are generated deeper in the substrate (>4um) can be collected. The ability to collect electrons that are generated deeper in the substrate is one of the main reasons for the better responsivity and demodulation contrast of CAPD pixels with respect to competing technologies. The voltage used for demodulation controls the electric field intensity and thus the drift velocity of the generated electrons. Therefore with higher demodulation voltage:

- Demodulation contrast is higher.
- Responsivity is higher.
- Current through the substrate increases, sensor power is higher, and more heat is generated within the sensor due to resistive losses.

3.6 Noise Sources

Thus far, the factors that determine the signal amplitude have been discussed. However, to determine the phase SNR, the factors that affect noise as well must be identified. The most significant sources of noise are pixel reset noise and photon shot noise.

3.6.1 Pixel Reset Noise

Capacitors have an inherent reset noise. The amplitude of this noise in terms of charge is given by Equation 39.

$$N_T = \sqrt{kTC} \tag{39}$$

The amplitude of this noise in terms of number of electrons is given by Equation 40.

$$n_T = \frac{\sqrt{kTC}}{q_e} \tag{40}$$

3.6.2 Photon Shot Noise

Photon generation is governed by probability because the generation of photons is a quantum process. The rate of photon generation has a Poisson distribution. Similarly, the reflection of photons by the target and the conversion of photons to electrons within the pixel are also quantum processes that have a Poisson distribution. As a result, if the total number of electrons generated is n_e, the standard deviation (n_s) of n_e is given by Equation 41.

$$n_s = \sqrt{n_e} \tag{41}$$

With increases in integration time or incident power, confidence increases proportionally. However, shot noise increases as a square root at the same time. Therefore, SNR increases only as square root when shot noise is the dominant form of noise. Note that n_e consists of all generated electrons because of the incident ambient photons and the modulated signal photons.

With increase in demodulation contrast, confidence increases proportionally. Because demodulation contrast is only responsible for rearranging electrons and not for generating electrons, increases in demodulation contrast does not lead to an increase in shot noise. As a result, SNR increases proportionally with demodulation contrast.

3.6.3 Summary

When the number of generated photons is small, n_T dominates. When the number of photons is large, n_s dominates.

When confidence is relatively low, pixel reset noise is the dominant form of noise. Likewise, when confidence is relatively high, shot noise is the dominant form of noise.

3.7 Signal-to-Noise Ratio (SNR)

The phase SNR is governed by the relationship in Equation 42.

$$Phase\ SNR \propto \frac{Signal}{Noise} \propto \frac{\mathrm{n_m} \times C_d}{\sqrt{n_s^2 + n_T^2}} \propto \frac{\mathrm{n_m} \times C_d}{\sqrt{n_e + n_T^2}} \tag{42}$$

However, because depth resolution is determined by Equation 43, d_{res} is therefore determined by Equation 44.

$$depth\ resolution = depth\ noise = \frac{range \times 2\pi}{phase\ SNR} = \frac{c}{2f_m \times (phase\ SNR)} \tag{43}$$

$$d_{res} = N_d \propto \frac{c \times \sqrt{n_e + n_T^2}}{\mathrm{n_m} \times f_m \times C_d}$$

where:

- f_m is the modulation frequency and
- c is the speed of light. (44)

When pixel reset noise is the dominant form of noise in the system, Equation 43 reduces to Equation 45.

$$N_d \propto \frac{c \times n_T}{\mathrm{n_m} \times f_m \times C_d} \tag{45}$$

That is, depth noise is inversely proportionate to the number of electrons collected. Therefore, increasing integration time or illumination power improves the depth noise proportionally in this region of operation.

When ambient light intensity is low and when shot noise is the dominant form of noise in the system, Equation 43 reduces to Equation 46.

$$N_d \propto \frac{c}{\sqrt{n_m} \times f_m \times C_d} \tag{46}$$

That is, depth noise is inversely proportional to the root of the number of electrons collected. Therefore, increasing integration time or illumination power improves the depth noise only by the root in this region of operation.

Also, note that the product of demodulation frequency and demodulation contrast is inversely proportional to depth noise. The product of demodulation contrast and demodulation frequency peaks at an optimal frequency because demodulation contrast decreases with frequency for a given pixel. The product of C_d and f at the optimal frequency is an important figure of merit of the pixel, because this product indicates the best attainable demodulation performance using the pixel. This frequency changes with demodulation voltage and typically ranges between 40 MHz to 80 MHz for first-generation TI ToF sensors.

