1. Calibration

대외비 1급

분류	Item Name	공정 Spec.		Unit	검사 방법	비고
		하한	상한			
Initial Setting	Setting_LC_pattern_center_x	0	0	mm	the x axis position of the center LED.	
	Setting_LC_pattern_center_y	0	0	mm	the y axis position of the center LED.	
	Setting_LC_pattern_center_z	0	0	mm	the distance between the LED plate and the entrance pupil of the lens of the ToF device.	
	lens_spots	70	134		number of LED spots that are detected.	
Optical Char	cx	104.5	120.5	pixel	Limit for the center pixel in x direction (should be uniformly around the center pixel). First try can be +/- 5, statistical data can change the range later.	Rx center
	cy	78.5	94.5	pixel	Limit for the center pixel in y direction (should be uniformly around the center pixel). First try can be +/- 5, statistical data can change the range later.	
	fx	162.6	172.6	pixel	Limit for the focal length in x direction (should be uniformly around starting parameter value refer to lens data sheet). First try can be +/- 5, statistical data can change the range later.	
	fy	162.6	172.6	pixel	Limit for the focal length in y direction (should be uniformly around starting parameter value refer to lens data sheet). First try can be +/- 5, statistical data can change the range later.	
Fitting Quality	projection_error	0.001	0.24	pixel	Fitting Quality: ([이미지 상("측정된") 특징점(LED) 위치] – [렌즈 모델에 의해 "계산된" 특징점 위치])의 분산 (Squared Mean Error)	difference between actual LED positions and lens model fit
Distortion Parameter	r1	0	0		radial distortion	open cv lens model parameter
	r2	0	0		radial distortion	
	r3	0	0		radial distortion	
	k1	0	0		tangential distortion	
	k2	0	0		tangential distortion	
Rotational Vector	rvec_x	0	0		Limit for the x value of the rotation vector (should be uniformly around 0 and match for x, y, z value).	
	rvec_y	0	0		Limit for the y value of the rotation vector (should be uniformly around 0 and match for x, y, z value).	
	rvec_z	0	0		Limit for the z value of the rotation vector (should be uniformly around 0 and match for x, y, z value).	

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1. Calibration

대외비 1급

분류	Item Name	공정 Spec.		Unit	검사 방법	비고
		하한	상한			
Field of View	HFoV_1	28	37		horizontal field of view to the left (from center)	
	HFoV_2	28	37		horizontal field of view to the right (from center)	
	VFoV_1	22	30		vertical field of view to the top (from center)	
	VFoV_2	22	30		vertical field of view to the bottom (from center)	
ICW	icw_max_amp_0	50	1800		80MHz : Max of value of Internal Chip Wiggling Amplitude	
	icw_min_amp_0	50	1800		80MHz : Min of value of Internal Chip Wiggling Amplitude	
	icw_max_amp_1	50	1800		60MHz : Max of value of Internal Chip Wiggling Amplitude	
	icw_min_amp_1	50	1800		60MHz : Min of value of Internal Chip Wiggling Amplitude	
Difect/Valid Pixels	DarkCurrent_defect_pixel_count	0	40		(The ToF pixels of the IRS image sensor can be placed in a grayscale mode) to measure the dark current of all pixels, number of defect pixels for dark current.	
	FPN_defect_pixel_count	0	40		The FPN (fixed pattern noise) value describes the inhomogeneity of the reset values of the ToF pixels. The reset values are the pixels' starting values of the exposure period: FPN Map 에서의 Defect Pixel 숫자	
	FPPN_defect_pixel_count_0	0	40		80MHz : FPPN Image에서의 Defect Pixel 숫자	
	FPPN_defect_pixel_count_1	0	40		60MHz : FPPN Image에서의 Defect Pixel 숫자	
	Amplitude_defect_pixel_count_0	0	40		80MHz : Amplitude Image에서의 Defect Pixel 숫자	
	Amplitude_defect_pixel_count_1	0	40		60MHz : Amplitude Image에서의 Defect Pixel 숫자	
	Intensity_defect_pixel_count	0	40		Intensity Image에서의 Defect Pixel 숫자	
	DME_defect_pixel_count_0	0	40		80MHz : Dynamic Mixing Efficiency Image에서의 Defect Pixel 숫자	
	DME_defect_pixel_count_1	0	40		60MHz : Dynamic Mixing Efficiency Image에서의 Defect Pixel 숫자	
	valid_pixel_count	37000	38528		total number of valid pixels.	-> Val 중복
	defect_pixel_count	0	40		number of defect pixels	-> Val 중복
	defect_cluster_size	0	1		cluster size of defect pixels. (large clusters create big 'dark spots' in the image.)	Val측정

