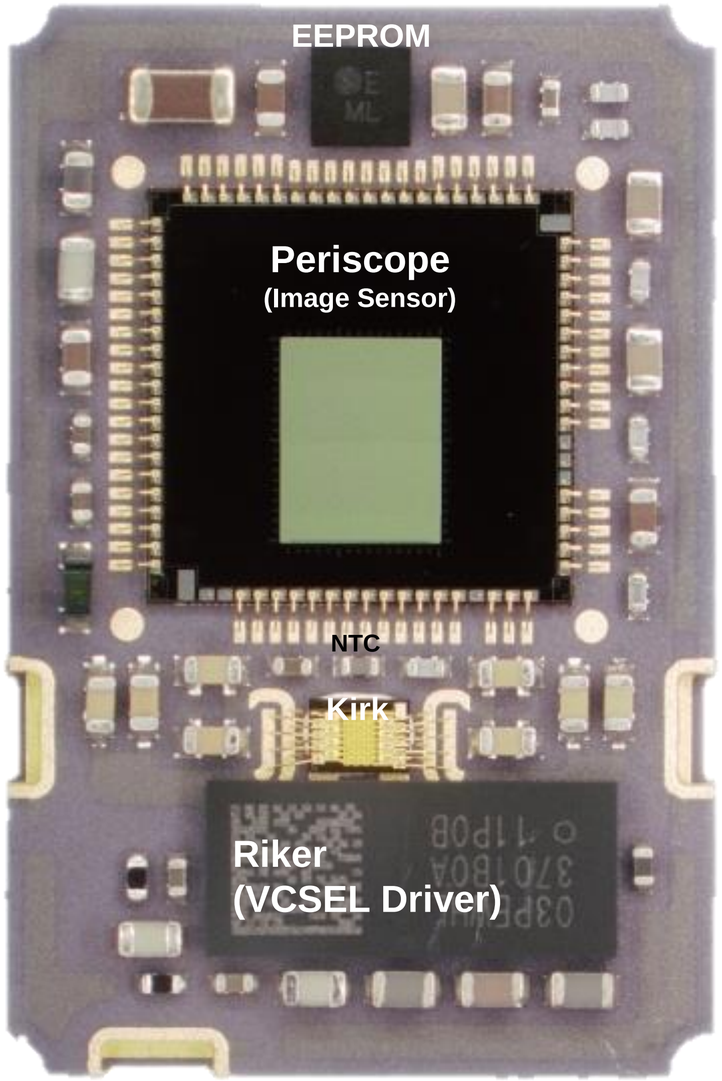
Unified Calibration

1. Jasper module outline

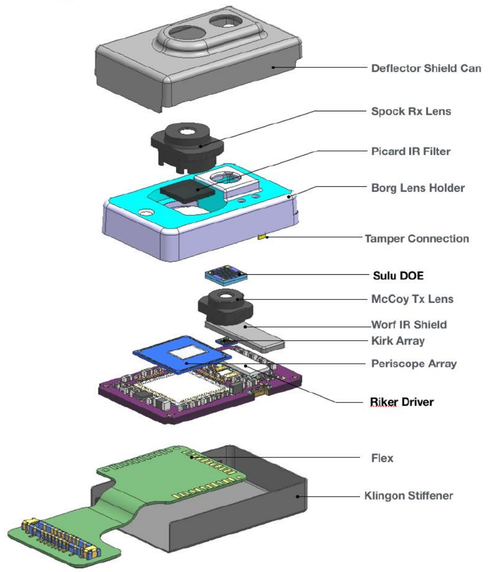


EEPOM : 256kbyte data storage of manufacturing information, Pixel data, Tester data, current value