3.8 Well Capacity: Saturation

Each pixel can collect a maximum number of electrons on Node-A and Node-B. This maximum limit is called *well capacity*. As discussed previously, when SNR must be improved, integration time or illumination power can be increased. However, after a point, n_e must go beyond the well capacity. One way to overcome this limitation is to repeat the same measurements multiple times with shorter integration times to achieve the intended cumulative integration time.

ToF Camera Sensor: Frame Rate

Each frame is divided into a similar set of measurements called sub-frames, as shown in Figure 4-1. Each sub-frame has all the measurements necessary for phase computation. Multiple sub-frames are used to overcome the limitations of pixel saturation, and therefore enhance the dynamic range of the system.

Frame				
Sub-frame-1	Sub-frame-2	………	Sub-frame-n	Frame dead time

Figure 4-1. Sub-Frames

Each sub-frame is divided into quads, as shown in Figure 4-2. Each quad can have a different phase between illumination and sensor modulation signals.

Sub-frame				
Quad-1	Quad-2	Quad-3	………	Quad-n

Figure 4-2. Quads

Each quad is further split into four stages, as shown in Figure 4-3. Table 4-1 describes these stages.

Quad			
Reset	Integration	Readout	Quad dead time

Figure 4-3. Stages

Table 4-1. Quad Stage

Quad stage	Description
Reset	The sensor is reset to clear the accumulated signal.
Integration	The sensor and illumination are modulated by the TFC. The sensor acquires the raw ToF signal.
Readout	The raw pixel data in the selected region of interest is readout by the TFC to an external ADC and is then read by the TFC.
Dead time	The sensor and ADC are inactive. The TFC places itself and the ADC in low-power mode.

To achieve a higher frame rate for a fixed integration time and number of pixels to be readout, a combination of the following suggestions can be used:

- Decrease the number of sub-frames and
- Decrease the quad dead time or the frame dead time.

The ratio of total integration time over the entire frame to the total frame time is called the *integration duty cycle* (d_{TI}). If dead time is reduced, d_{TI} increases. d_{TI} decides the ratio of peak power to average power in the system.

ToF Receiver Optics

The receiver optics consists of a lens that forms the image on the sensor and additional filters, if required. The lens controls the field of view (FoV), aperture (light collection area), and depth of field (DoF).

5.1 Field of View (FoV)

FoV is one of the first parameters chosen when a ToF system is designed. A typical field of view is shown in Figure 5-1. FoV must be chosen appropriately as per the coverage requirements of the application. For example, for a short-range, gesture-recognition application for laptops, a wide field of view is more suitable because the subjects are close to the camera. On the other hand, for an application such as gesture-recognition for TVs, a narrow field of view may be appropriate because the subjects are far away.

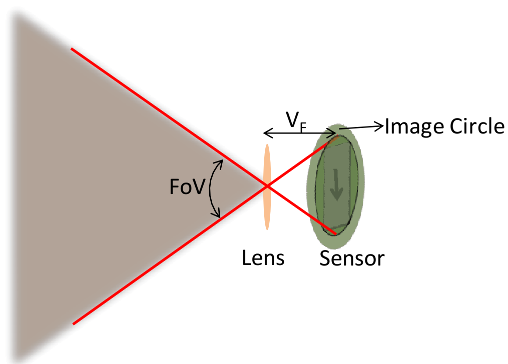


Figure 5-1. Field of View (FoV)

The diagonal FoV (Equation 47) is a function of the distance between the optical center of the lens and the sensor (V_F) and the sensor diagonal (D_S). In practice, for applications where the subject distance is much larger than focal length of the lens, V_F is nearly equal to the focal length of the lens.

$$\frac{D_S}{F} \approx \frac{D_S}{V_F} = 2 \times \tan\left(\frac{FoV}{2}\right) \tag{47}$$

Likewise, horizontal FoV (HFoV) and vertical FoV (VFoV) are related to the sensor width (W_S) and height (H_S) respectively, as shown by Equation 48 and Equation 49.

$$\frac{W_S}{F} \approx \frac{W_S}{V_F} = 2 \times \tan\left(\frac{HFoV}{2}\right) \tag{48}$$

$$\frac{H_S}{F} \approx \frac{H_S}{V_F} = 2 \times \tan\left(\frac{VFoV}{2}\right) \tag{49}$$

Sensor size can be observed by Equation 48 and Equation 49 because the sensor size is fixed. Thus, when the FoV requirements are chosen, the focal length of the lens is automatically determined. If the FoV is wider, focal length is smaller. Although focal length is not the only factor that determines the lens stack height, a smaller focal length typically means a smaller lens stack height.

