Distance image sensors
S11961-01CR, S11962-01CR, S11963-01CR, S12973-01CT

Contents

HAMAMATSU

PHOTON IS OUR BUSINESS

Distance image sensors are image sensors that measure the distance to the target object using the TOF (time-of-flight) method. Used in combination with a pulse modulated light source, these sensors output phase difference information on the timing that the light is emitted and received. The sensor signals are arithmetically processed by an external signal processing circuit or a PC to obtain distance data.

1. Features

- High-speed charge transfer
- Wide dynamic range and low noise by non-destructive readout (S11961/S11963-01CR, S12973-01CT)
- Built-in column gain amplifier (S11963-01CR)
  Gain: × 1, × 2, × 4
- Fewer detection errors even under fluctuating background light (charge drain function)
- Real-time distance measurement

[Table 1-1] Product lineup

Type	Linear		Area	
Type no.	S11961-01CR	S12973-01CT	S11962-01CR	S11963-01CR
Pixel height	50 μm		40 μm	30 μm
Pixel pitch	20 μm	22 μm	40 μm	30 μm
Number of pixels	256	64	64 × 64	160 × 120
Video data rate	5 MHz		10 MHz	

2. Structure

Distance image sensors consist of a photosensitive area, shift register, output buffer amplifier, bias generator, timing generator, and so on. The block diagram is shown in Figure 2-1. Distance image sensors are different from typical CMOS image sensors in the following manner.

・Pixel structure that allows high-speed charge transfer
・Outputs two phase signals representing distance information from two output terminals

Like a typical CMOS image sensor, the output signal from the photosensitive area is processed by the sample-and-hold circuit or column gain amplifier circuit, scanned sequentially by the shift register, and read out as voltage output.

[Figure 2-1] Block diagram
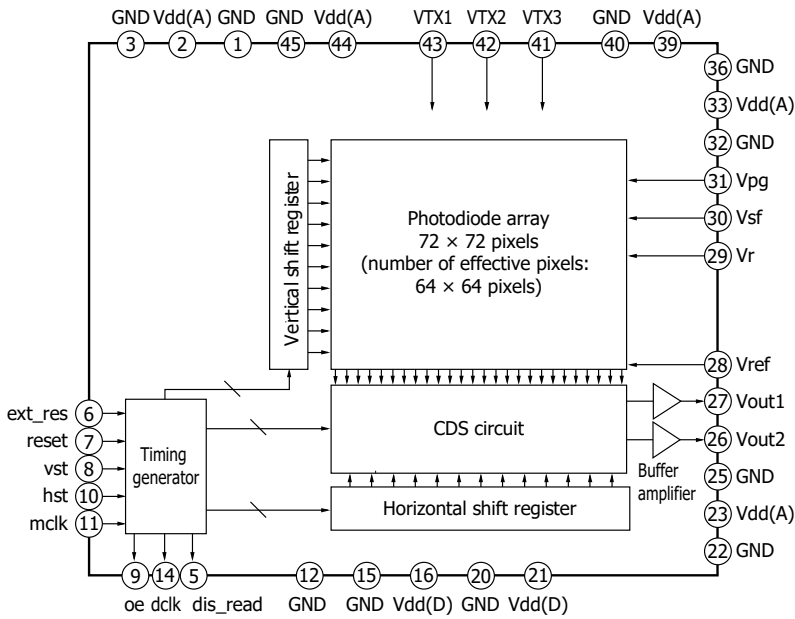(a) S11961-01CR, S12973-01CT
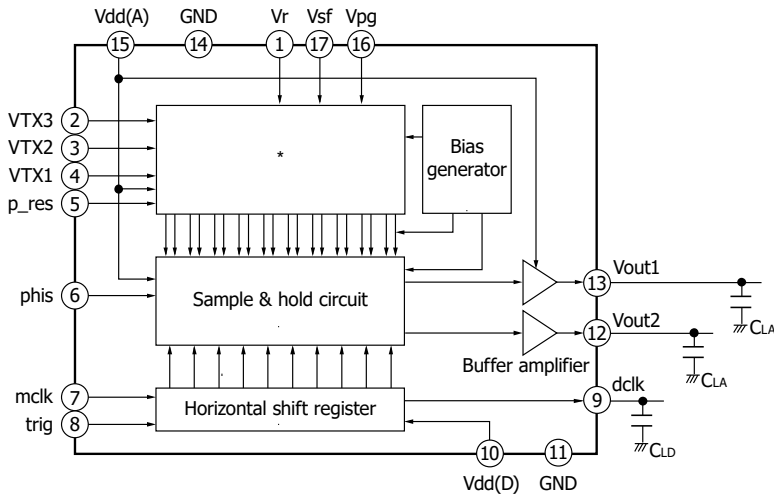
* S11961-01CR: 272 pixels, number of effective pixels 256
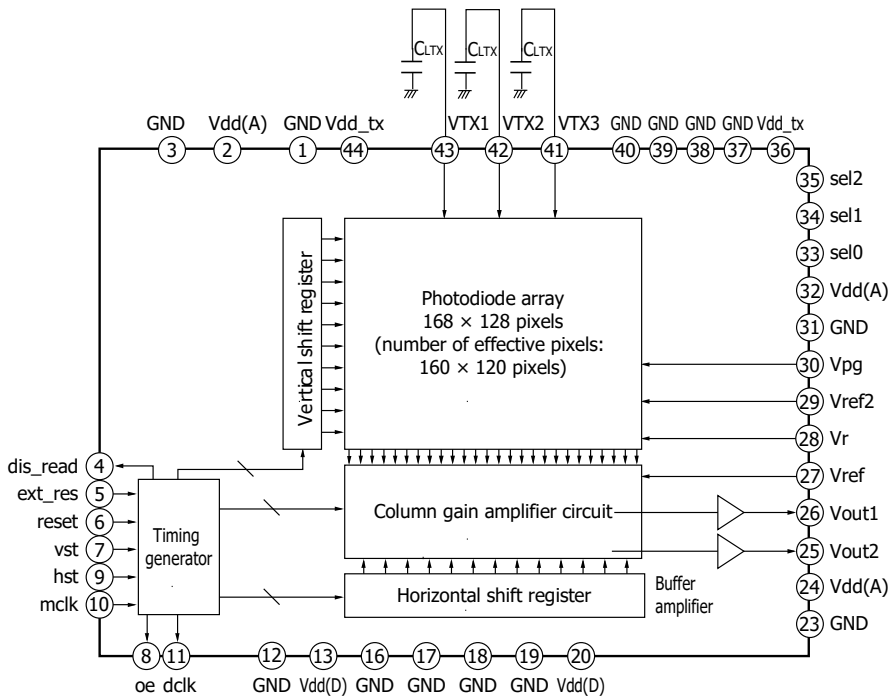 S12973-01CT: 80 pixels, number of effective pixels 64

KMPDC0649EA

(b) S11962-01CR

KMPDC0438EC

HAMAMATSU
PHOTON IS OUR BUSINESS

3

(c) S11963-01CR

KMPDC0443ED

3. Operating principle

3-1. Phase difference (indirect) TOF (time-of-flight)

The timing chart of the photosensitive area of the distance image sensor is shown in Figure 3-1. Output voltages Vout1 and Vout2 obtained by applying charge-to-voltage conversion on accumulated charges Q1 and Q2 based on their integration capacitances Cfd1 and Cfd2 are expressed by equations (3-1) and (3-2).

$\text{Vout1} = Q1/Cfd1 = N \times Iph \times \{(T_0 - Td)/Cfd1\} \dots (3\text{-}1)$
$\text{Vout2} = Q2/Cfd2 = N \times Iph \times (Td/Cfd2) \dots (3\text{-}2)$

Cfd1, Cfd2: integration capacitance of each output
N: charge transfer clock count
Iph: photocurrent
T_0: pulse width
Td: delay time

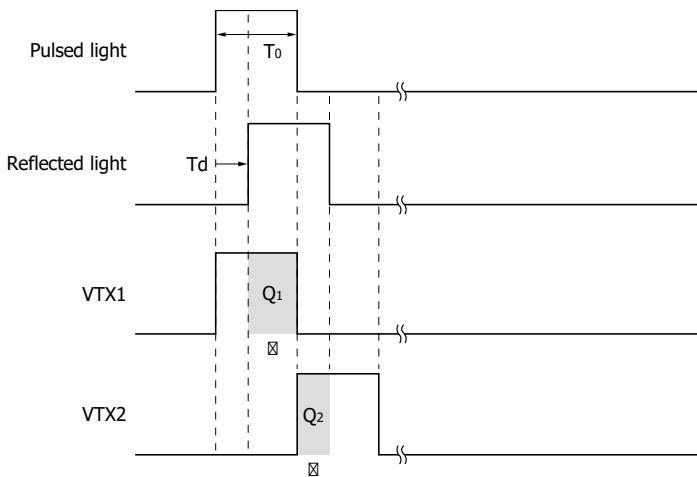Delay time Td when Cfd1=Cfd2 in equations (3-1) and (3-2) is expressed by equation (3-3).

$Td = \{Vout2/(Vout1 + Vout2)\} \times T_0 \dots (3\text{-}3)$

Using the values (Vout1, Vout2) output according to the distance, distance (L) is expressed by equation (3-4).

$L = 1/2 \times c \times Td = 1/2 \times c \times \{Vout2/(Vout1 + Vout2)\} \times T_0 \cdots (3\text{-}4)$

c: speed of light (3×10^8 m/s)

[Figure 3-1] Timing chart of photosensitive area

KMPDC0470EA

The structure and surface potential of the photosensitive area of the distance image sensor are shown in Figure 3-2. Typical CMOS image sensors can be driven with a single power supply, but the transfer time needed for the charge to move from the photosensitive area to the integration area is in the microsecond order. On the other hand, high-speed charge transfer (nanosecond order) is possible on CCD image sensors, but they require multiple voltage inputs including high voltage.

To achieve the high-speed charge transfer (several tens of nanoseconds) needed to acquire distance information, we have developed a pixel structure that enables high-speed charge transfer like the CCDs in the CMOS process. This has allowed distance image sensors to achieve the high-speed charge transfer needed for distance measurement.