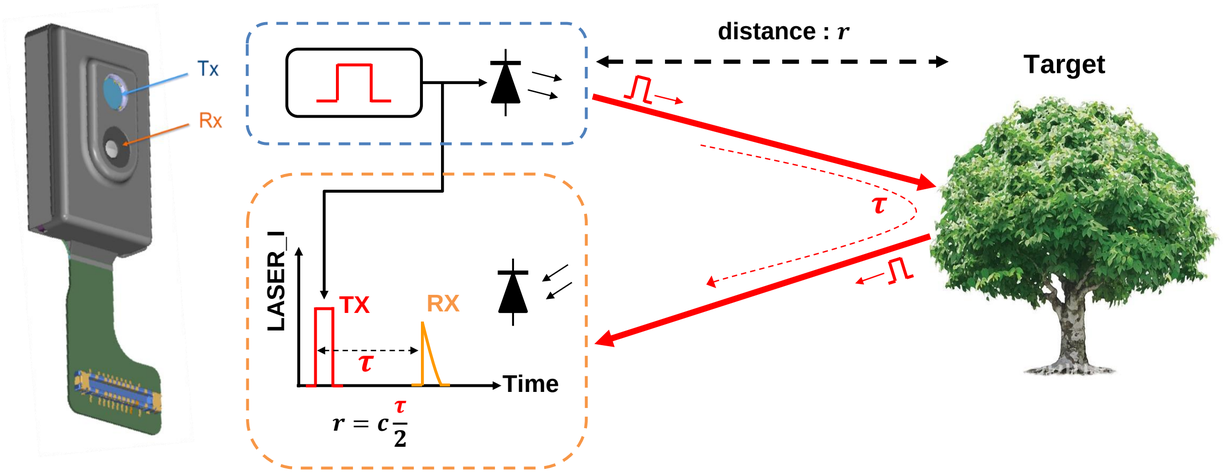
Periscope : It is embedded with backside illuminated SPAD pixel, Super-pixel selection network(SSN), Time-to-Digital Converters(TDCs), PRI modulation, Super-pixel histogram builder, temperature sensor, LPDP high speed serial interface.

Periscope specification Clock frequency : 12 MHz
Supply voltage : Pixel, Analog 3.0V, SPAD -20V
Pixel size : 10 um square
Resolution : 140 x 181, 1 line is reference pixel

Riker : 4-channel, high-speed laser diode array driver that can drive repeating and high current pulses. Riker provides various protection blocks and built-in fault detection mechanisms.



Direct Time of Flight



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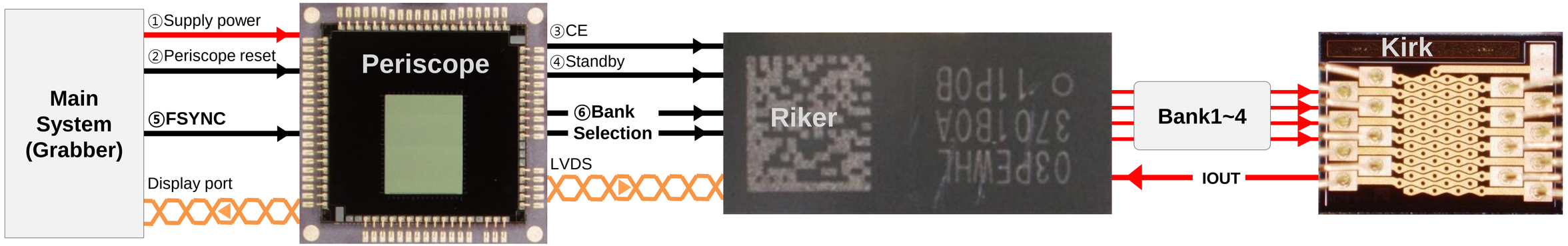
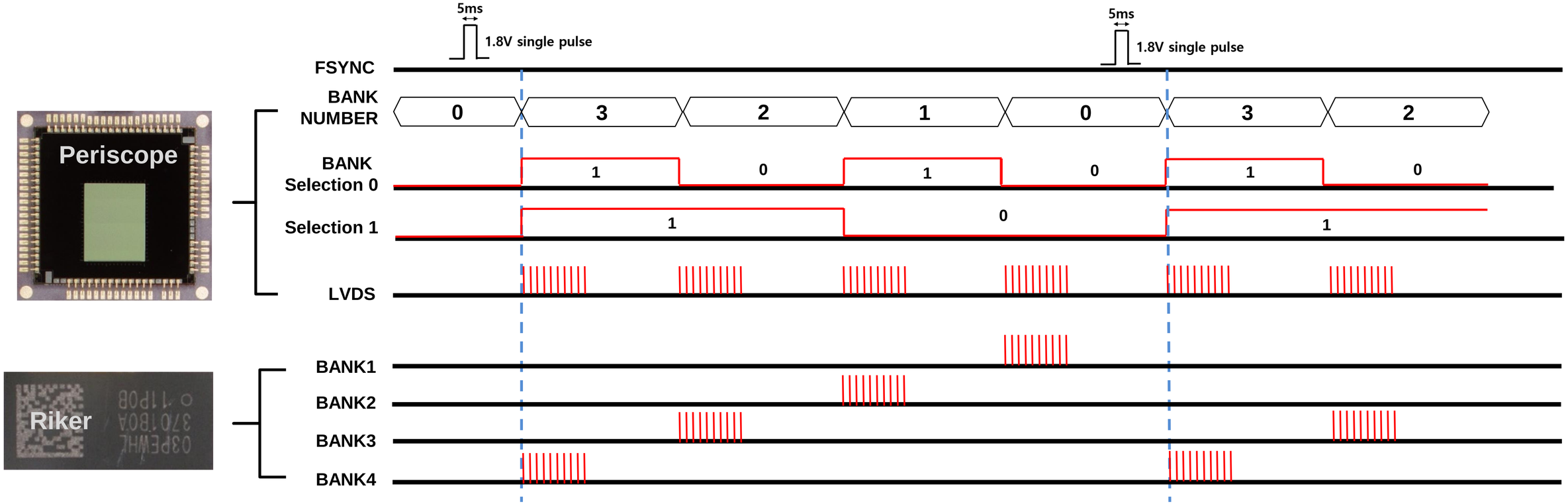
Unified Calibration