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1. Calibration

대외비 1급

분류	Item Name	공정 Spec.		Unit	검사 방법	비고
		하한	상한			
Noise Parameter	noise_param0_0	0.02	0.03		80MHz : a=[Amplitude_std(LED OFF) 과 Amplitude_mean(LED OFF) 그래프의 기울기]	
	noise_param1_0	2.08	3.08		80MHz : b=[Amplitude_std(LED OFF) 과 Amplitude_mean(LED OFF) 그래프의 y 절편]	
	noise_param2_0	0.005	0.0161		80MHz : c=[Amplitude_std-aA-b와 Intensity(VCSEL On, LED On) 그래프의 기울기]	
	noise_param3_0	27	33		80MHz : SBI(Suppression of Baground Illumination) 과 관련 있는 Factor Chip Generation(예 B11, B12, ...)별 상수 값을 가짐	
	noise_param0_1	0.02	0.03		60MHz : a=[Amplitude_std(LED OFF) 과 Amplitude_mean(LED OFF) 그래프의 기울기]	
	noise_param1_1	4.43	5.43		60MHz : b=[Amplitude_std(LED OFF) 과 Amplitude_mean(LED OFF) 그래프의 y 절편]	
	noise_param2_1	0.005	0.0161		60MHz : c=[Amplitude_std-aA-b와 Intensity(VCSEL On, LED On) 그래프의 기울기]	
	noise_param3_1	25.5	31.5		60MHz : SBI(Suppression of Baground Illumination) 과 관련 있는 Factor Chip Generation(예 B11, B12, ...)별 상수 값을 가짐	
Phase/Amplitude	phase_std_mean_0	0.002	0.01	m	80Mhz : the mean phase standard deviation.	
	phase_std_max_0	0.0035	0.06	m	80Mhz : the maximum phase standard deviation.	
	amplitude_mean_0	500	1300	DN	80Mhz : the mean amplitude. Lower limit is defined by 200 for a good S/N ratio, upper limit is defined by 1400 to avoid pixel saturation.	
	amplitude_max_0	650	1400	DN	80Mhz : the maximum amplitude. Lower limit is defined by 200 for a good S/N ratio, upper limit is defined by 1400 to avoid pixel saturation.	
	amplitude_wiggling_offset_0	0.5	0.9		80Mhz : the amplitude wiggling offset. Offset limits are set between 0.6 and 1.0 (smooth limits that can be adapted for each batch of ToF modules).	
	amplitude_wiggling_amplitude_max_0	0.03	0.06		80Mhz : the maximum amplitude for the amplitude wiggling fit.	
	phase_wiggling_amplitude_max_0	0.015	0.1		80Mhz : the maximum amplitude for the phase wiggling fit.	

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1. Calibration

대외비 1급

분류	Item Name	공정 Spec.		Unit	검사 방법	비고
		하한	상한			
ETC	fppn_std_0	0	0.0075	m	80Mhz : the standard deviation of the FPPN.	
	temp_compensation_0	0.0005	0.0025	m/K	80Mhz : the temperature compensation. Depends on VCSEL.	
	phase_noise_ratio_mean_0	0.7	1.55		80Mhz : the ratio between phase signal and noise parameters. Noise parameters are global settings.	
	efficiency_mean0	0.025	0.125	DN*m^2/microseconds	80Mhz : the mean efficiency value (in DN*m^2/μs).	
	efficiency_std_0	0	0.021	DN*m^2/microseconds	80Mhz : the standard deviation for the efficiency value (in DN*m^2/μs).	
	dme_mean0	0.6	1		80Mhz : the mean dynamic mixing efficiency value.	
	dme_std_0	0	0.035		80Mhz : the standard deviation of the dynamic mixing efficiency.	
Phase/Amplitude	phase_std_mean_1	0.002	0.01	m	60Mhz : the mean phase standard deviation.	
	phase_std_max_1	0.0035	0.06	m	60Mhz : the maximum phase standard deviation.	
	amplitude_mean_1	500	1300	DN	60Mhz : the mean amplitude. Lower limit is defined by 200 for a good S/N ratio, upper limit is defined by 1400 to avoid pixel saturation.	
	amplitude_max_1	650	1400	DN	60Mhz : the maximum amplitude. Lower limit is defined by 200 for a good S/N ratio, upper limit is defined by 1400 to avoid pixel saturation.	
	amplitude_wiggling_offset_1	0.7	0.95		60Mhz : the amplitude wiggling offset. Offset limits are set between 0.6 and 1.0 (smooth limits that can be adapted for each batch of ToF modules).	
	amplitude_wiggling_amplitude_max_1	0.04	0.086		60Mhz : the maximum amplitude for the amplitude wiggling fit.	
	phase_wiggling_amplitude_max_1	0.015	0.09		60Mhz : the maximum amplitude for the phase wiggling fit.	