The number of electrons generated in each pulse emission is several e-. Therefore, the operation shown in Figure 3-2 is repeated several thousand to several tens of thousands of times, and then the accumulated charge is read out. The number of repetitions varies depending on the incident light level and the required accuracy of distance measurement.
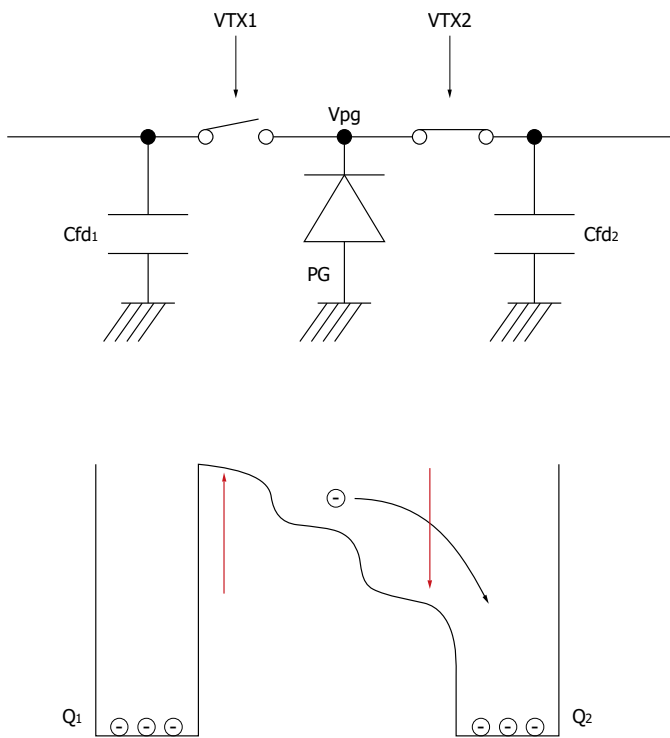
[Figure 3-2] Structure and surface potential of photosensitive area
(a) VTX1: on, VTX2: off (in the case of Figure 3-1①)
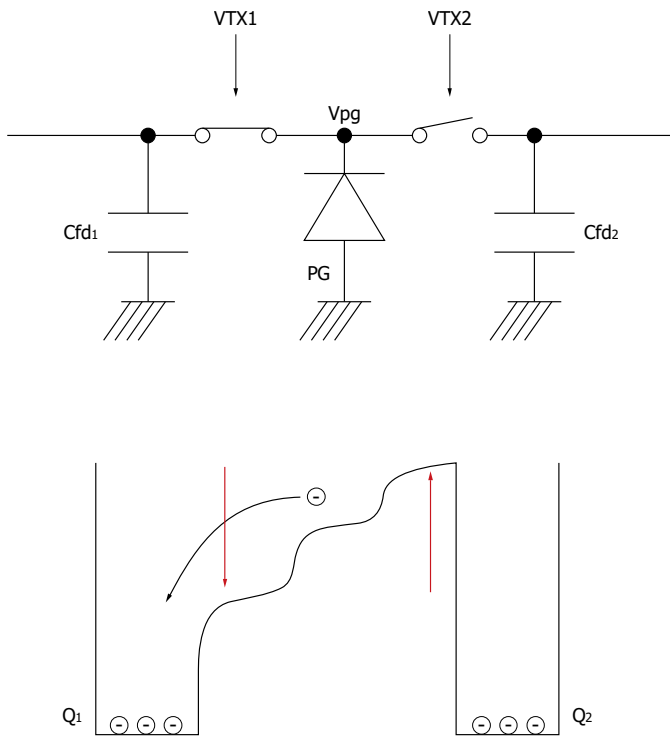
KMPDC0471EA

(b) VTX1: off, VTX2: on (in the case of Figure 3-1②)

KMPDC0472EA

[Table 3-1] Distance measurement range and VTX1, VTX2, and light-emission pulse widths

Distance measurement range max. (m)	VTX1, VTX2, light-emission pulse widths (ns)
4.5	30
6	40
9	60

Note: Light travels approximately 30 cm in 1 ns.

3-2. Timing chart

Figure 5-2 shows the timing chart for the S11963-01CR when a signal is read out twice in a frame. The first time, the signal immediately after a pixel reset is read out, and the second time, the signal after signal integration is read out. Pulse emission and signal integration are repeated in the period within the frame in Figure 3-3 (the number of repetitions must be set according to the required distance accuracy). If you want to perform non-destructive readout, repeat pulse emission, signal integration, and signal readout.

[Figure 3-3] Timing chart (S11963-01CR)
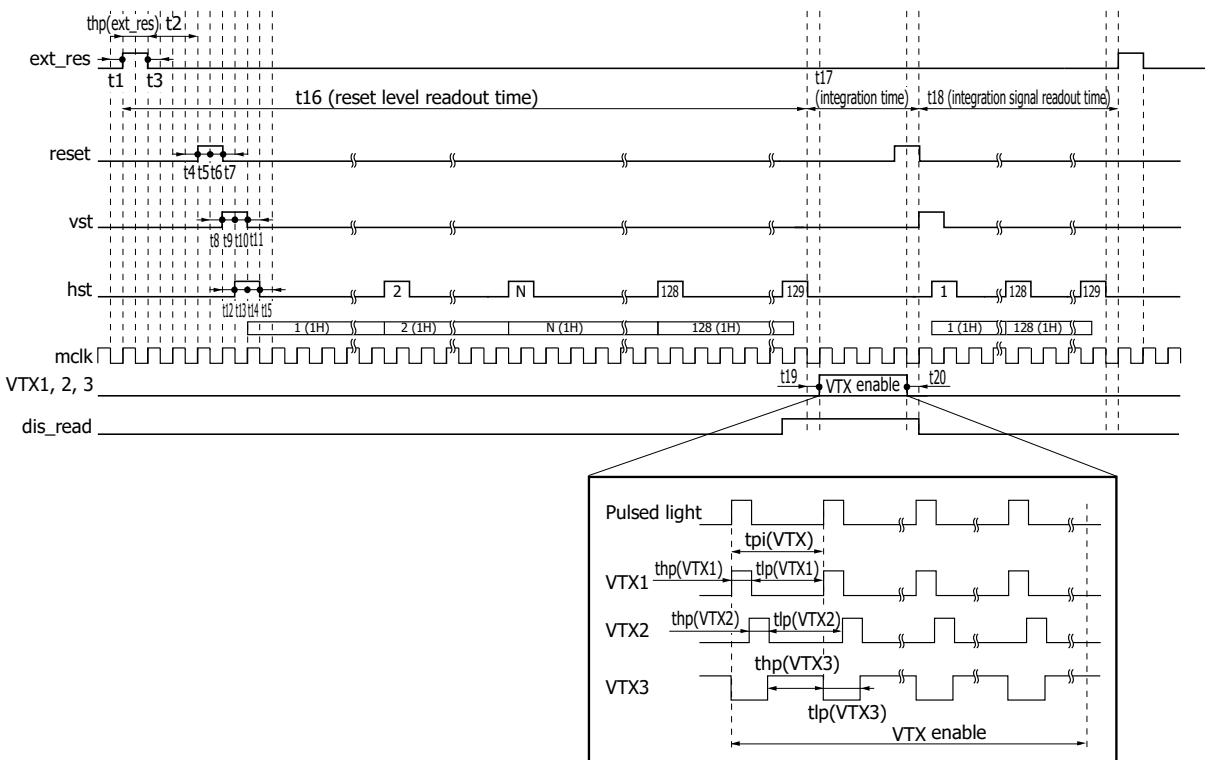
KMPDC0444EB

3-3. Charge drain function

A distance image sensor has charge transfer gates (VTX1, VTX2), which transfer the charges that are generated at the photosensitive area, and a charge drain gate (VTX3), which discharges unneeded charges. When VTX1 and VTX2 are off and VTX3 is on, the charge drain function is turned on without the accumulation of signal charges. This makes it possible to drain unneeded charges caused by ambient light during the non-emission period. The charge drain function enables the following:

① Detection of high-speed pulses
   Signal charges from pulse laser diodes and other high-speed pulse light sources can be integrated efficiently.
② Shutter operation

[Figure 3-4] Structure of photosensitive area

KMPDC0635EA
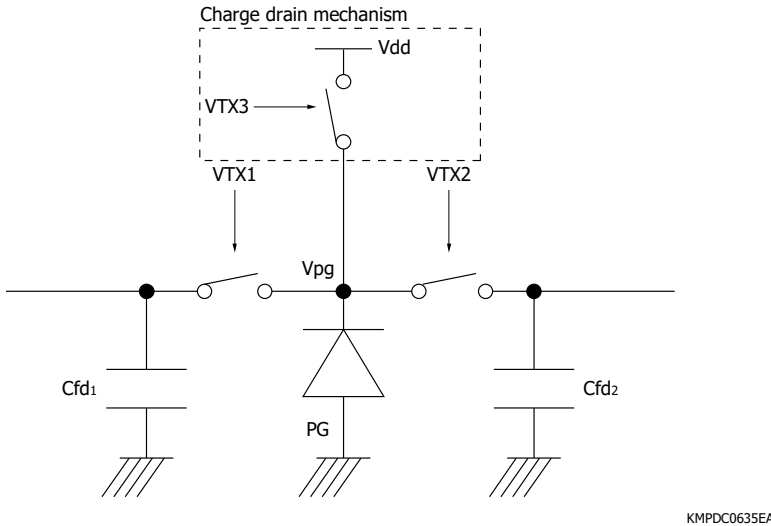
[Figure 3-5] Timing chart of photosensitive area

KMPDC0634EA
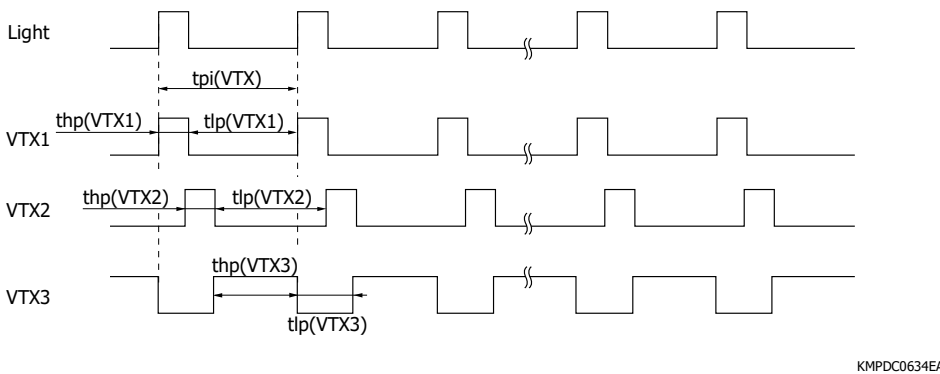
3-4. Non-destructive readout

If the incident signal is strong (the object is close and has high reflectance) or if the ambient light is strong, the distance image sensor saturates easily, so the integration time must be reduced. If the incident signal or ambient light is weak, the integration time must be increased.
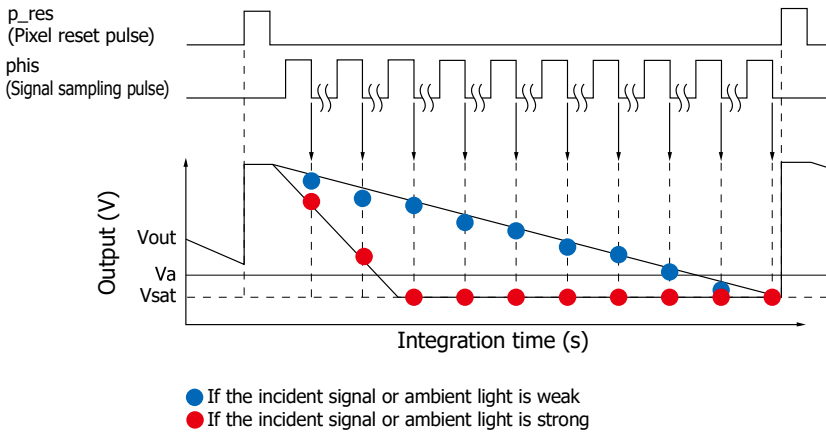
These issues can be solved by using non-destructive readout (S11962-01CR: not supported). With non-destructive readout, signals with different integration times in a frame can be read out. Wide dynamic range is achieved by selecting the signal with the optimal integration time.