5.2 Aperture

The aperture of a lens can be defined as the effective area of the lens that collects light from the scene. A reasonable assumption is that this area is circular in shape and the diagonal can be denoted as D. The ratio of focal length (f) to D is called the *f-number* (f.no) of a lens. For a given focal length, if the f-number is higher, D is smaller and thus aperture is smaller. Conversely, if the f-number is lower, D is larger and thus aperture is larger. Equation 50 provides a summary.

$$\text{aperture} = \frac{\pi D^2}{4} = \frac{\pi f^2}{4 \times (f.no)^2} \tag{50}$$

If the aperture is higher, light collected is higher. Therefore, illumination power requirements are lower. For a given focal length, the f-number should be lower. Typically, lenses with lower f-numbers are more difficult to construct and are thus more expensive.

5.3 Depth of Field (DoF)

DoF is an indicator of the range of the scene that is in focus, as shown in Figure 5-2. For example, if system-1 has all the objects in the scene from a distance of 1 m to 3 m in focus and system-2 has all the objects in the scene from a distance of 2 m to 3m in focus, system-1 has a greater DoF. DoF is controlled by the aperture of the lens. If the aperture is higher, DoF is lower and vice-versa. In most cases, DoF is usually not the limiting factor because the aperture is limited at the higher end by the practical values of the lens f-number. However, in some specific cases, when objects at a wide range of distances must be in focus simultaneously, DoF may limit the aperture.

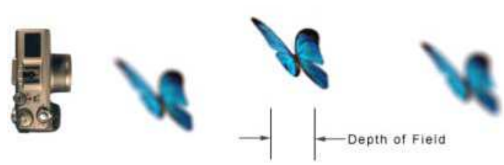


Figure 5-2. Depth of Field

Illumination Module

The ideal illumination source is shown in Figure 6-1. The illumination source consists of one or more light emitters that are driven by a modulating current source to emit light in unison. Typical light sources used are LEDs or laser diodes. The number of emitters required and the amount of power that must be emitted depends on the system performance required.

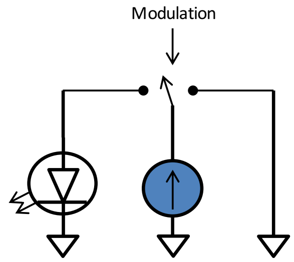


Figure 6-1. Ideal Illumination Source

6.1 Optical Wavelength Choice

The wavelength of the light emitted by the illumination must fall within the optical bandwidth of the filter used on the sensor. In most scenarios, using a modulated light that is not visible to the human eye is preferred. Therefore, a typical TI ToF sensor optical filter is in the near-IR region.

6.2 Timing and Modulation

Illumination modulation is active during the integration time and can be turned off for the rest of the time. The phase of the illumination with respect to sensor demodulation is stepped from quad to quad, as shown in Figure 6-2.

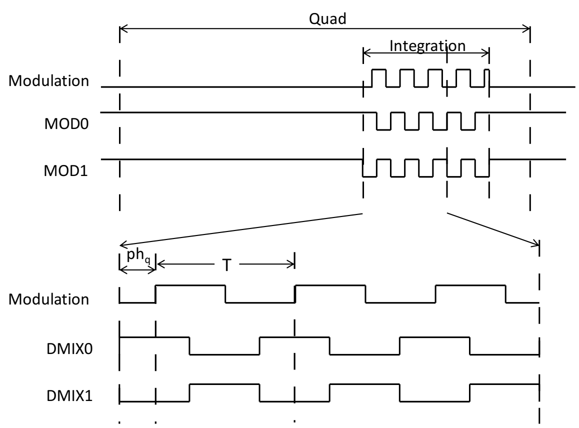


Figure 6-2. Illumination Phase

Like the sensor, the illumination source should be able to modulate well at the frequency of operation. Typically, laser sources are capable of achieving significantly higher modulation frequency as compared to LEDs. Most high-frequency LEDs available today have their 3-dB roll-off frequency between 10 MHz and 30 MHz. Laser diodes, on the other hand, have their 3-dB roll-off frequencies beyond 100 MHz. Therefore, TI ToF sensors can be operated at their optimal frequency in conjunction with laser diodes. Whereas, with LEDs, the sensors may have to be operated at lower, sub-optimal frequencies.