1. Calibration

대외비 1급

분류	Item Name	공정 Spec.		Unit	검사 방법	비고
		하한	상한			
ETC	fppn_std_1	0	0.0075	m	60Mhz : the standard deviation of the FPPN.	
	temp_compensation_1	0.0005	0.0025	m/K	60Mhz : the temperature compensation. Depends on VCSEL.	
	phase_noise_ratio_mean_1	0.7	1.55		60Mhz : the ratio between phase signal and noise parameters. Noise parameters are global settings.	
	efficiency_mean1	0.025	0.12	DN*m^2/microseconds	60Mhz : the mean efficiency value (in DN*m^2/μs).	normalize amplitudes by exposure time, distances, target reflectivity(value of the signal strength per exposure time)
	efficiency_std_1	0.0025	0.021	DN*m^2/microseconds	60Mhz : the standard deviation for the efficiency value (in DN*m^2/μs).	
	dme_mean1	0.7	1.2		60Mhz : the mean dynamic mixing efficiency value.	per-pixel demodulation performance (DME = “dynamic mixing efficiency”), AC contrast (modulated pixels) over DC contrast (unmodulated pixels). The contrast is a quality measure of the time-of-flight technology.
	dme_std_1	0	0.04		60Mhz : the standard deviation of the dynamic mixing efficiency.	
Common Noise Factors	dark_current_mean	0	0.0025	DN/s	mean dark current in the ToF chip (in DN/s).	
	fpn_mean	2026	2070	DN	mean value of FPN.	fixed pattern noise
Beam Profile	beam_profile1_min	0.65	1.45		Central Beam Profile value중 minimum 값	profile analysis of efficiency or plane intensity images
	beam_profile1_max	0.7	1.7		Central Beam Profile value중 maximum 값	
	beam_profile2_min	0.5	1.3		Middle Beam Profile value중 minimum 값	
	beam_profile2_max	0.7	1.6		Middle Beam Profile value중 maximum 값	
	beam_profile3_min	0.4	1		Outer Beam Profile value중 minimum 값	
	beam_profile3_max	0.6	1.4		Outer Beam Profile value중 maximum 값	
Temperature	illumination_temperature	17	52	℃	temperature of the illumination source (VCSEL) during data acquisition. (VCSEL and other electrical components may do some further restrictions.)	

2. Validation

대외비 1급

분류	Item Name	공정 Spec.		검사 방법	비고
		하한	상한		
Amplitude Factor	amplitude_max_value	0	2000	Amplitude mean map의 max값	
	amplitude_max_of_maxs_value	0	2000	Amplitude max map의 max값	Uniformity
	amplitude_mean_value	0	2000	Amplitude mean map의 mean값	
	amplitude_min_value	0	2000	Amplitude mean map의 min값	
	amplitude_min_of_mins_value	0	2000	Amplitude min map의 min값	Uniformity
	amplitude_std_value	0	2000	Amplitude mean map의 표준편차 값	
	amplitude_std_temporal_value	0	2000	Amplitude Std map의 mean값	
Confidence Value	confidence_0_value	38478	90000	Number of pixels with 100% Confidence Level	
	confidence_1_value	-2000	2000	Invalid Pixel Count	
	confidence_2_value	-2000	2000	N/A	
	confidence_3_value	-90000	90000	N/A	
	confidence_4_value	-90000	90000	N/A	
	confidence_5_value	-90000	90000	N/A	
	confidence_6_value	-90000	90000	N/A	
	confidence_7_value	-90000	50	Number of pixels with 87.5% Confidence Level	고객spec X, 내부spec O
	number_of_calibrated_pixels_in_roi_value	34675	90000	the number of pixels that can be used for the measurement(masking pixels with insufficient lighting and defect pixels)	
	valid_pixels_percentage_value	-1000	1000	Ratio of valid_pixels in ROI	
Plane Fitting	plane_error_max_value	-100	100	Fitted plane using calibrated 3D point cloud	
	plane_error_mean_value	-100	100	Fitted plane using calibrated 3D point cloud	
	plane_pan_angle_value	-1.5	1.5	angle of plane fit about x-axis	
	plane_stddev_value	0	100	Fitted plane using calibrated 3D point cloud	
	plane_tilt_angle_value	-1.5	1.5	angle of plane fit about y-axis	