Note that the reset noise that occurs within a pixel can be canceled by computing the difference between two specific signals obtained by non-destructive readout.

An even wider dynamic range can be achieved in non-destructive readout by setting a threshold voltage (Va) [Figure 3-6] and selecting a signal that does not exceed the threshold. To do this, however, a signal processing circuit must be attached externally.

[Figure 3-6] Non-destructive readout

● If the incident signal or ambient light is weak
● If the incident signal or ambient light is strong

KMPDC0636EA

3–5. Subtracting signals caused by ambient light

The charge drain function allows draining of unneeded charges accumulated during the light emission period. However, unneeded charges caused by ambient light and the like are also accumulated during the non-emission period (VTX1 and VTX2 are on). The way to eliminate these unneeded charges is to calculate the difference between the following two signals read out within a single frame and extract only the AC signal component. One of the signals is that obtained under the combination of light pulse (AC light) and ambient light (DC light), and the other is that obtained only under ambient light. This enables more accurate distance measurements.

[Figure 3-7] Function for subtracting signals caused by ambient light
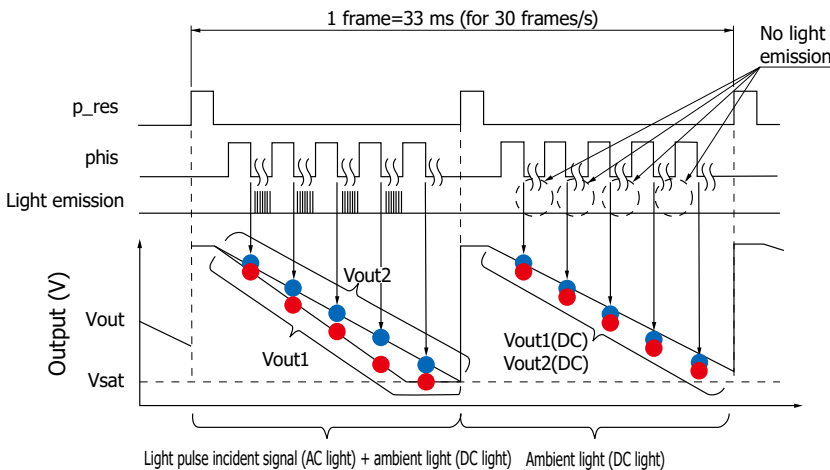
$$L \propto (1/2) \times c \times To \times \{Vout2 - Vout2(DC)\}/[\{Vout1 - Vout1(DC)\} + \{Vout2 - Vout2(DC)\}]$$

L: distance to the target object
c: speed of light
To: pulse width
Vout1, Vout 2: output generated from signal light
Vout1(DC), Vout2(DC): output generated from ambient light

KMPDC0640EB

3-6. Calculating the frame rate

Frame rate=1/(Time per frame)
=1/(Integration time + Readout time) $\cdots$(3-5)

Integration time:
It is necessary to be changed by the required distance accuracy and usage environment factors such as fluctuating background light.

It is possible to read out only the signal level without reading out the reset level signal. However, noise will increase because the pixel reset noise cannot be removed. Sensitivity variations in the photosensitive area will also increase because the fixed pattern noise in each pixel cannot be removed either.

When operating in non-destructive readout mode:
Time per frame = Integration time + (Readout time × Non-destructive readout count) $\cdots$(3-6)

[Linear image sensor]

Readout time = $\frac{1}{\text{Clock pulse frequency}}$ × Number of horizontal pixels

=Time per clock (Readout time per pixel) × Number of horizontal pixels $\cdots$(3-7)

Calculation example of readout time (clock pulse frequency=5 MHz, number of horizontal pixels=272)

Readout time = $\frac{1}{5 \times 10^6 \text{ [Hz]}}$ × 272

= 200 [ns] × 272
= 0.0544 [ms] $\cdots$(3-8)

[Area image sensor]

Readout time = $\frac{1}{\text{Clock pulse frequency}}$ ×Horizontal timing clock* × Number of vertical pixels

= Time per clock (Readout time per pixel) × Horizontal timing clocks × Number of vertical pixels
$\cdots$(3-9)

Calculation example of readout time
(clock pulse frequency =10 MHz, horizontal timing clocks* =208, number of vertical pixels =128)

Readout time = $\frac{1}{10 \times 10^6 \text{ [Hz]}}$ × 208 × 128

= 100 [ns] × 208 × 128
= 2.662 [ms]

* Horizontal timing clock 208 = charge transfer 40 + total number of horizontal pixels 168

4. How to use

4-1. Configuration example

A configuration example of a distance measurement system using the distance image sensor is shown in Figure 4-1. The system consists of the distance image sensor, light source and its driver circuit, light emitting/receiving optical system, timing generator, and arithmetic circuit for calculating distance. The distance accuracy depends greatly on the light source emission level and the light emitting/receiving optical system.

[Figure 4-1] Configuration example of distance measurement system
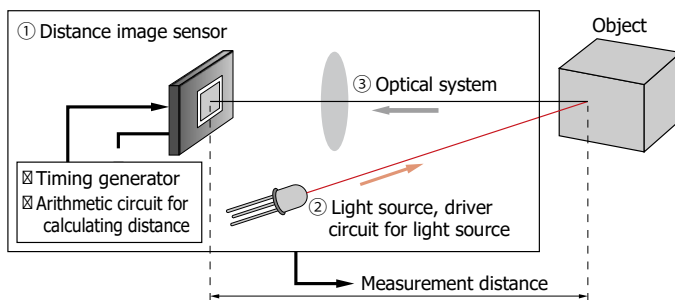
KMPDC0473EA

4-2. Light source selection

When the distance image sensor is used to measure distance, a light source (LED or pulse laser diode) suitable for the pulse width of the distance image sensor's charge transfer clock must be selected. For example, to measure up to 4.5 m, the pulse width of the charge transfer clock and the light emission pulse width must be set to 30 ns. Thus, the response speed of the light source needs to be around 10 ns or less for rise and fall times. Since the light source must be irradiated in a line in the case of the S11961-01CR and S12973-01CT distance linear image sensors and over an area in the case of the S11962-01CR and S11963-01CR distance area image sensors, large output power is required. For this, multiple light sources are sometimes used. When multiple light sources are used, a driver circuit for driving the multiple light sources at high speeds and high output is also required.
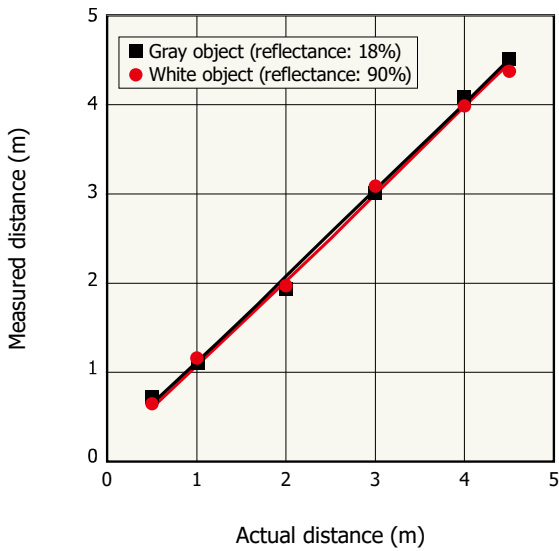
5. Distance measurement examples

5-1. Distance measurement (S11961-01CR, S12973-01CT)

For your reference, the following is an example of distance measurement using the S11961-01CR or S12973-01CT and an evaluation light source under the following conditions.

[Conditions]
- S11961-01CR or S12973-01CT distance image sensor (measured at the center pixel)
- Non-destructive readout
- Integration time=30 ms
- Charge transfer clock width VTX1, 2=30 ns
- Light receiving lens: F=1.2, light receiving angle=37.5° × 27.7°
- Light source (LED): output=10 W, duty ratio=0.3%, light emission pulse width=30 ns, λ=870 nm
- Light projection angle=10° × 10°
- Ambient light: room light level
- Ta=25 °C

[Figure 5-1] Distance measurement characteristics (S11961-01CR, S12973-01CT, typical example)

KMPDB0495EA

[Figure 5-2] Distance accuracy vs. actual distance (S11961-01CR, S12973-01CT, typical example)
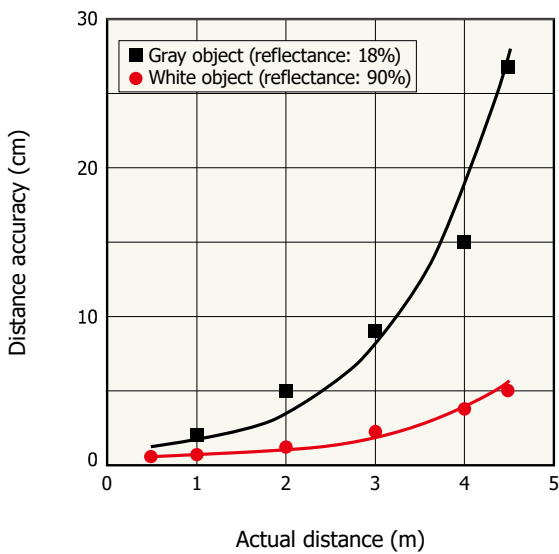
KMPDB0496EA

5-2. Short distance measurement (S11961-01CR, S12973-01CT)

Figures 5-3 and 5-4 show a measurement example for short distance (up to 100 cm).