6.3 Illumination Power Requirement

For the power calculation, work backwards from the depth noise requirement. As discussed earlier, depth noise is given by Equation 51:

$$distance\ noise = N_d \propto \frac{c \times \sqrt{n_e + n_T^2}}{\mathrm{n_m} \times f_m \times C_d} \tag{51}$$

Therefore, to reduce the depth noise, n_m must increase, Equation 52 shows.

$$n_m \propto p_i \times t_I \tag{52}$$

Therefore, n_m can be increased by increasing the illumination power during integration time (p_I) or by increasing the integration time. For SNR performance, increasing p_I is preferred because increasing t_I also increases the ambient light collected. p_I is related to the illumination power emitted during integration time (p_E) by Equation 53:

$$p_E = \frac{p_I \times 4\pi \times d^2 \times no.of\ pixels}{r \times aperture}$$

where:

- d is the subject distance and
- r is the reflectivity of the subject in the scene. (53)

The average illumination power during the entire frame can be calculated by Equation 54:

$$p_{Eavg} = \frac{p_E \times d_{TI}}{frame\ time} = p_E \times d_{TI} \times fps$$

where:

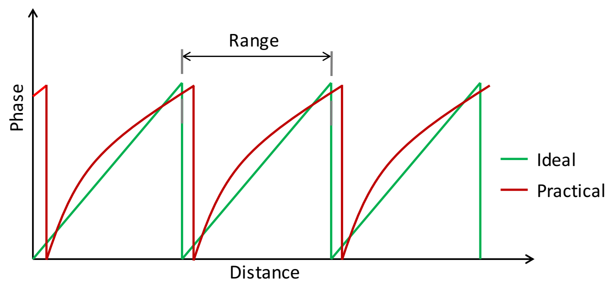
- d_{TI} is integration duty cycle and
- f_{ps} is the frame rate. (54)

Converting Phase to Distance

In the ideal scenario without phase offset and gain and linearity errors, Equation 55 describes the relationship between the real-world distance and the measured phase.

$$distance = \frac{phase \times range}{2\pi} \tag{55}$$

In reality, the relationship between distance and phase might be a curve, as shown in Distance and Phase Relationship.



Distance and Phase Relationship

7.1 Offset Correction

Apart from the delay resulting from the distance of the object from the camera, the total measured ToF contains the difference in delays of modulation signal and demodulation signal. The orange and blue arrows indicated in Figure 7-1 represent the two paths.

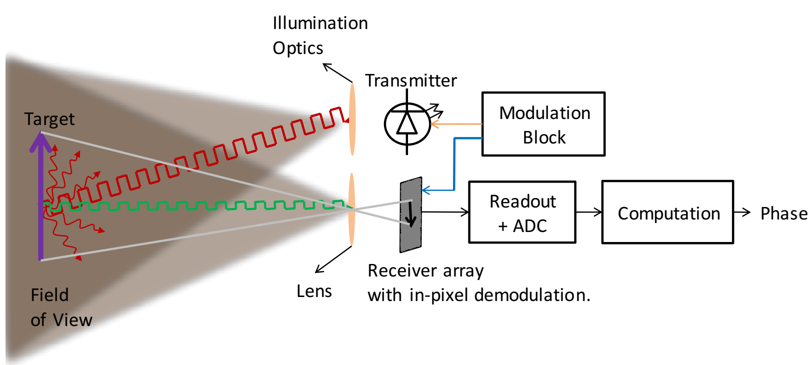


Figure 7-1. Offset Correction Paths

The illumination modulation path consists of the modulation driver delay and the LED or laser electrical to optical delay. The sensor modulation path consists of the sensor demodulation driver delay and the intra-sensor routing delays (which typically are not significant and the discussion of such delays is beyond the scope of this document).

For each system, a factory calibration can be done to correct offset error. An object can be placed at a known distance in the scene and the difference between the actual and measured distance is the offset. This offset can then be stored in permanent memory on the board. During normal operation, offset can be subtracted from the measured value to obtain the actual phase. TI TFCs support fixed offset calibration. The offset correction value can be programmed into a TFC register to cancel the fixed offset.

Temperature can change the offset error because the change in delay with respect to temperature can be different for the sensor demodulation path than for the illumination modulation path. Therefore, the total phase correction to be applied has two components, as Equation 56 shows.