2. Jasper module operating sequence





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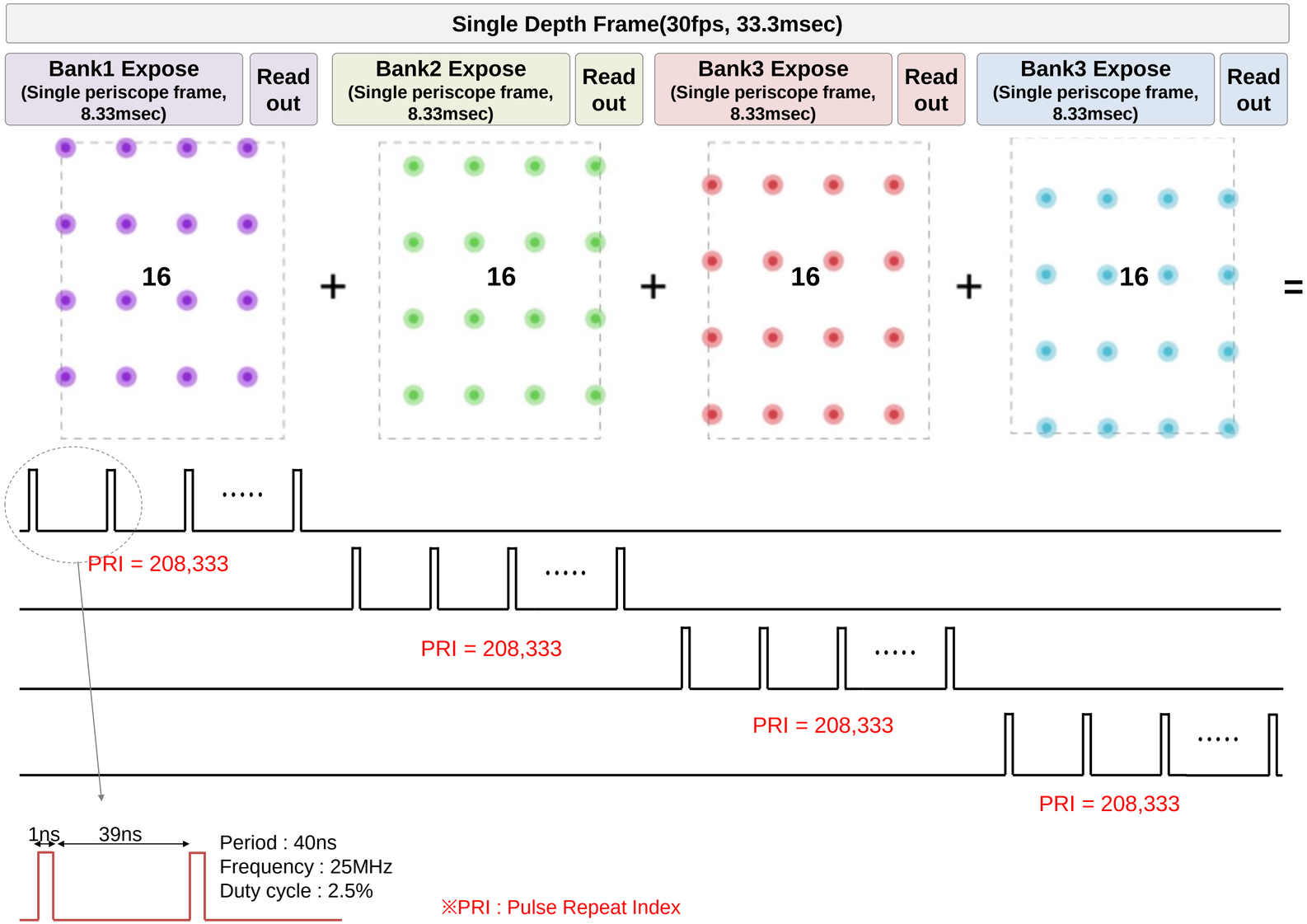
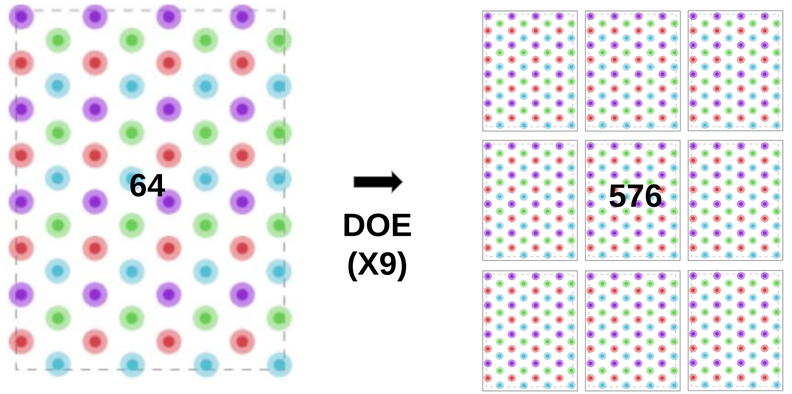
Unified Calibration