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2. Validation

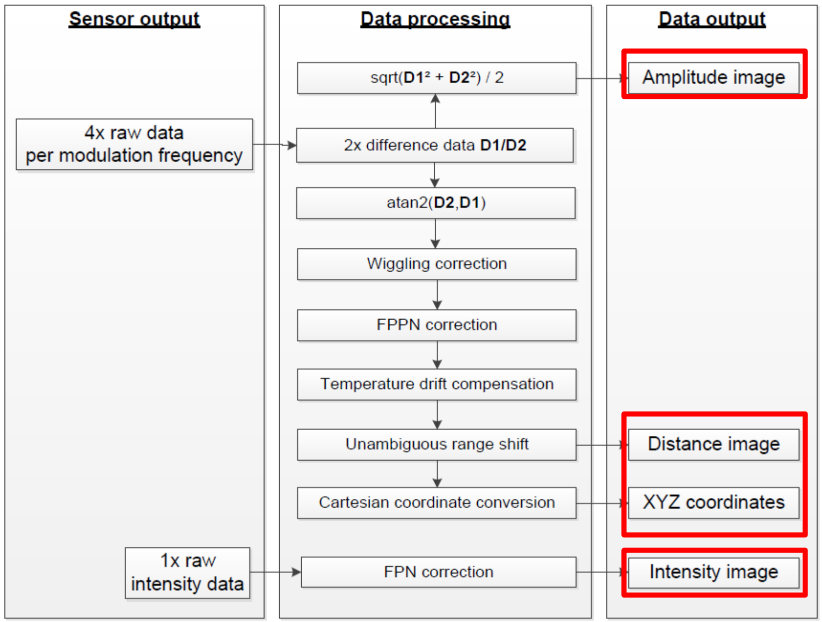
대외비 1급

분류	Item Name	공정 Spec.		검사 방법	비고
		하한	상한		
Performance Factors	depth_accuracy_value	-10	10	Depth mean Map의 평균값 - Ground Truth = 종합 거리 오차	
	depth_accuracy_percent_value	-1.5	1.5	(Depth mean Map의 평균값 - Ground Truth)/Ground Truth*100 = 종합 거리 오차율	
	depth_accuracy_q90_percent_value	0		Depth 오차율 중, (38528개의 픽셀중) Q90값 (크기순상 Worst에서 10% 해당값)	
	depth_precision_spatial_value	0	100	각 Depth Map 프레임당 Fitting을 하여 그 차이(difference map)를 각 프레임 마다 구하고, 그 값들을 평균	
	single_shot_depth_error_value	-100	100	Spatial depth error(Fitted Plane --> Ground Truth)	
	depth_precision_temporal_value	0		Depth STD Map(주어진 프레임들에서 각 픽셀들의 STD값만 추출한 map)의 평균값	
	depth_precision_temporal_q90_value	0		Depth STD Map의 Q90 값	
	centre_noise_value	0	5	Temporal noise of the depth values in ROI(central) 5x5	
Percent Value	percent_flagged_flying_value	0	100		
	percent_flagged_lens_value	0	100		
	percent_flagged_low_signal_value	0	100		
	percent_flagged_mpi_amp_value	0	100		
	percent_flagged_mpi_dist_value	0	100		
	percent_flagged_saturation_value	0	100		
ETC	flatness_value	-99999	99999		Not Been Shared
	predicted_centre_noise_value	-99999	99999		
	q90_value	-100	100		Unknown of which Q90 Value of
	q90_sys_value	-100	100		Unknown of which Q90 Value of
	val_time_value	-9999999	999999	Validation Process tact time	
	wall_offset_value	-100	100		

3. Index

대외비 1급

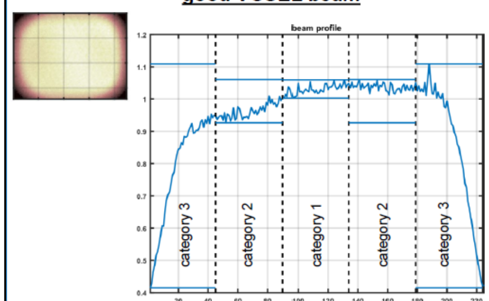
Data processing chain



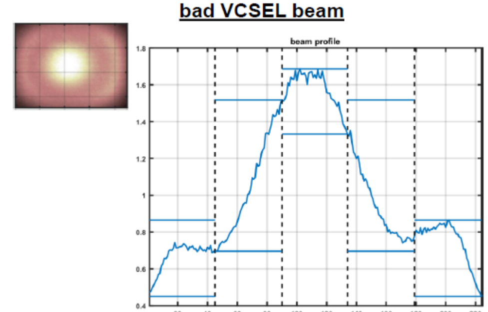
Beam profile calculation

- The beam profile analysis is sensitive to the typical VCSEL diffusor error of increased light output in the central beam. The implemented procedure to get key values for pass/fail limits is:
  - take the maximum values of all valid pixels per column of a efficiency image to get a beam profile
  - divide the profile into five equal sections
  - categorize the five sections into three regions:
    - central region (category 1)
    - mid region (category 2)
    - outer region (category 3)
  - normalize the profile by the average value of category 2
  - apply pass fail limits to the minimum and maximum off all three categories (→ 6 values with limits)

good VCSEL beam



bad VCSEL beam



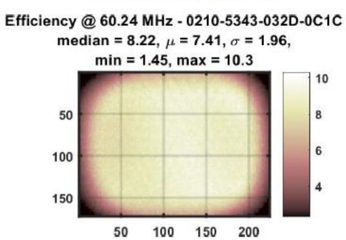
3. Index

대외비 1급

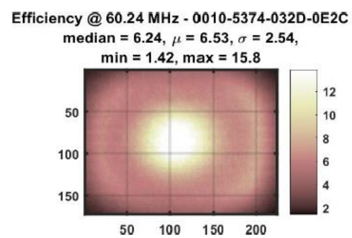
Efficiency

- The "efficiency" describes a per-pixel, frequency dependent value of the signal strength per exposure time
- wiggling-free amplitude, normalized by
  - exposure time in μs
  - squared radial distance in m
  - cosine of incident angle (assuming Lambertian reflectance)
  - reflectivity of target surface
- The mean of all valid pixels can be used as a performance value
- The standard deviation of all valid pixels can be used to indicate the homogeneity of the illumination
- The resulting pixel matrix may also be used for beam profile analysis

good VCSEL beam

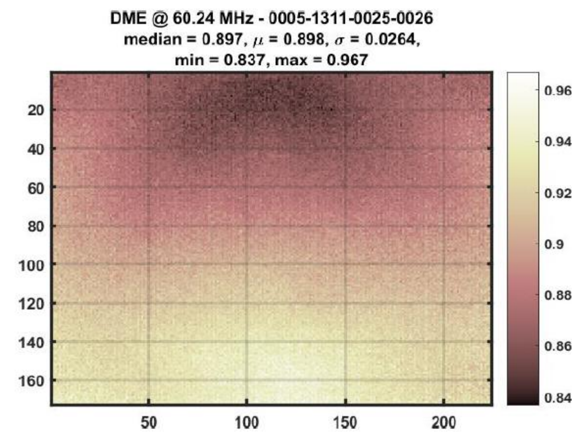


bad VCSEL beam



Dynamic mixing efficiency

- Dynamic mixing efficiency (DME) is defined as AC contrast (modulated pixels) over DC contrast (unmodulated pixels). The contrast is a quality measure of the time-of-flight technology. (For a deeper explanation of contrast see ToF basics.)
- A high DME indicates a good time-of-flight performance. Strong variations within the pixel matrix are an indicator for sensor errors or defect pixels.