[Conditions]
- Distance image sensor: S11961-01CR or S12973-01CT (measured at the center pixel)
- Integration time=20 ms
- Charge transfer clock width VTX1, 2=30 ns, VTX3=3300 ns
- Light receiving lens: F=1.2, light receiving angle=37.5° × 27.7°
- Light source (LED): output=10 W, duty ratio=0.9%, light emission pulse width=30 ns, λ=870 nm
- Light projection angle=10° × 10°
- Ambient light: room light level
- Ta=25 °C
- When measuring short distance (5 to 20 cm): change the sensor and light source positions

[Figure 5-3] Distance measurement characteristics (short distance, S11961-01CR, S12973-01CT, typical example)
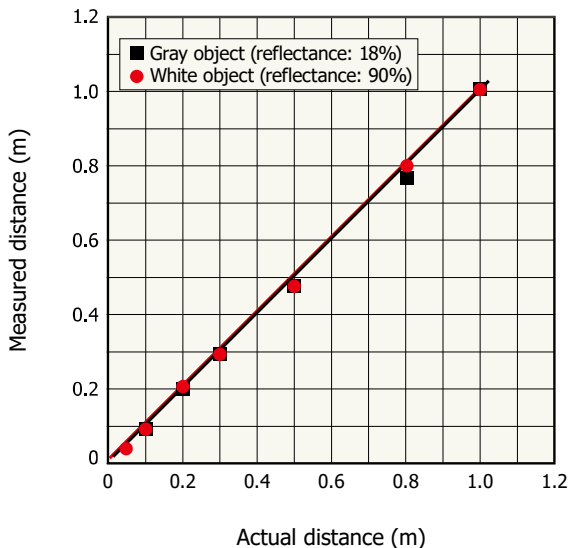
KMPDB0497EA

[Figure 5-4] Distance accuracy (short distance, S11961-01CR, S12973-01CT, typical example)

KMPDB0498EA

HAMAMATSU

PHOTON IS OUR BUSINESS

13
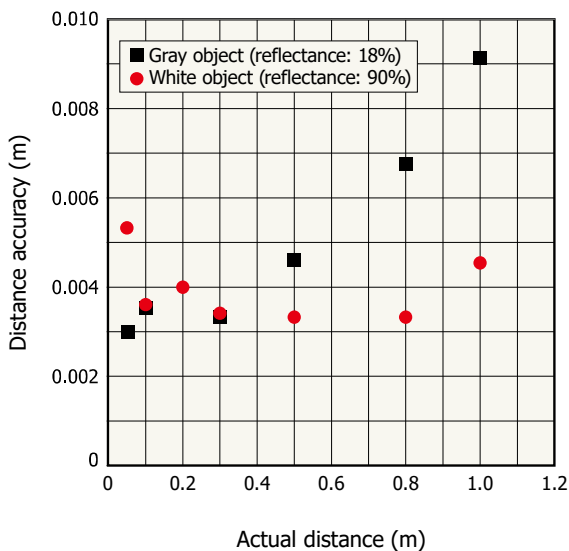
5-3. Improving the distance accuracy by averaging the measurement data

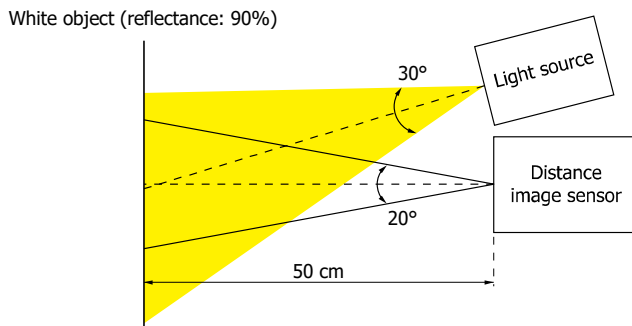One method to improve the distance accuracy is averaging the measurement data. There are two averaging methods. One is averaging over time, and the other is averaging over multiple pixels. Figure 5-5 shows an example of averaging over multiple pixels.

[Figure 5-5] Example of averaging over multiple pixels

· Distance image sensor: S11961-01CR or S12973-01CT
  (using pixels with relatively uniform incident light levels)
· Distance between the sensor and target object to be detected: 50 cm
· Diffuser: 30° × 30°
· Light receiving lens: f=12 mm, light receiving angle=20° × 20°
· Light source: LED, light emission pulse width=30 ns, light emission cycle=300 kHz

KMPDC0639EB

Measured distances of N pixels around and including the center pixel are averaged, and the variation in this parameter over 100 frames is determined.

[Figure 5-6] Example of improving the distance accuracy (by averaging over multiple pixels)
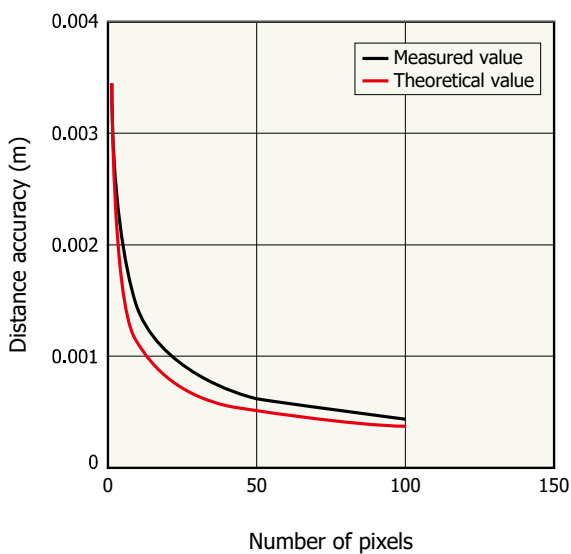
KMPDB0499EA

5-4. Measuring the distance to a cylinder

The following are measurement examples when a metal cylinder (about ϕ10 cm) and a white cylinder (diffuser) are used for target objects. In the case of a metal cylinder with regular reflection, fairly accurate measurement is possible when the cylinder is in front of the light source but not when it is off aligned.

[Figure 5-7] Example of metal cylinder

[Figure 5-8] Output vs. light incident pixel no.
 (a)   Metal cylinder
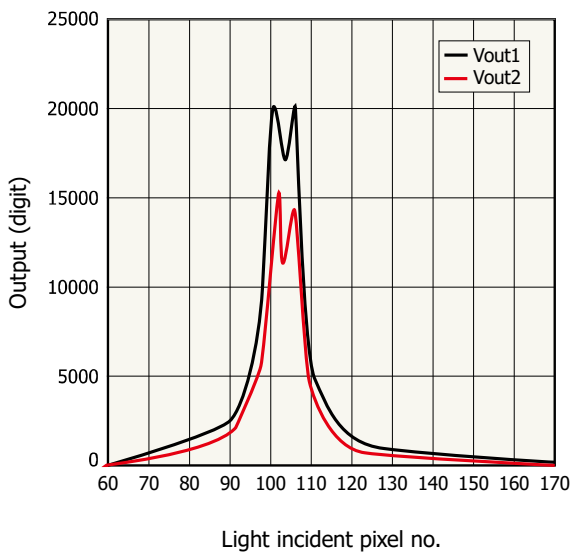
KMPDB0500EA

(b)　White cylinder

Light incident pixel no.

KMPDB0501EA

[Figure 5-9] Measured distance vs. light incident pixel no.
(a)　Metal cylinder

Light incident pixel no.

KMPDB0502EA

(b) White cylinder

Light incident pixel no.
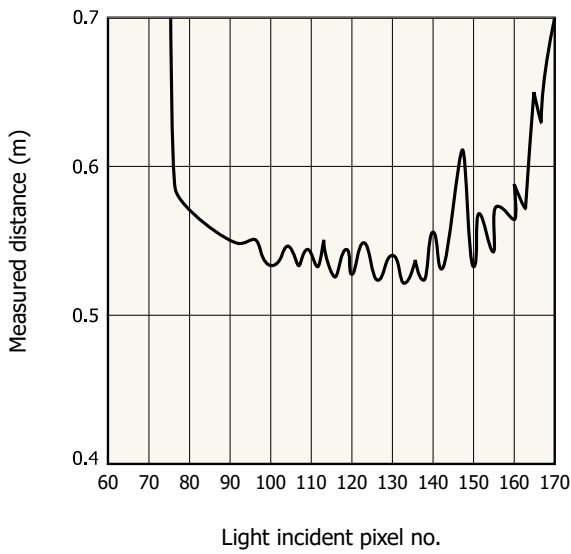
KMPDB0503EA

5-5. Distance measurement (S11961-01CR, S12973-01CT) using pulse laser diode

The following is an example of distance measurement taken under the following conditions.

[Conditions]
- S11961-01CR or S12973-01CT distance linear image sensor
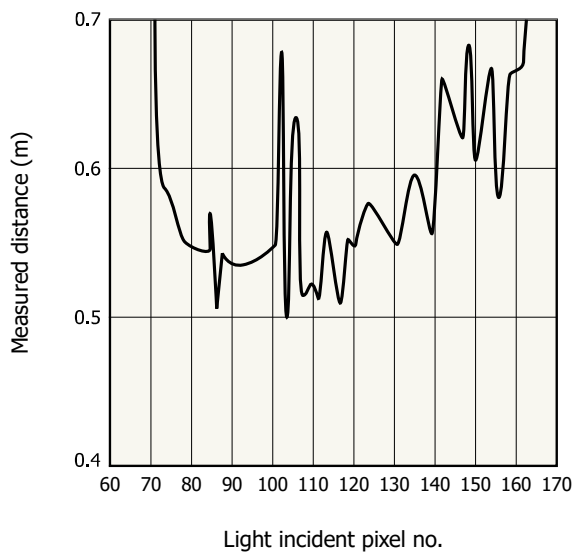- Light source: pulse laser diode (for evaluation within Hamamatsu)
    Peak power=50 W, λ=870 nm, pulse width=50 ns, duty ratio=0.1%, FOV=40°×2° (horizontal × vertical)
- Target object: standard diffuser panel, white (reflectance: 90%), black (reflectance: 10%)
- Light receiving lens: SPACECOM L8CSWI (f=8 mm, F=1.2, 1/3 inch CS mount)
- Ambient light: under fluorescent lamp
- The data of a pixel with the highest return light level is extracted.

[Figure 5-10] Distance measurement example [white object (reflectance: 90%)]

Actual distance (mm)
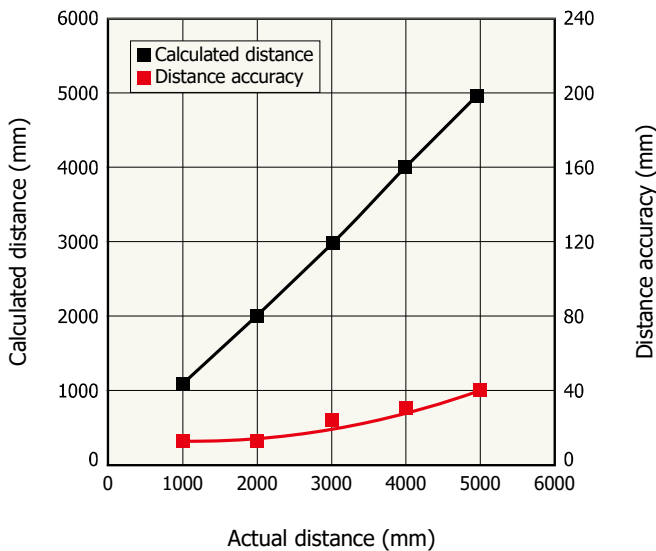
KMPDB0509EA

[Figure 5-11] Distance measurement example [black object (reflectance: 10%)]
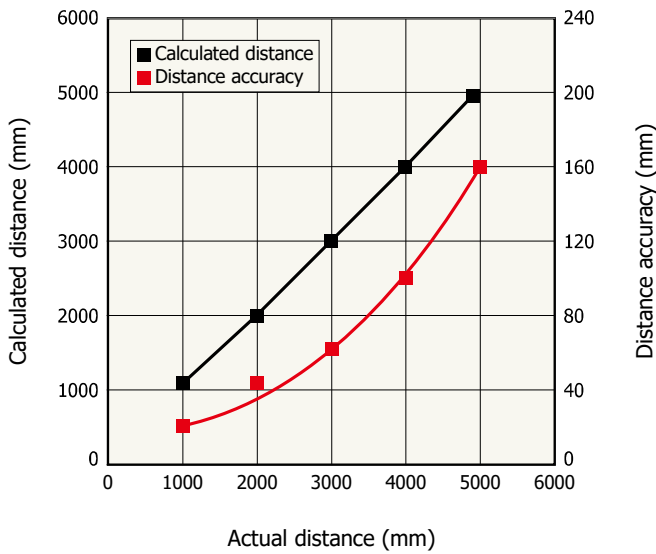
KMPDB0510EA

5-6. Distance measurement (S11963-01CR)

The following is an example of distance measurement taken under the following conditions.