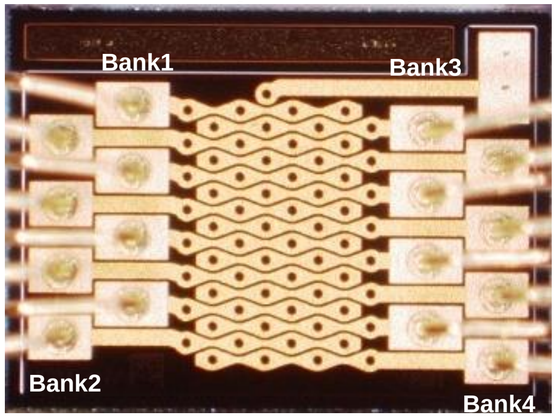
3. VCSEL Firing Sequence



208,333 x 40ns x 4 = 33.33ms → 30fps



VCSEL(Lumentum)



64 emitters

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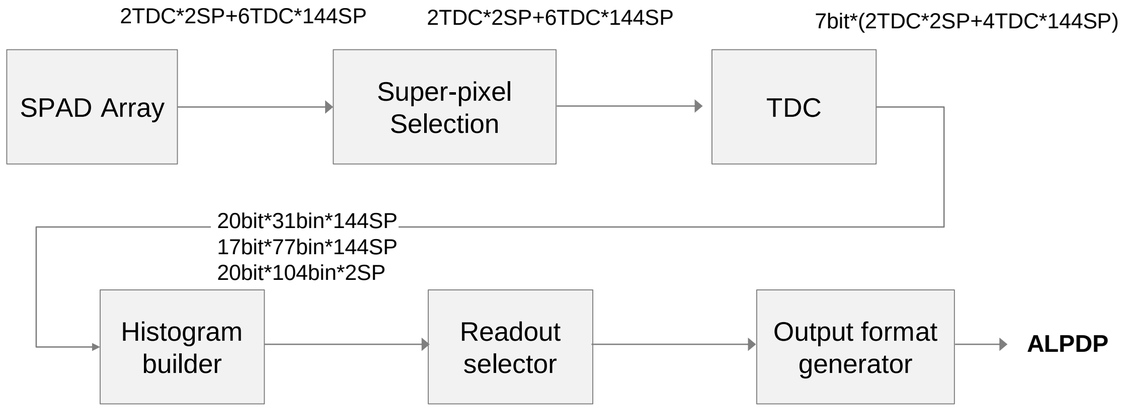
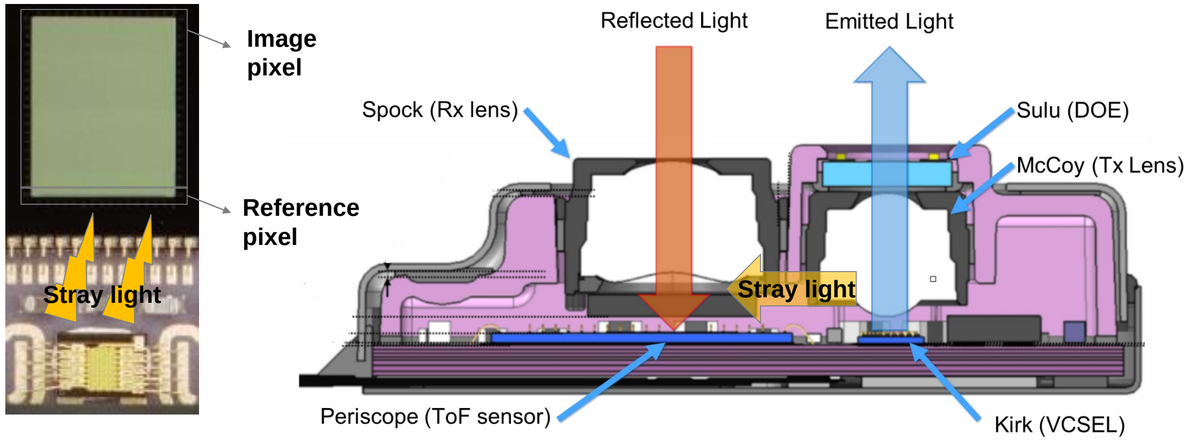
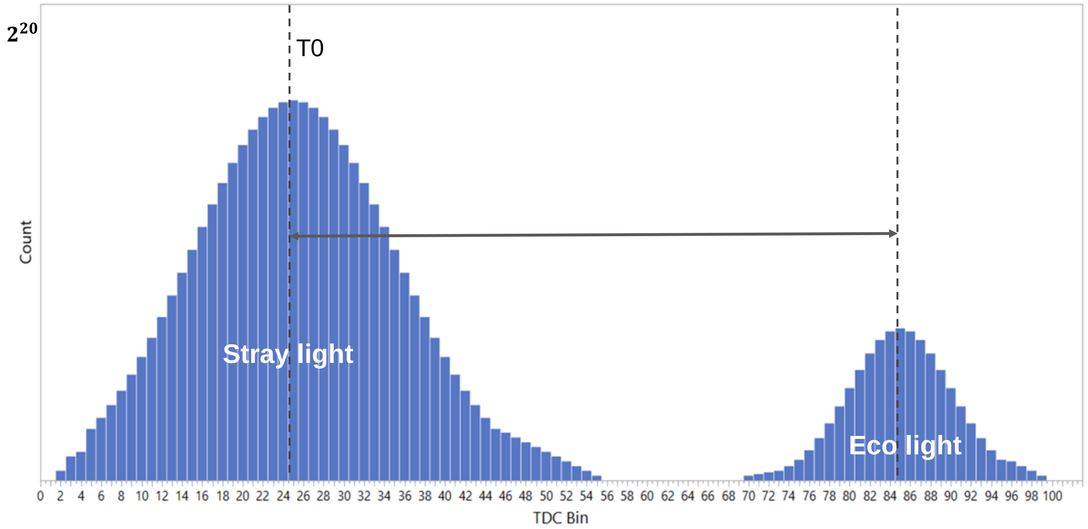
Unified Calibration