Tx의 Uniformity_유 의미 가능성

Simulation background - Parameters

대외비 1급

【Parameter of module】

In the case of our calculation which is mentioned in this document, we divided the module and operating environment into the following 5 categories. Each category is as follows. And, Figure 1 in the below is the schematic. Also, we are supposing that the light from light source is emitted after formatting to square shape by the filed of view which is decided by optical lens (θ_H, θ_V).

1．Target object
- Distance up to target object L [m]
- Reflectance of target object R [%]

2．Projector
- Output of light source P [W/sr]
- Projection light efficiency E_P[%]
- Duty ratio
- Accumulation time T_{acc} [s]
- Half-value angle of light source θ_{Source}
- Projection angle (H・V) θ_H、θ_V [°] (Described as $\theta_{Emission}$ in the figure)

3．Ambient light
- Intensity of ambient light P_{amb} [W/m^2]
- Transmission wavelength range of band-pass filter (short・long wavelength) λ_{short} , λ_{long} [nm]

4．Receiver
- Efficiency of optical lens E_R [%]
- Transmission ratio against signal of band-pass filter E_F [%]
- F-number of optical lens
- Focal length of optical lens f [m]

5．Sensor
- Pixel size(H・V) H_{pix} , V_{pix} [m] (Area=S_{Pix})
- Aperture ratio FF [%]
- Sensitivity S_{sens}
- Pixel capacitance Cfd
- Maximum voltage amplitude V_{max}[V]
- Random noise RN [uV]
- Dark output V_D [V/sec]

Ref. "Estimation of light source of distance image sensor", Hamamatsu

Simulation background - Schematic

대외비 1급

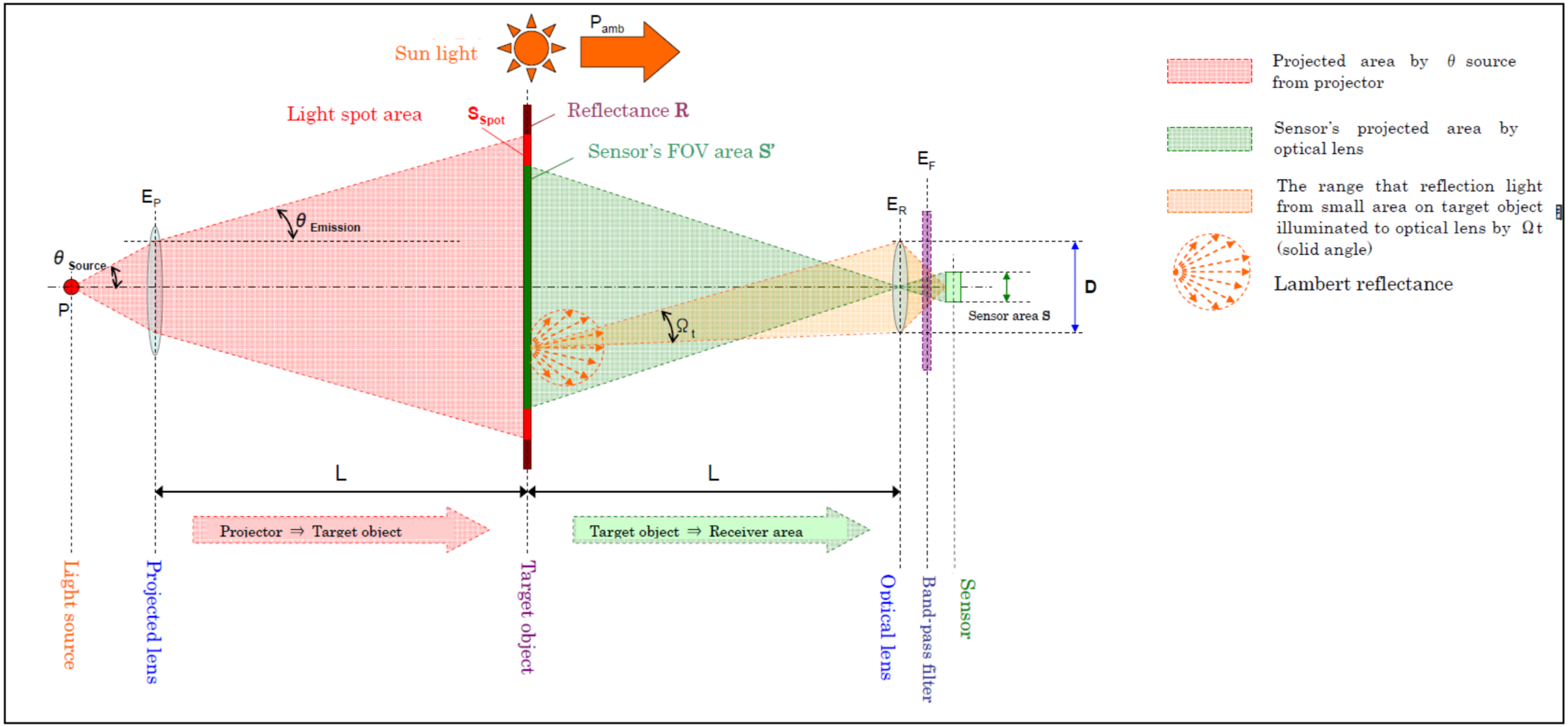
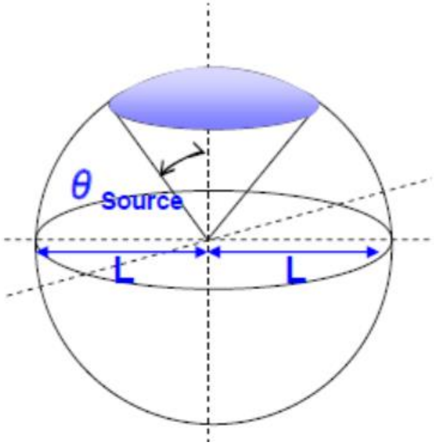