Total Phase Correction = phase_corr + phase_corr_temp

where:

- phase_corr is the fixed offset and
- phase_corr_temp is the component that varies with temperature. (56)

The change in delay can be modeled with a linear approximation, as shown in Equation 57:

$$\text{phase\_corr\_temp} = \text{coeff\_illum} \times (T_{illum} - T_{illum\_calib}) + \text{coeff\_sensor} \times (T_{sensor} - T_{sensor\_calib}) \quad (57)$$

coeff_illum and coeff_sensor are coefficients of phase change with respect to temperature for the illumination modulation path and sensor demodulation path, respectively. T_{illum_calib} and T_{sensor_calib} are the temperatures measured using external temperature sensors near the illumination driver and the sensor, respectively, at the reference ambient temperature. Reference ambient temperature is defined as the temperature at which phase_corr is measured.

Unlike fixed-phase offset correction, temperature calibration is typically performed only one time on each new design rather than on every system. To calibrate, ambient temperature is changed to obtain the least two operating points other than the reference temperature. The values of phase offset measured in the experiments can be substituted into Equation 57 to calculate the coefficients. TI TFCs support temperature calibration. The calculated coefficients can be programmed into the TI TFCs to compensate for temperature changes during normal operation.

At the hardware design level, changes in delay resulting from temperature can be reduced by minimizing the modulation path delays. Typically, the variation in delay resulting from temperature is usually proportional to the absolute path delay.

7.2 Gain and Linearity Correction

Considering Equation 58, range is a function of speed of light and modulation pulse period and is given by Equation 59.

$$distance = \frac{phase \times range}{2\pi} \quad (58)$$

$$range = \frac{T \times c}{2} \quad (59)$$

In practical systems, the accuracy of T is determined by the accuracy oscillator and the modulation PLL. Inaccurate values of T results in incorrect conversion factors from phase to distance.

Among modulation signals and demodulation functions, if one of these is a perfect square and the other is a sinusoid, phase changes linearly with distance. In the ideal case, as discussed in Section 3.3, the parametric representation of I/Q with changes in phase is a circle. However, the practical plot (as shown in Figure 7-2) may resemble a square (shown in red) or may resemble a rhombus (shown in blue).

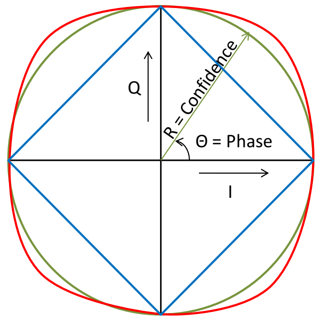


Figure 7-2. Parametric: Practical Plot

To fix the linearity error, two approaches can be used. The first approach is to sweep the phase offset of the modulation signal with respect to the demodulation signal and measure the phase of a fixed object in the scene. The difference in the applied phase offset and the measured phase is an indicator of the nonlinearity. A look-up table or a function can be generated using the measured values. This mapping can be used to correct the actual phase measurements during normal operation.

The second approach is to actually use a movable object for calibration. An object can be moved through the usable range of the ToF system in steps to determine the relationship between measured phase and actual distance. This relationship can be used for calculating distance from phase directly.

De-Aliasing

The unambiguous range of a ToF system is defined by the modulation frequency (F). This range is given by Equation 60.

$$R = \frac{C}{2F} \tag{60}$$

where:

- C is the speed of light in the medium.

For example, for a modulation frequency of 50 MHz, R = 3 m in open air. If the total range of the application is beyond the unambiguous range for a given modulation frequency, de-aliasing can be enabled to extend the unambiguous range. This technique employs two modulation frequencies. The unambiguous range is given by Equation 61.

$$R = \frac{C}{2 \times GCD(F1, F2)} \tag{61}$$

Using Auxiliary Data

As part of the depth data, the TI TFCs also provide confidence and ambient per pixel apart from phase. Confidence data are an indicator of signal strength received. Ambient data are an indicator of the amount of non-signal light received. The TI TFCs optionally provide phase, confidence, and ambient histogram information that can be used to meter the scene with very little additional computation on the external host.

9.1 Using the Confidence Information

Confidence can be used to implement filters because confidence is an indicator of strength of the received signal. For example, a simple mask filter can be implemented if confidence is greater than the threshold. If confidence is greater than the threshold, use the phase information. Otherwise discard the phase information.