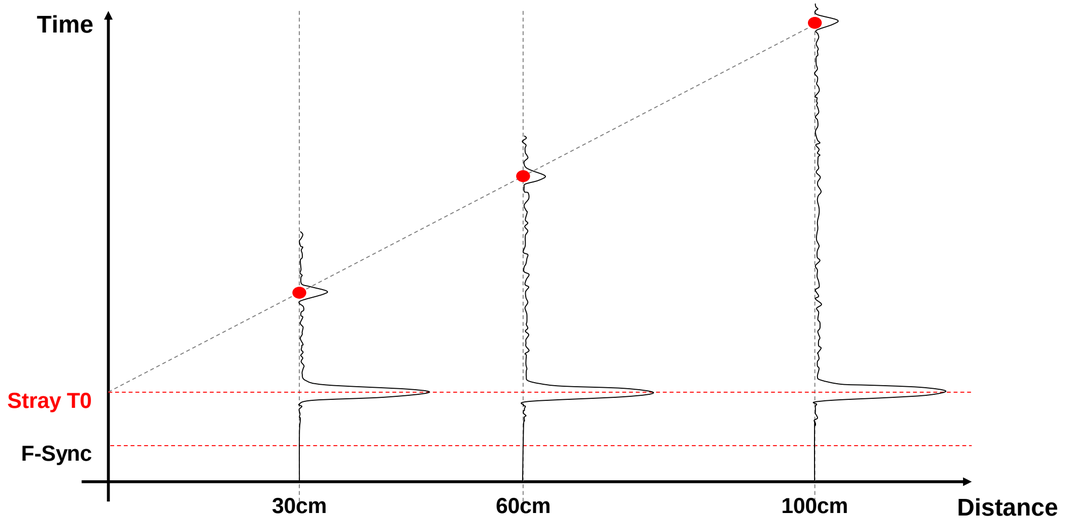
4. How Periscope(SPAD) works-simplified

Stray and reflected light are captured by reference and image pixel, TDC converts the arrival time of light into digitized bin number.
Histogram builder makes the histogram of TDC bin counts