Figure 1 Schematic of module for calculation

Simulation background - Definition

대외비 1급

Black box is applied to simulation



Estimation of incident light

spot light source P_{Spot} [W/m2] is calculated by light source output P [W/sr], solid angle of projector [sr], projection efficiency E_P [%],and spot area S_{Spot}.

$$P_{Spot}[W/m^2] = P[W/sr] \times \frac{a}{L^2}[sr] \times E_P[\%] \times \frac{1}{S_{Spot}[m^2]} \qquad (1)$$

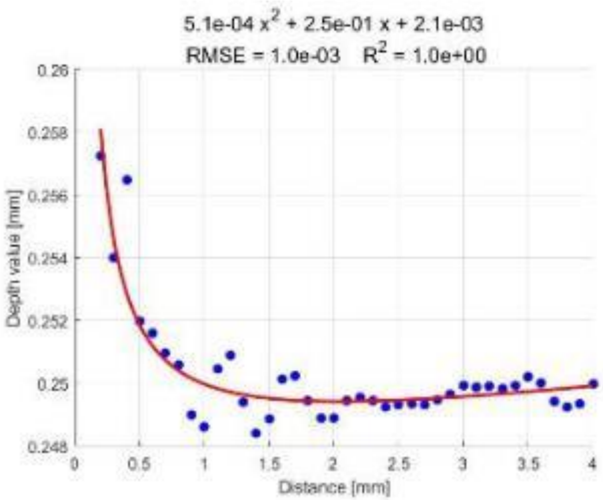
$$S_{Spot} = 2L\tan\theta_H \times 2L\tan\theta_V$$

the area which is calculated by angle consisted by θ_{Source}

$$a = 4\pi\left(\frac{L}{\cos\theta_{Source}}\right)^2 \sin^2\frac{\theta_{Source}}{2}$$

$$a = (LD/\cos(\theta_{source}))$$

L_D : distance to object



diameter of optical lens is D [m],
the angle of θ_R which is consists of a certain point and diameter of optical lens is

$$\theta_R = \tan^{-1}\left(\frac{D}{2L}\right) \qquad (2)$$

$$\Omega_t = 4\pi\sin^2\frac{\theta_R}{2}[sr] \qquad (3)$$

$$\text{Radiance} : \frac{Maximum\ Optical\ Power}{2\times Distance(mm)\times tan\left(\frac{FoI_H}{2}\right)\times 2\times Distance(mm)\times tan\left(\frac{FoI_V}{2}\right)}$$

Simulation background - Definition 대외비 1급

Optical power per pixel is calculated by

$$\text{Optical power per pixel}: \\ Radiance \times Area(mm^2) \times Solid\ Angle(sr) \times Reflectance \times Optical\ efficiency\ (sensor\ fill\ factor, lens, filter)$$

Amplitude decreasing factor defines from Alpha modules result that fitted to exponential decay equation.

Optical power reduction (amplitude attenuation) exponential decay fitting : $= A\ exp\ (-B*distance)+C$

shot N_L, random noise N_R, dark current shot noise N_D

$$N\,[e^-] = \sqrt{N_L^2 + N_R^2 + N_D^2}$$

$$N_L\,[e^-] = \sqrt{Q_{pix}[e^-] + Q_{pix}(amb)[e^-]} \qquad N_R\,[e^-] = RN\,[V] \times C_{fd}\,[F]\,/\,e\,[C] \qquad N_D\,[e^-] = \sqrt{V_D[V/s] \times T_{acc}[s] \times C_{fd}[F]/e[C]}$$

System noise fact will be fitted by measured result.