[Conditions]
- S11963-01CR distance image sensor (measured at the center pixel)
- Integration time=2 ms
- Charge transfer clock width VTX1, 2=40 ns, VTX3=920 ns
- Light receiving lens F=1.2, light receiving angle=37.5° × 27.7°
- Light source (LED 8 × 8): 10 W, λ =870 nm
- Light projection angle=17.2° × 17.2°
- Ambient light: room light level
- Ta=25 °C

[Figure 5-12] Measured distance, distance accuracy vs. actual distance
[white object (reflectance: 90%), S11963-01CR, typical example]
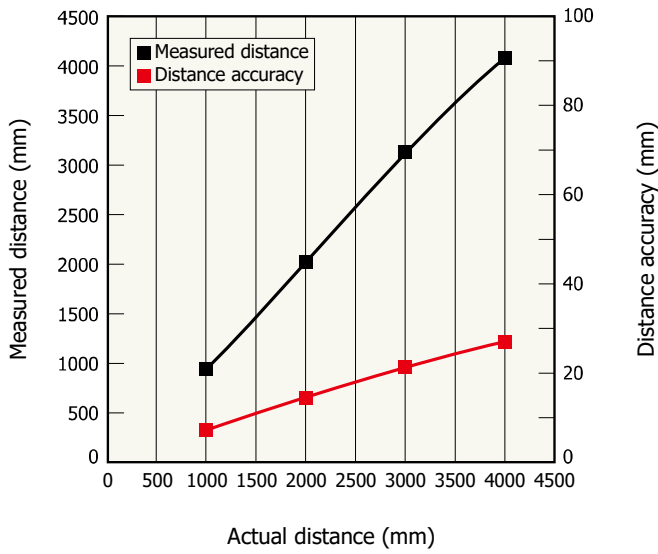
KMPDB0513EA

[Figure 5-13] Measured distance, distance accuracy vs. actual distance
[gray object (reflectance: 18%), S11963-01CR, typical example]
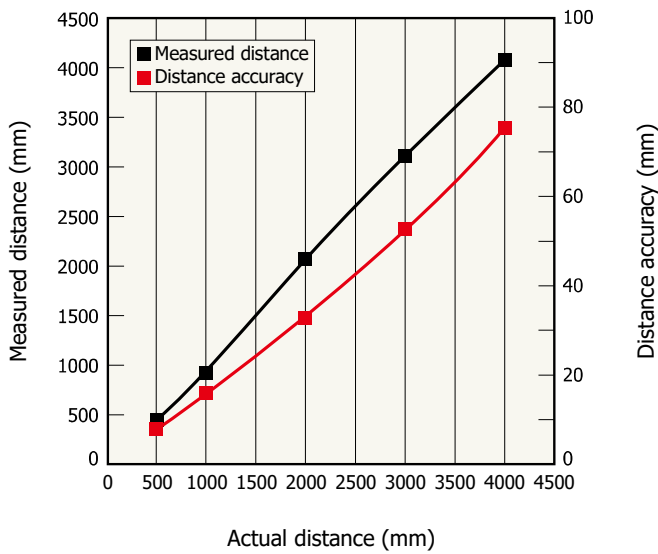
KMPDB0514EA

5-7. Short distance measurement (S11963-01CR)

Figures 5-14 and 5-15 show a measurement example for short distance (up to 100 cm).

[Conditions]
- S11963-01CR distance image sensor (measured at the center pixel)
- Integration time=10 ms
- Charge transfer clock width VTX1, 2=20 ns, VTX3=460 ns
- Light receiving lens F=2.0, f=3 mm, light receiving angle=37.5 × 45°
- Light source (LED × 8): 5.6 W, λ =850 nm
- Light projection angle=±45°
- Ambient light: room light level
- Ta=25 °C

[Figure 5-14] Measured distance, distance accuracy vs. actual distance
　　　　　　[white object (reflectance: 90%), evaluation kit for S11963-01CR, typical example]
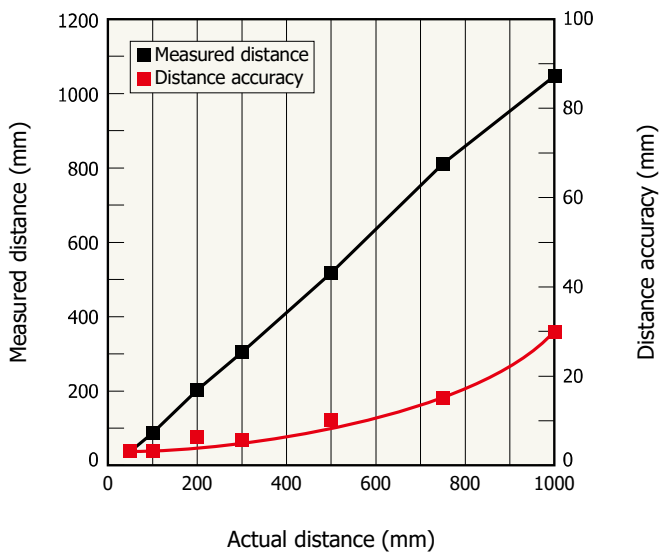
KMPDB0515EA

[Figure 5-15] Measured distance, distance accuracy vs. actual distance
[gray object (reflectance: 18%), evaluation kit for S11963-01CR, typical example]
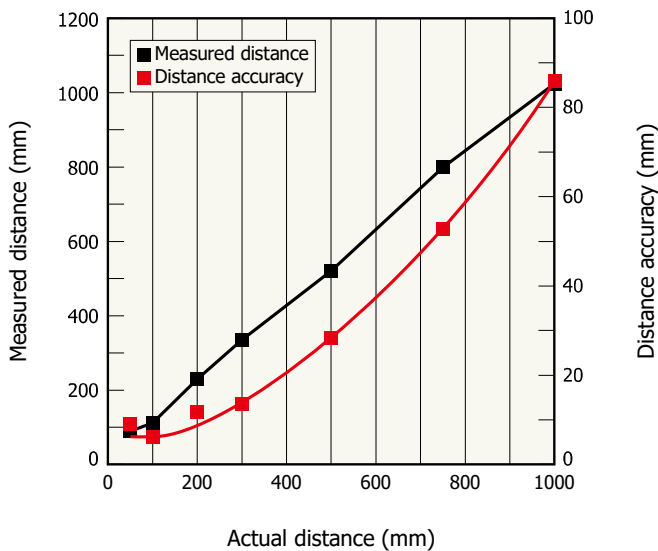

KMPDB0516EA

6. Calculating the incident light level

If you want to construct a camera module using a distance image sensor, you need to set the parameters according to the operating conditions to maximize the performance of the sensor. For example, when outdoors under strong sunlight, various measures need to be taken such as reducing the integration time or suppressing the incident sunlight using a band-pass filter to avoid pixel saturation.
How much to reduce the integration time or which band-pass filter is most suited in reducing the sunlight to the appropriate level varies depending on the operating conditions. To make things easier, we created a model of the camera module configuration and derived an equation that simply calculates the incident light level (signal light, ambient light) per pixel.

Camera module parameters
The following are main parameters of a camera module that uses a distance image sensor. In addition, Figure 6-1 shows the schematic. We assume that the light from the light source is shaped into a rectangle by the angle of view (θ_H, θ_V) determined by the lens and directed on the sensor.

(1) Target object
• Distance to the target object L [m]
• Reflectance of the target object R [%]

(2) Light projection section
• Light source output P [W/sr]
• Light projection efficiency E_P [%]
• Duty ratio "duty"
• Integration time Tacc [s]
• Light emitter's angle at half maximum θ source [V]
• Light projection angle (horizontal, vertical) θ_H, θ_V [°]

HAMAMATSU

PHOTON IS OUR BUSINESS

(3) Ambient light
• Sunlight intensity Pamb [W/m^2]
• Band-pass filter's transmission wavelength range (short-wavelength side, long-wavelength side) λ short , λ long [nm]

(4) Photosensitive area
• Light receiving lens efficiency E_R [%]
• Band-pass filter's signal light transmittance E_F [%]
• Light receiving lens F value
• Light receiving lens focal distance f [m]

(5) Distance image sensor
• Pixel size (horizontal, vertical) Hpix, Vpix [m] (area Spix)

• Fill factor FF [%]

• Photosensitivity Ssens [A/W]
• Pixel capacitance Cfd [F]
• Maximum voltage amplitude Vmax [V]
• Random noise RN [V]
• Dark output V_D [V/s]

[Figure 6-1] Schematic of camera module with built-in distance image sensor
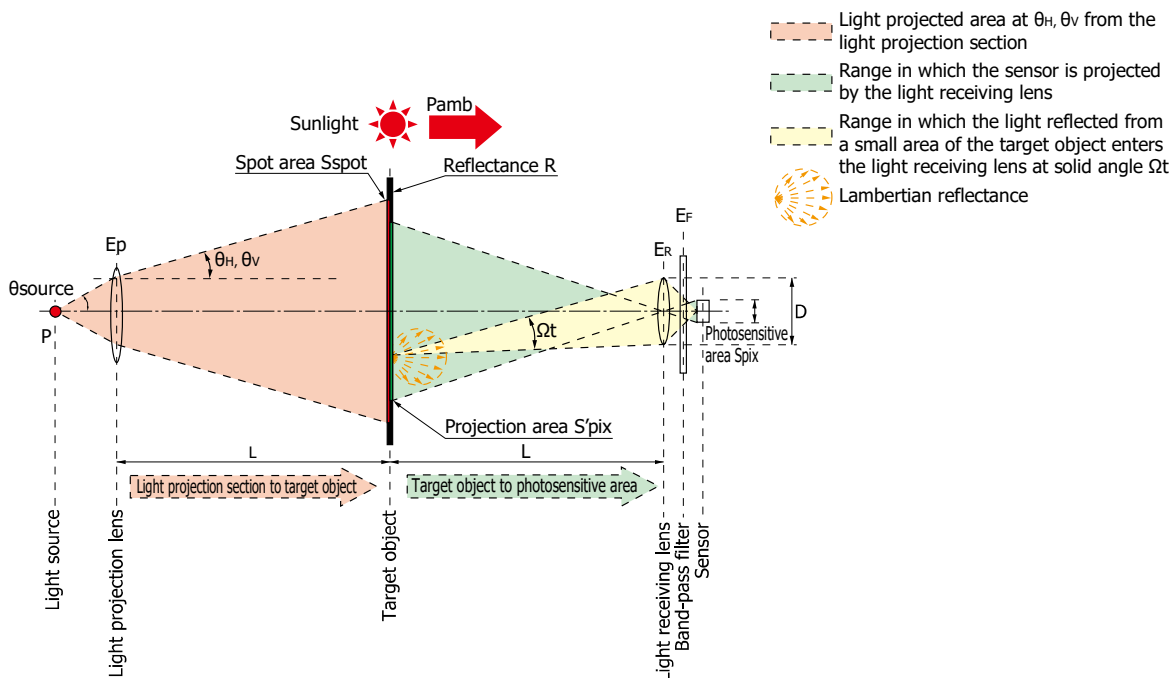
KMPDC0641EA