to estimate the time interval between stray light and eco light









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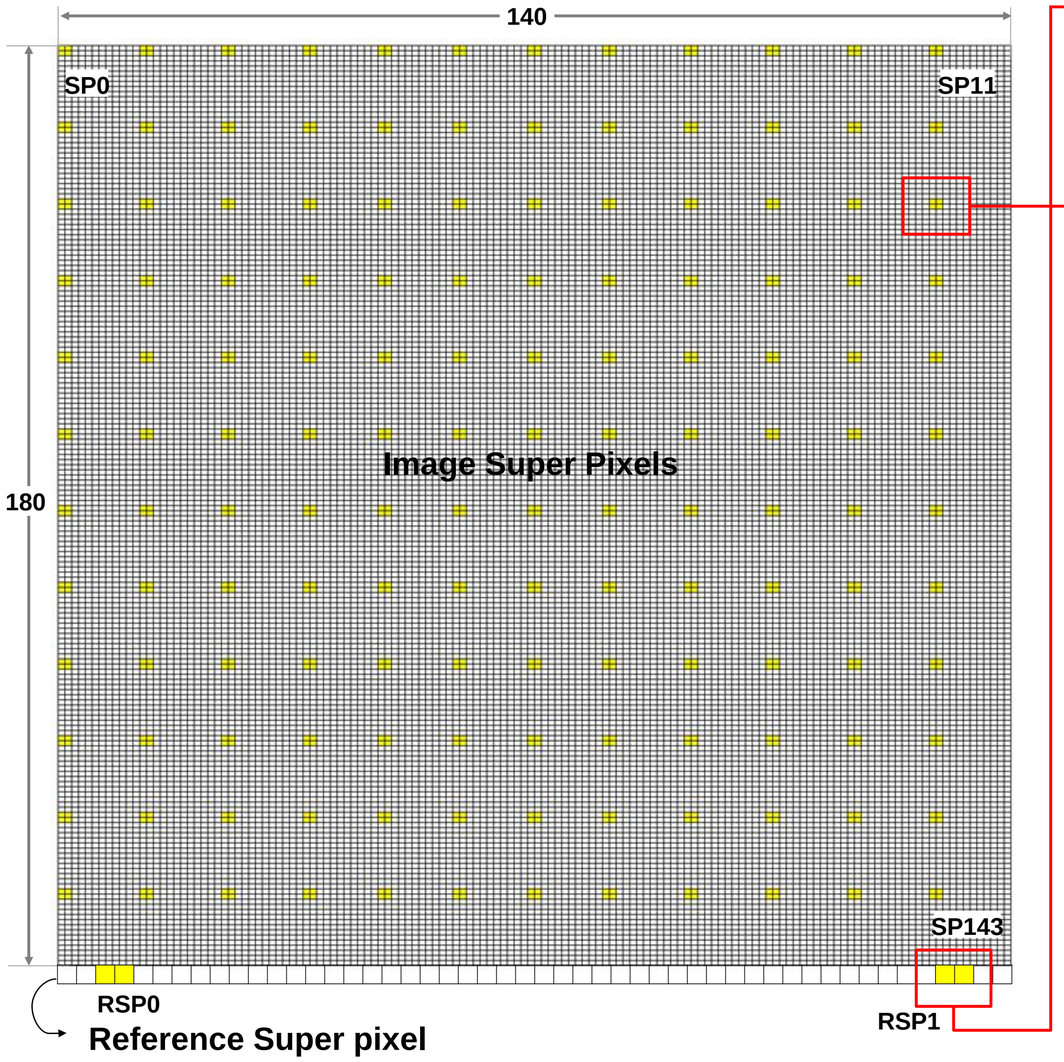
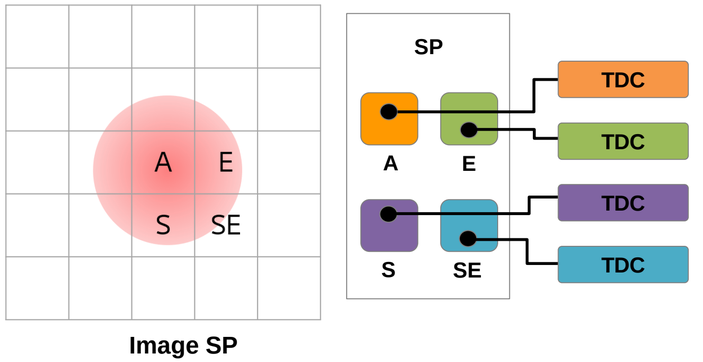
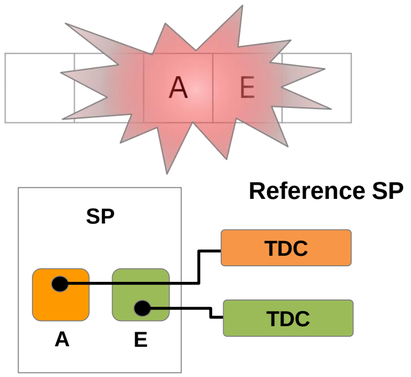
Unified Calibration