Calculated final signal & depth noise value :

$$\text{Signal}: Optical\ Power\ per\ pixel \times optical\ power\ reduction \times \frac{Duty\ ratio \times Sensitivity \times Exposure\ time(s)}{1.602E{-}19\ (coulomb\ to\ no.of\ e^-)}$$

$$\text{Depth noise}: \text{distance} \times \frac{1}{2\pi} \times \frac{c}{2 \times Freq.} \sqrt{\frac{2}{subframe\ \#}} \times \frac{Noise}{k_{tot} \times signal} \times \text{fitting constant.}$$

,Where k_{tot} : *modulation contrast*

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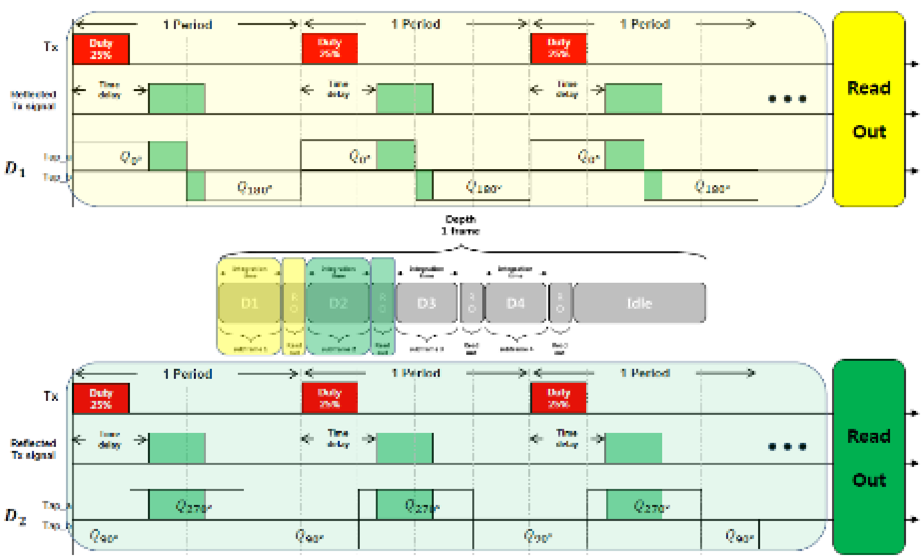
후방용 ToF 공유용 자료 정리

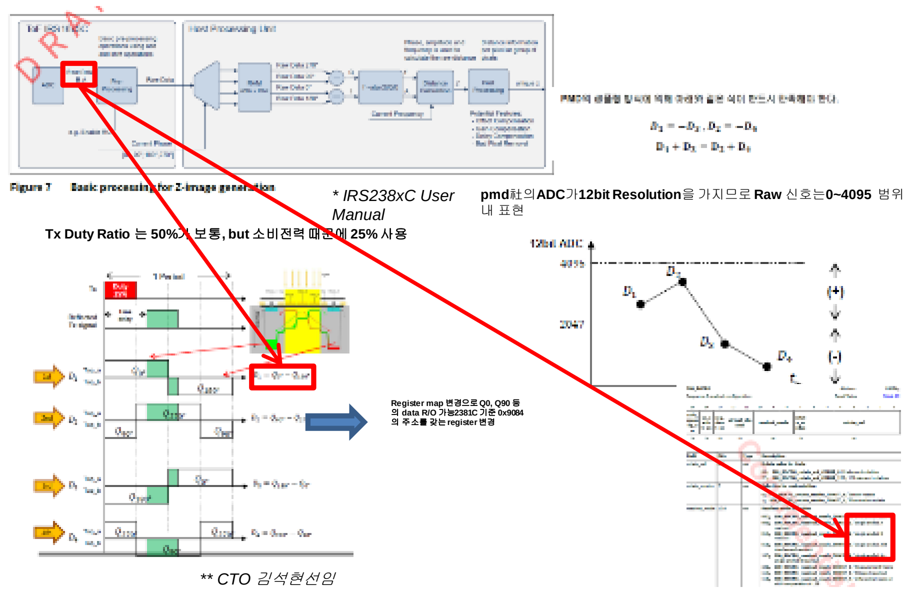
대외비 1급

센서의 configuration

-. USECASE default 기준 VD sync 파형 정리 및 data 축적, read out, idle time, sleep timing 정보 공유
-. Phase raw data의 output configuration 및 이론적인 내용 공유
-. Post processing tree 공유
-. 기타 센서 관련 part 내 공유



** CTO 광학기술팀 김석현선임 자료



** CTO 김석현선임 자료

* IRS2381C registerDescription_ Rev1.0

신규 센서

As is

-. PMD에서 제공한 Focusing용 Python Script를 이용하여, Focusing 완료 (w/ 천세환 사원) – 모듈 동작 확인(python)

-. Sensor Configuration을 통하여 VCSEL 구동 확인 및 USECASE cfg 생성 – 모듈 동작 확인(python)

-. Focusing Script 이용하여, raw data(Phase 0, 90, 180, 270) 출력, dual demodulation frequency (80MHz, 60MHz) – 모듈 동작 확인(python)

-. 알려진 수식을 이용하여, 각 frequency 별 Depth 추출 및 .csv file 형태로 저장. – 모듈 동작 확인 (python)