A generic n × n spatial filter can be implemented where the weights are multiplied with confidence. For example, a smoothing filter can be implemented as shown in Equation 62.

$$phase(i,j) = sum(phase\ matrix(i,j)\ o\ (filter\ matrix)\ o\ (confidence\ matrix(i,j)))/sum(confidence\ matrix(i,j)) \quad (62)$$

The operator o signifies the element-by-element product (Hadamard product) of the matrices. The definitions of the matrices in Equation 62 are given in Equation 63, Equation 64, and Equation 65.

$$filter\ matrix = \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix} /16 \quad (63)$$

$$filter\ matrix(i,j) = \begin{bmatrix} p(i-1,j-1) & p(i-1,j) & p(i-1,j+1) \\ p(i,j-1) & p(i,j) & p(i,j+1) \\ p(i+1,j-1) & p(i+1,j) & p(i+1,j+1) \end{bmatrix} \quad (64)$$

$$confidence\ matrix(i,j) = \begin{bmatrix} c(i-1,j-1) & c(i-1,j) & c(i-1,j+1) \\ c(i,j-1) & c(i,j) & c(i,j+1) \\ c(i+1,j-1) & c(i+1,j) & c(i+1,j+1) \end{bmatrix}$$

where:

- c(i,j) is the confidence for pixel(i,j),
- p(i,j) is the phase for pixel(i,j), and
- the filter matrix is an example of a Gaussian filter. (65)

9.2 Using the Ambient Information

Typically, the TI ToF sensors have built-in optical filters in order to filter out unwanted ambient light. However, in practical scenarios, ambient light has spectral components that match the signal light and thus pass through the filter. The ToF sensor pixels develop a common-mode signal as a result of ambient light. The phase computation relies only on the differential signal and, therefore, ambient light does not affect phase measurements directly. However, ambient light reduces pixel dynamic range. Furthermore, the shot noise resulting from the common-mode signal can result in differential noise and thus an increase in phase noise. Therefore, knowing the level of ambient light is important in order to optimize system settings.

Example Problem 1:

Loss of dynamic range because of a high ambient. Some pixels are saturated.

Solution:

Increase the number of sub-frames and reduce the integration time per sub-frame to collect the same amount of signal light while avoiding pixel saturation.

Example Problem 2:

High phase noise because of a high ambient.

Solution:

Increase the illumination peak power and reduce the integration time to reduce the ambient light collected while keeping the amount of signal light collected the same.

Note that the ambient information consists of true unfiltered ambient light as well as a non-demodulated signal. Therefore, if the demodulation contrast is lower, the ambient appears to be higher.

9.3 Using the Histogram Information

Histograms give a concise summary of the entire scene and this information can be used to trigger actions on the host without much additional computation. Some example scenarios are:

Scenario 1:

The system must be placed in a high-power mode only when an object is detected as nearer than the threshold.

Solution:

The phase histogram is used to check if any pixels are within the threshold and triggers a transition to high-power mode.

Scenario 2:

The system must perform an auto power control based on the signal strength received.

Solution:

Illumination power is increased or decreased, based on the confidence histogram.

System Trade-Offs

As a summary of the previous sections, the key relations that govern the system-level trade-offs are described in this section.

The relationship of illumination power with the other key system parameters is approximately Equation 66:

$$p_{Eavg} \propto fps \times Number\ of\ Pixels \times \left[\frac{d \times f.no \times \tan(FoV)}{D_s}\right]^2$$

where:

- fps = frame rate,
- d = distance of the subject,
- D_S = sensor diagonal,
- FoV = field of view, and
- f.no = ratio of focal length to aperture diameter of the image forming lens. (66)

For low-illumination power and high-ambient scenarios, the relationship between d_{res} and p_E is approximately Equation 67:

$$d_{res} \propto \frac{1}{C_d \times f_m \times p_{Eavg}} \tag{67}$$

For high-illumination power and low-ambient scenarios, the relationship between d_{res} and p_E is approximately Equation 68:

$$d_{res} \propto \frac{1}{C_d \times f_m \times \sqrt{p_{Eavg}}}$$

where:

- Cd = Demodulation contrast and
- f_m = frequency of modulation. (68)

10.1 Trade-Off Example: Pixel Binning versus Depth Resolution

Problem:

The system has a strict limitation on the maximum power available.

The depth resolution requirement is 8 mm. However, at maximum power, the attainable depth resolution is approximately 10 mm.