Calculation method

First, we calculate the light spot level Pspot [W/m^2] on the target object [equation (6-1)].

$$\text{Pspot} = P \times \frac{A}{L^2} \times Ep \times \frac{1}{\text{Sspot}} \quad \ldots(6\text{-}1)$$

P: Light source output [W/sr]
A: Area of a spherical surface obtained by cutting a sphere with radius L at an angle of θ source

$\dfrac{A}{L^2}$: solid angle of the projected light [sr]

EP: light projection efficiency [%]

Sspot: area of the light spot projected on the target object [m^2]

[Figure 6-2] Area A on the spherical surface
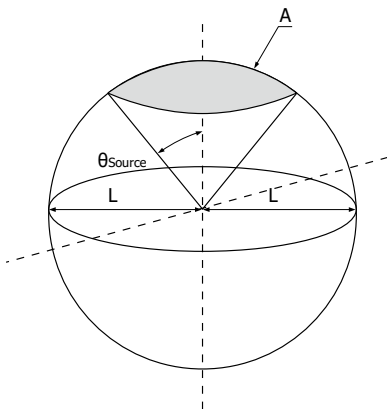

KMPDC0650EA

Sspot is given by equation (6-2).

$$\text{Sspot} = 2L\tan\theta_H \times 2L\tan\theta_V \quad \ldots \text{(6-2)}$$

A is given by equation (6-3).

$$A = 2\pi\{1 - \cos(\theta\text{source})\} \times L^2 \ldots \text{(6-3)}$$

Next, we calculate angle of the reflected light from a small area of the target object that enters the light receiving lens. If the diameter of the light receiving lens is D [m], the angle θ_R formed between a given point on the target object and the edge of the light receiving lens is given by equation (6-4).

$$\theta_R = \tan^{-1}\left(\frac{D}{2L}\right) \quad \ldots \text{(6-4)}$$

If we use θ_R, solid angle Ωt [unit: sr] is given by equation (6-6).

$$\Omega t = 4\pi\sin^2\frac{\theta_R}{2} \quad \ldots \text{(6-6)}$$

θ_R varies depending on the position on the target object, but here it is approximated to a fixed value. Of the reflected light diffused in all directions from the target object, we assume the portion corresponding to Ωt to enter the lens.

The region on the target object that the distance image sensor can receive the reflected light of corresponds to the projection plane of the pixels displayed on the object through the light receiving lens. The relationship between pixel area Spix and the pixel projection area S'pix on the target object is given by equation (6-7).

$$S'pix = \left(\frac{L}{f}\right)^2 Spix \quad \text{. . . (6-7)}$$

We determine the level of signal light and ambient light that hit and reflect off the target object and enter a single pixel through the lens. To simplify the calculation, we assume the target object to be a perfect diffuser. If the incident light level is I [W], the reflected light level is I/π [W/sr] for a point light source and I [W/sr] for an extremely wide surface light source such as sunlight. The signal light level Ppix [W] entering a single pixel is given by equation (6-8).

$$Ppix = Pspot \times R \times \frac{1}{\pi} \times \Omega t \times S'pix \times E_R \times E_F(sig) \times FF \quad \text{. . . (6-8)}$$

The ambient light level Ppix(amb) [W] entering a single pixel is given by equation (6-9).

$$Ppix(amb) = Pamp \times R \times 1 \times \Omega t \times S'pix \times E_R \times E_F(amb) \times FF \quad \text{. . . (6-9)}$$

$E_F(sig)$: band-pass filter transmittance for signal light
$E_F(amb)$: band-pass filter transmittance for ambient light

Output voltage Vpix [V] generated from the signal light is given by equation (6-10).

$$Vpix = Ppix \times Tacc \times duty \times (Ssens/Cfd) \quad \text{. . . (6-10)}$$

Tacc: integration time [s]
duty: duty ratio
Ssens: photosensitivity [A/W]
Cfd: pixel capacitance [F]

Output voltage Vpix(amb) [V] generated from the ambient light is given by equation (6-11).

$$Vpix(amb) = Ppix(amb) \times Tacc \times duty \times (Ssens/Cfd) \quad \text{. . . (6-11)}$$

Distance accuracy

Using the levels of signal light and ambient light entering a single pixel determined above, we calculate the distance accuracy of the camera module. Photocurrent Ipix [A] per pixel generated by the signal light is given by equation (6-12).

$$Ipix = Ppix \times Ssens \text{ . . . (6-12)}$$

The number of electrons Qpix [e⁻] per pixel generated by the signal light is given by equation (6-13).

Qpix = Ipix × Tacc × duty/e . . . (6-13)

= Ppix × Ssens × Tacc × duty/e

e: quantum of electricity=1.602 × 10^{-19} [C]

The number of electrons Qpix(amb) [e$^-$] per pixel generated by the ambient light is given by equation (6-14).

Qpix(amb) = Ppix(amb) × Ssens × Tacc × duty/e . . . (6-14)

Next, noise components are described. The amplitudes of light shot noise N_L, random noise N_R, dark current shot noise N_D are given by the following equations [unit: e$^-$].

$$N_L = \sqrt{Qpix + Qpix(amb)} \quad . . . (6\text{-}15)$$

$$N_R = RN × Cfd/e \quad . . . (6\text{-}16)$$

RN: random noise [μV]

$$N_D = \sqrt{V_D × Tacc × Cfd/e} \quad . . . (6\text{-}17)$$

V_D: dark output [V]

Total noise N [e$^-$] is given by equation (6-18).

$$N = \sqrt{N_L^2 + N_R^2 + N_D^2} \quad . . . (6\text{-}18)$$

The S/N is the ratio of the number of signal electrons Qpix to N.

Distance accuracy σ [m] is given by equation (6-19).

$$\sigma = \frac{N}{Qpix} × \frac{cT_0}{2} \quad . . . (6\text{-}19)$$

c: speed of light
T_0: light emission pulse width

Calculation example
Table 6-1 shows an example of camera module parameters. Using these values, we calculate the output voltages generated from the signal light and ambient light.

A = 2π (1 − cos14°) × 1^2 = 0.18664 [m^2]

Sspot = 2 tan 45° × 2 tan 2.5° = 0.17464 [m^2]

$$\theta_R = \tan^{-1}\left(\frac{f}{2FL}\right) = \tan^{-1}\left(\frac{2.8 \times 10^{-3}}{2 \times 1.2}\right) = 0.066845[°]$$

$$\Omega t = 4\pi \sin^2\frac{0.066845045°}{2} = 4.276 \times 10^{-6}[sr]$$

$$S'pix = \left(\frac{1}{2.8 \times 10^{-3}}\right)^2 (20[\mu m] \times 50[\mu m]) = 1.2755 \times 10^{-4}[m^2]$$

$$Pspot = 100 \times \frac{0.18664}{1^2} \times 0.6 \times \frac{1}{0.17464} = 64.1[W/m^2]$$

$$Ppix = 64.1 \times 0.1 \times \frac{1}{\pi} \times 4.276 \times 10^{-6} \times 1.2755 \times 10^{-4} \times 0.6 \times 0.88 \times 0.3 = 176.3[pW]$$

$$Ppix(amb) = 1000 \times 0.1 \times 1 \times 4.276 \times 10^{-6} \times 1.2755 \times 10^{-4} \times 0.6 \times 0.06 \times 0.3 = 590.4[pW]$$

$$Vpix = 176.3 \times 10^{-12} \times 15 \times 10^{-3} \times 0.001 \times \{0.3/(40 \times 10^{-15})\} = 19.8[mV]$$

$$Vpix(amb) = 590.4 \times 10^{-12} \times 15 \times 10^{-3} \times 0.001 \times \{0.3/(40 \times 10^{-15})\} = 66.4[mV]$$

The voltages generated from the signal light and ambient light are 1.24% and 4.15% of the saturation voltage of a single pixel, respectively. In terms of the number of electrons, they are given by the following equations.

$$Qpix = 176.3 \times 10^{-12} \times 0.3 \times 15 \times 10^{-3} \times 0.001/(1.602 \times 10^{-19}) = 4952.2[e^-]$$

$$Qpix(amb) = 590.4 \times 10^{-12} \times 0.3 \times 15 \times 10^{-3} \times 0.001/(1.602 \times 10^{-19}) = 16584.3[e^-]$$

Noise components and total noise are given by the following equations.

$$N_L = \sqrt{4952.2 + 16584.3} = 146.8[e^-]$$

$$N_R = 500 \times 10^{-6} \times 40 \times 10^{-15}/(1.602 \times 10^{-19}) = 124.8[e^-]$$

$$N_D = \sqrt{1 \times 15 \times 10^{-3} \times 40 \times 10^{-15}/(1.602 \times 10^{-19})} = 61.2[e^-]$$

$$N = \sqrt{146.8^2 + 124.8^2 + 61.2^2} = 202.2[e^-]$$

The distance accuracy is given by the following equation.

$$\sigma = \frac{202.2}{4952.2} \times \frac{3 \times 10^8 \times 30 \times 10^{-9}}{2} = 0.184[m]$$

Figure 6-3 shows the actual measurement of the distance accuracy when a light source is driven with Hamamatsu's evaluation kit and the distance is measured and the calculated distance accuracy determined by entering the evaluation kit parameters in the above equations. The calculated values tend to show poorer results.