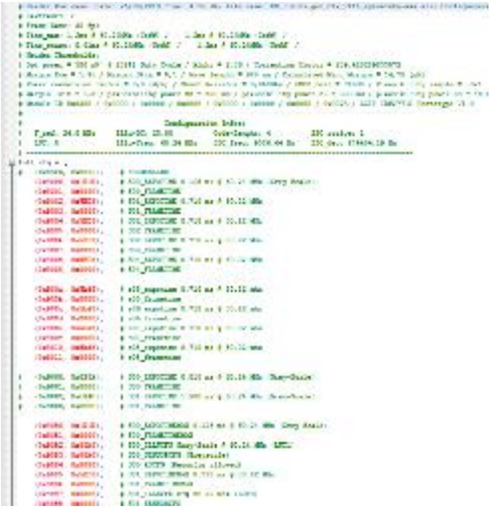
To Be

-. 60MHz, 80MHz raw data configuration fine tunning - 모듈 동작 확인 (python)

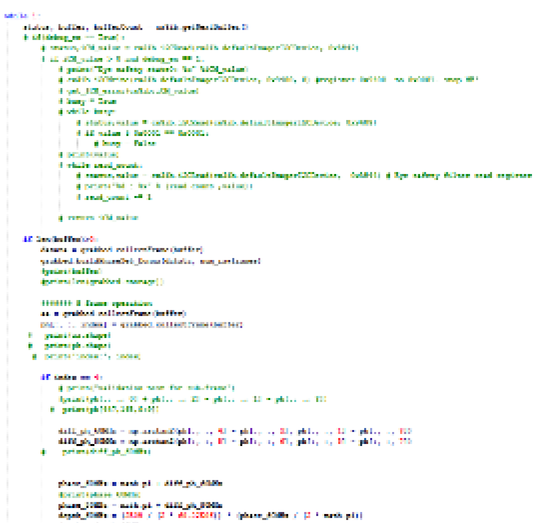
-. 제공 받은 Fake Calibration data를 메모리에 write 한 뒤, Royale 을 통해서 확인. – 모듈 동작 확인 (별도 S/W)

-. Calibration 을 위한 Grabber용 S/W 모듈을 이용하여, NTI Box 로 Calibration 진행. – Calibration

Sensor Configuration을 통하여 VCSEL 구동 확인 및 USECASE cfg 생성 – 모듈 동작 확인(python)



Focusing Script 이용하여, raw data(Phase 0, 90, 180, 270) 출력, dual demodulation frequency (80MHz, 60MHz) – 모듈 동작 확인(python)



S.LSI 센서 Calibration 검토

대외비 1급

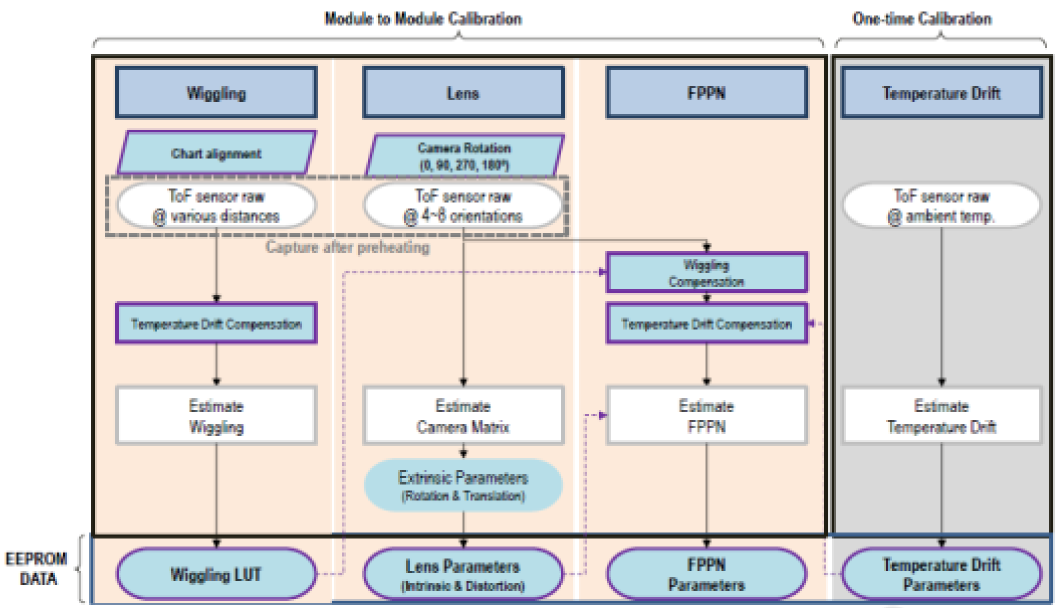
S.LSI 센서 Calibration

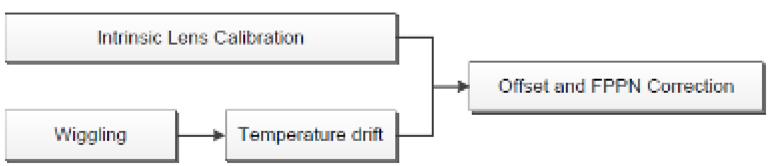
As is

-. 삼성 LSI 센서의 Calibration logic tree 및 장비 검토

To Be

-. Pmd 와 삼성 LSI 센서의 Calibration 장비 및 logic 비교





LG이노텍