The system requires 160 × 120 pixels, but the sensor has 320 × 240 pixels.

Solution:

Trade the number of pixels for depth resolution. Binning can be used to bin four pixels into one. This binning reduces the illumination power requirement by almost four times (this reduction is not exactly four times because the pixel reset noise is added as well). However, if the same power is retained, d_{res} reduces by at least 50% of the original value. Therefore, less than a 5-mm resolution is obtained with 160 × 120 pixels.

10.2 Trade-Off Example: Illumination Power vs f.no

Problem:

The system has a strict limitation on the maximum power available.

f-number of the lens currently selected is 2.0.

For the depth resolution requirement, the calculated power is 2x as much as the maximum limit.

Solution:

Trade the lens f-number for illumination power. A better lens with an f-number of 1.4 can be chosen. This improvement brings down the power requirement by approximately 2x. In this case, a more expensive lens must be chosen.

10.3 Trade-Off Example: Dynamic Range vs Noise

Problem:

The system has requirements for high dynamic range. For example, the minimum object distance is 30 cm and the maximum object distance is approximately 3 m.

With the number of sub-frames equal to 2, the pixels corresponding to the objects at a distance of 30 cm become saturated because the illumination power is adjusted so that the system meets certain depth resolution requirements at 3 m.

Solution:

Trade SNR for a higher dynamic range. Increase the sub-frames to 4 or 8 and keep the total integration time the same. With this higher number of sub-frames, the number of photons collected in each quad decreases and thus the pixels are less likely to saturate. As a result of this increase in number of sub-frames, the effect of pixel reset noise increases because of the greater number of reset, integration, and readout cycles. Therefore, the overall SNR suffers. Illumination power, however, can be increased to overcome this SNR reduction.

10.4 Trade-Off Example: Ambient vs Peak Illumination Power

Problem:

The system must function in high ambient light conditions, such as outdoor environments.

With a given integration time per quadrant, some pixels become saturated or very noisy.

Solution:

Increase the peak illumination power and reduce the integration time per quad to keep the overall illumination energy per quad constant. Increasing the peak power helps to increase the ratio of useful signals to ambient signals. Thus, the total number of photons collected per pixel decreases. As a positive side effect, the photon shot noise resulting from ambient light decreases as well. The downside to increasing the peak power is that the illumination drive current increases and thus the electrical efficiency of the illumination module will most likely decrease.

System Design: Step-by-Step Guide

11.1 First Draft of Specifications

Before getting into the details of a ToF system design, the following specifications of the system must be defined:

- Depth resolution. What is the required depth resolution at maximum distance?
- 2d resolution: number of pixels.
- Range: minimum and maximum object distances in the scene.
- Frame rate: number of frames per second.
- Field of view (FoV): the required horizontal and vertical field of view (and thus the diagonal field of view).
- Ambient light. Is the system going to be used in high ambient light scenarios?
- Cost sensitivity. Example questions to ask:
  - Is it ok to use a higher f-number lens that costs more?
  - Can laser diodes be used instead of LEDs?
- Size constraints. Example questions to ask:
  - Is it ok to use multiple emitters that are easily available versus one powerful emitter that is expensive and hard to procure?
  - For the FoV and the sensor size chosen, is the lens height ok?
- Temperature. Is the system going to be used in harsh environments?

11.2 Optics

Illumination and receiver optics play a very critical role in the system. For example, the illumination power varies as the square of the f.no of the lens. Therefore, a lens with as low f.no as possible is important to have. As far as the illumination optics are concerned, the illumination FoV to sensor FoV must match. If the illumination module consists of laser diodes, appropriate diffusers may have to be chosen to spread the light. If LEDs are being used for illumination, lenses that focus or widen the LED light output may have to be used.

11.3 The Right Trade-Offs

Refer to Chapter 10 for making quick guesses on the achievable trade-offs.

11.4 Output Data Format

TI ToF chipsets support a variety of data formats. Typically, DVP and SSI protocols are supported.

11.5 Getting to the First Prototype

TI puts out reference designs based on each ToF device. A good method is to base the prototype design on one of the reference designs and change the design minimally to obtain optimal performance. Usually, the illumination driver and the interface between the rest of the system and the TI ToF chipset depth output are the only parts of the design that significantly change.

Revision History

Changes from C Revision (May 2014) to D Revision	Page
• Changed Equation 66	28

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265