[Table 6-1] Example of camera module parameters

Group	Parameter	Symbol	Value	Unit
Target object	Distance to the target object	L	1	m
	Reflectance	R	10	%
Light emission	Light source output	P	100	W/sr
	Duty ratio	duty	0.001	-
	Integration time	Tacc	15	ms
	LED's angle at half maximum	θsource	7	°
	Light projection angle (horizontal: one side)	θ_H	45	°
	Light projection angle (vertical: one side)	θ_V	2.5	°
	Light projection efficiency	EP	60	%
Ambient light	Intensity	Pamb	1000	W/m^2
	Band-pass filter transmission wavelength (short-wavelength side)	λshort	800	nm
	Band-pass filter transmittance wavelength (long-wavelength side)	λlong	900	nm
	Band-pass filter transmittance (sunlight)	E_F(amb)	6	%
Light reception	Light receiving efficiency	E_R	60	%
	Band-pass filter transmittance (signal light)	E_F(sig)	88	%
	Light receiving lens F value	F	1.2	-
	Light receiving lens focal distance	f	2.8	mm

Group	Parameter	Symbol	S11961-01CR S12973-01CT	S11963-01CR	Unit
Sensor	Pixel size (horizontal)	Hpix	20	30	μm
	Pixel size (vertical)	Vpix	50	30	μm
	Fill factor	FF	0.3	0.25	-
	Photosensitivity (λ=830 nm)	Ssens	0.3	0.3	A/W
	Detection capacitance	Cfd	40	15	fF
	Voltage amplitude	Vmax	1.6	1.6	V
	Random noise	RN	500	500	μV
	Dark output	V_D	1	1	V/s

HAMAMATSU

PHOTON IS OUR BUSINESS

[Figure 6-3] Calculated and measured distance accuracy
　　　　　　(typical example, calculated value: light projection efficiency=light receiving efficiency=100%)
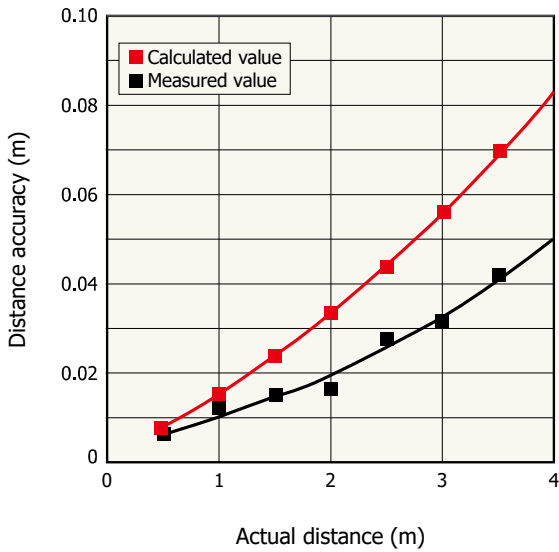
Measurement conditions
· Indoors (200 lx)
· Ambient light cut filter: none
· Distance image sensor: S11963-01CR
　　　　　　　　　　Integration time=30 ms
· Hamamatsu evaluation kit
· Light receiving lens: image format=1/3"
　　　　　　　　Field of view (horizontal ×
　　　　　　　　vertical)=37.5° × 27.7°
· Light source: LED array module
　　　　　　　Emission wavelength=870 nm
　　　　　　　Emission intensity=10 W
　　　　　　　Light projection angle (horizontal ×
　　　　　　　vertical)=±12.2°
　　　　　　　Light emission pulse width=30 ns
　　　　　　　Duty ratio=0.1%
· Target object: White board (reflectance=90%)

KMPDB0504EA

7. Calibration

Distance image sensors require distance calibration. The reasons why calibration is necessary are shown below.

[Reasons why calibration is necessary]
• Delay in the light emission timing
• Delay in the wiring between the sensor and light source
• Shape of the light emission pulse of light source
• Peripheral circuits

The following shows an example of the calibration method.

Distance L is given by equation (7-1).

$$L = \alpha \frac{Vout2}{Vout1 + Vout2} \times \frac{cT_0}{2} - Dofs \quad \text{...(7-1)}$$

α: slope
c: speed of light
T0: light emission pulse width
Dofs: Distance offset

You need to set the light emission timing delay (Light_pulse_delay), distance offset (Dofs), and slope (α).

Setting the light emission timing delay and distance offset
The calculated distance is shifted by changing the light emission timing delay and distance offset so that the calculated distance matches the actual distance.

Setting the slope α
① Set the light pulse peak exactly in the middle of the VTX1 and VTX2 peaks.
② Select two points in the linear range of distance, and calculate α to match the ideal line [Figure 7-1].

[Figure 7-1] Calculated distance vs. actual distance
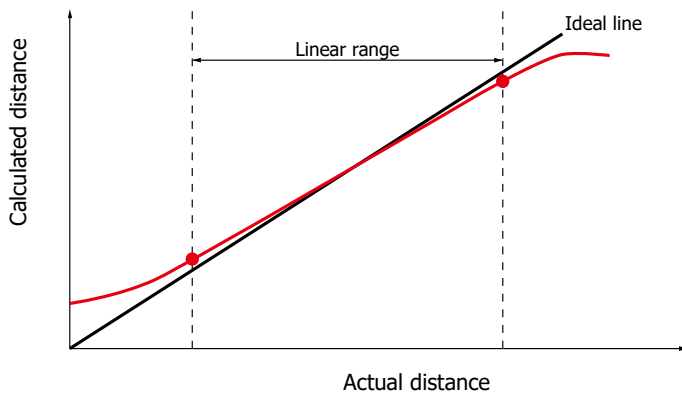

KMPDC0643EA

Approximate distance measurement becomes possible by performing the above calibration. If we want to further improve the distance measurement characteristics and bring the calculated distance closer to the actual distance, we set the sensitivity ratio (SR).

In equation (7-2), SR is added to the distance calculation equation (7-1).

$$L = \alpha \frac{Vout2}{(Vout1 \times SR) + Vout2} \times \frac{cT_0}{2} - Dofs \quad ...(7\text{-}2)$$

7-1. Calculating the sensitivity ratio (SR)

[Figure 7-2] Calculating the sensitivity ratio

KMPDC0644EA
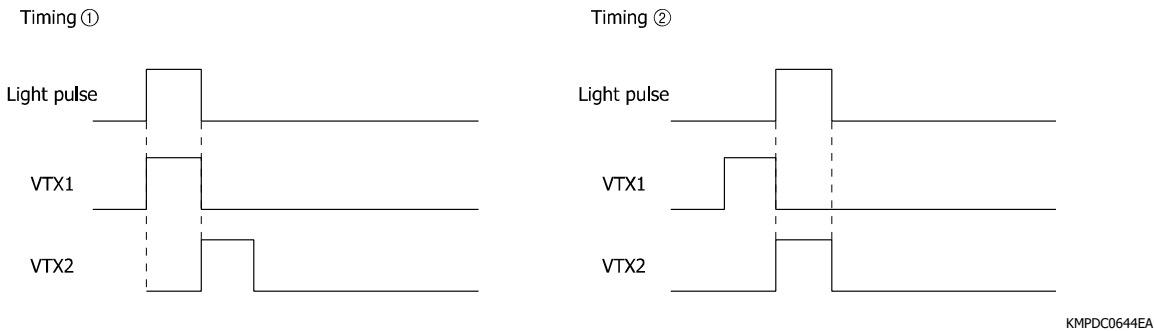
(1) Synchronize the incident light pulse with VTX1 and measure Vout1 (timing ①).
(2) Synchronize the incident light pulse with VTX2 and measure Vout2 (timing ②).
(3) Calculate SR from Vout1 and Vout2 measured in (1) and (2) [equation (7-3)].

$$SR = \frac{Vout2}{Vout1} \quad ...(7\text{-}3)$$

Perform these measurements in the dark state. We also recommend the light level to about half the saturation exposure.

7-2. Linear range and nonlinear range

The distance image sensor has a linear range and nonlinear range in distance measurement. The nonlinear range depends on the pulse waveform of the light source. This phenomenon is described below.

Signal charges shown in Figure 7-3 are accumulated due to the delay in the light pulse incident timing. The linear range (range in which distance calculation is possible) is between timing ① and ③ .
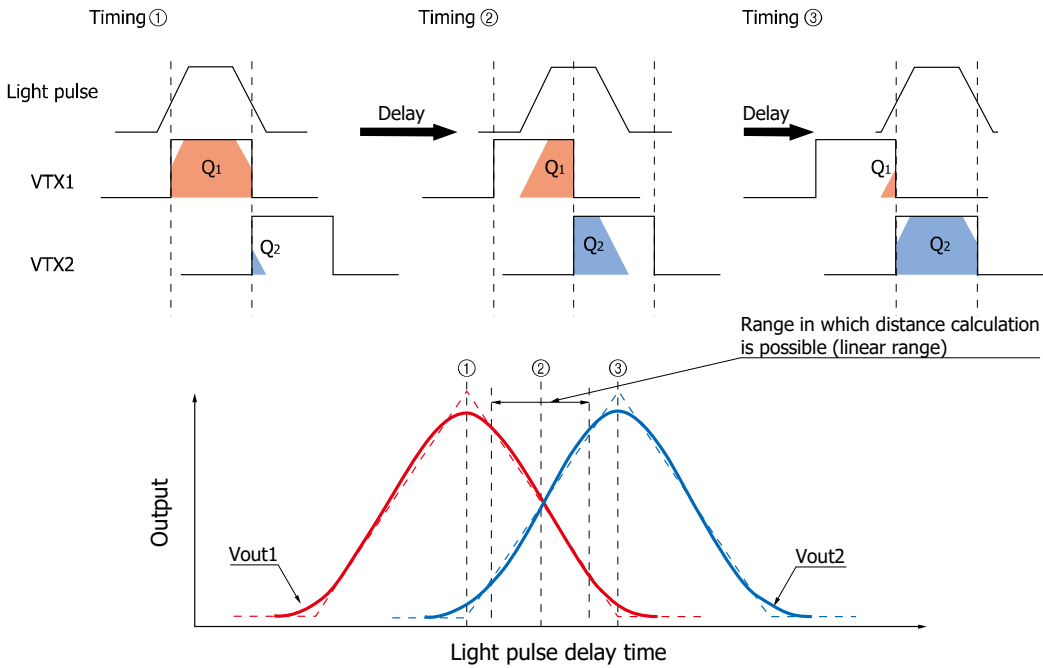
[Figure 7-3] Output vs. light pulse delay time (1)
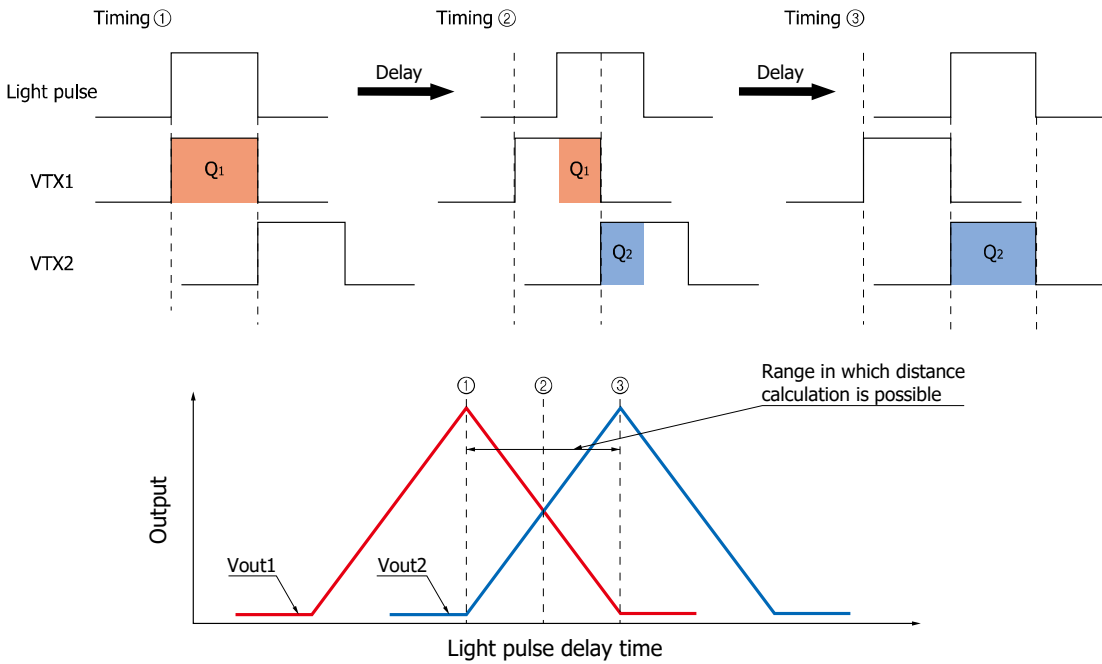
KMPDC0645EA

Actually, since the linear range of Vout1 and Vout2 is narrower because of the rise time and fall time of the light pulse, the linear range of distance measurement is also narrower.

[Figure 7-4] Output vs. light output delay time (2)

KMPDC0646EB

8. Characteristics

8-1. Light incident angle characteristics

The photosensitivity varies depending on the light incident angle. When we measured using the S11963-01CR distance area image sensor, the photosensitivity was about one-half at incident angle of ±50°.

[Measurement method]
The LED light source is directed so that only mostly collimated light is allowed to enter the distance image sensor through the aperture. The sensor-equipped circuit board placed on a rotary stage is installed so that its photosensitive area is aligned along the rotary axis of the rotary stage. The rotary stage is turned, and the incident angle characteristics of sensitivity are measured.
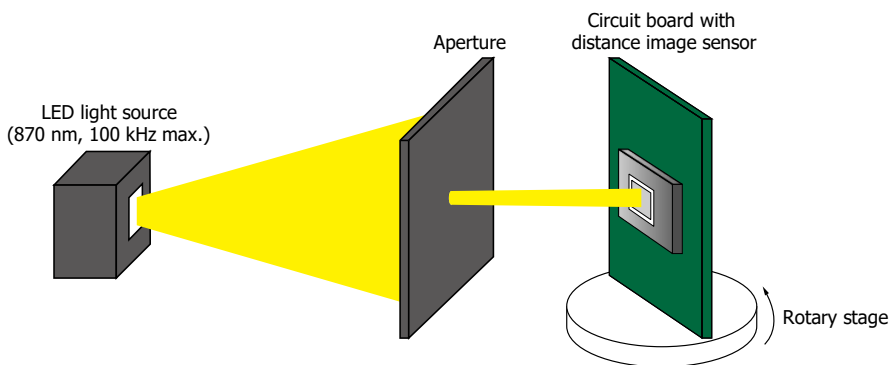
[Measurement conditions]
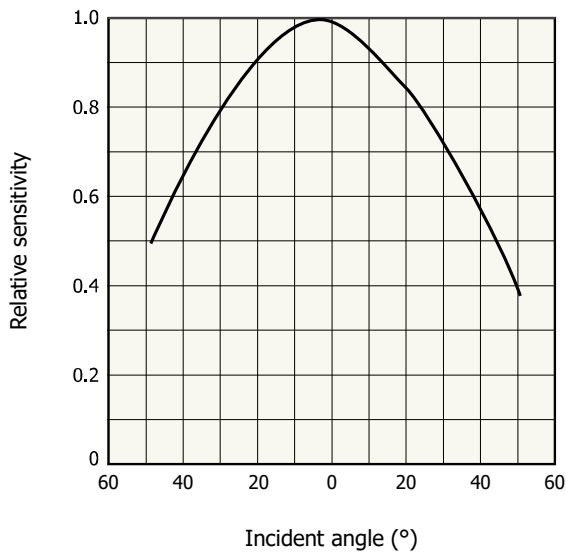Light pulse width=30 ns
VTX1=VTX2=30 ns
VTX3=19940

[Figure 8-1] Measurement method of the light incident angle characteristics of sensitivity

KMPDC0642EA

[Figure 8-2] Incident angle characteristics of sensitivity

KMPDB0506EA

8-2. Distance accuracy vs. incident signal level

Increasing the incident signal level is effective in improving the distance accuracy [Figure 8-3].

[Figure 8-3] Distance accuracy vs. number of incident signal electrons (S11961-01CR, S12973-01CT, typical example)


KMPDB0507EA

HAMAMATSU

PHOTON IS OUR BUSINESS
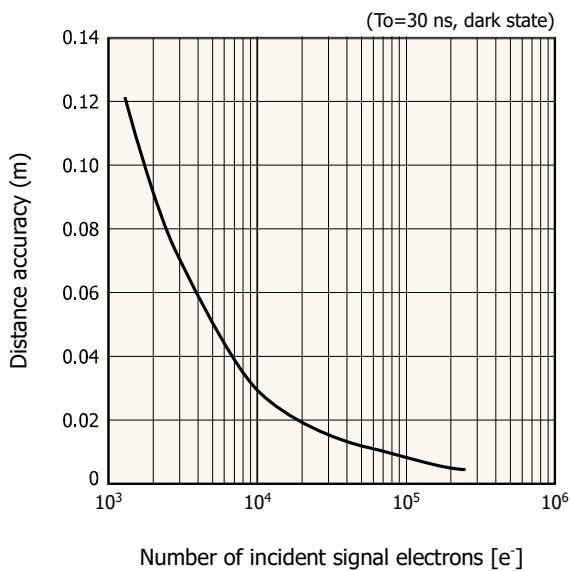
$$\text{Distance accuracy} \propto \sqrt{(N_R{}^2 + Nsh^2 + N_D{}^2)/S} \times (c \times To/2) \quad \cdots (8\text{-}1)$$

S: number of incident photons
N_R: readout circuit noise
Nsh: light shot noise
N_D: dark current shot noise
c: speed of light
To: light emission pulse width

8-3. Temperature characteristics of distance accuracy

If the incident signal level is high, the distance accuracy does not change much even when the temperature increases. If the incident signal level is low, the distance accuracy degrades when the temperature increases. This is because dark current shot noise increases as the temperature increases.

[Figure 8-4] Distance accuracy vs. chip temperature (S11961-01CR, S12973-01CT, typical example)


KMPDB0508EA
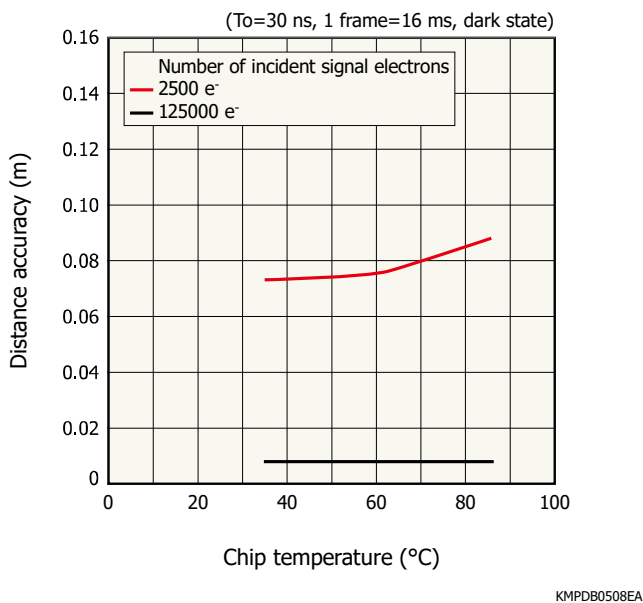
9. Evaluation kit

Figure 5-3 shows a configuration example using the evaluation kit for the distance image sensor. This evaluation kit can generate sensor drive timing with an FPGA and sensor bias voltage with a DAC-IC, perform A/D conversion on the sensor output signal, and transfer data to a PC via Ethernet. This evaluation kit can be driven with only a 5 V power supply.
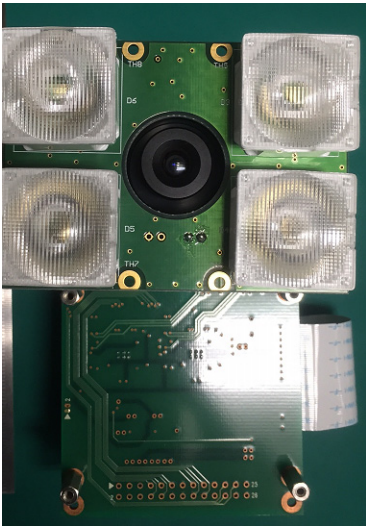Hamamatsu provides evaluation kits (with LED array and light receiving lens) for the S12973-01CT, S11961-01CR, and S11963-01CR.

[Figure 9-1] Configuration example of distance measurement using the evaluation kit
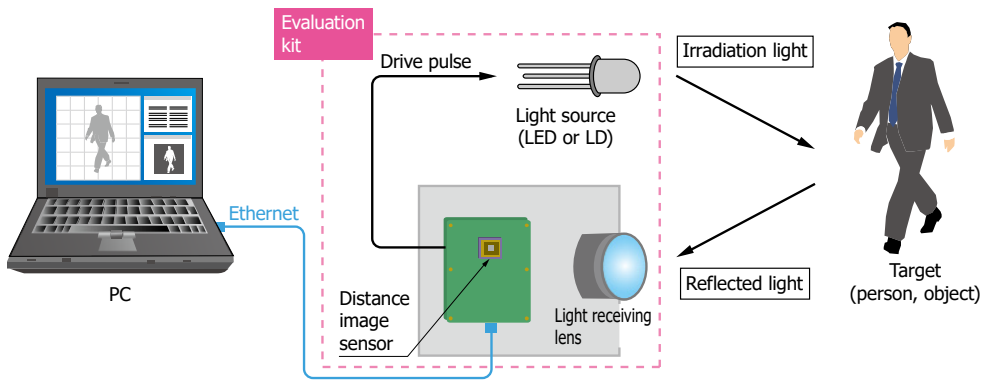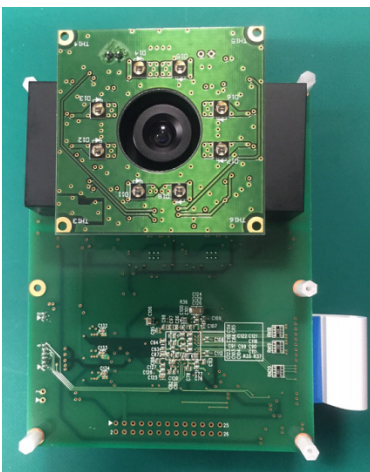

KMPDC0417EB

[Figure 9-2] Example of evaluation kit for linear image sensor

[Figure 9-3] Example of evaluation kit for area image sensor

[Figure 9-4] Example of evaluation kit (with case)