5. Super-Pixel Selection Network

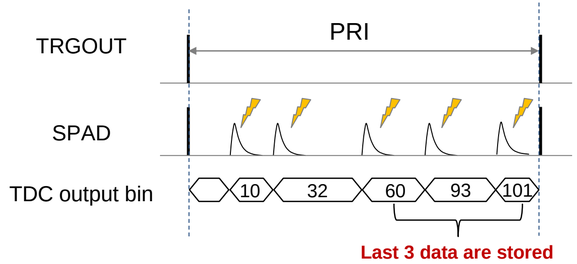




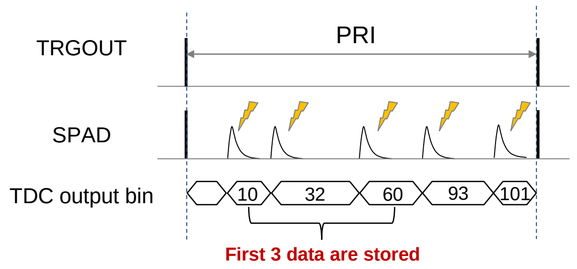


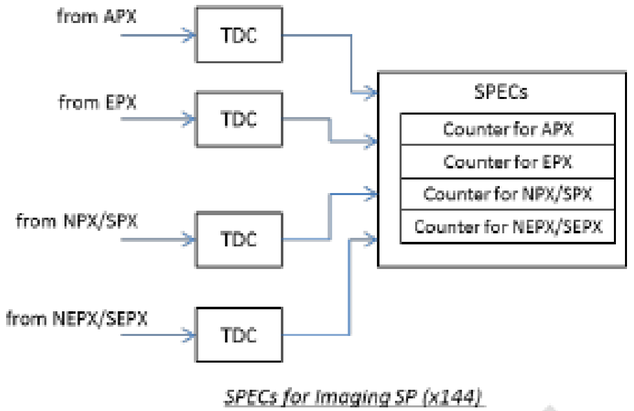
Spot Position Estimation Counter(SPEC)

TDC Data buffering (Image SP)

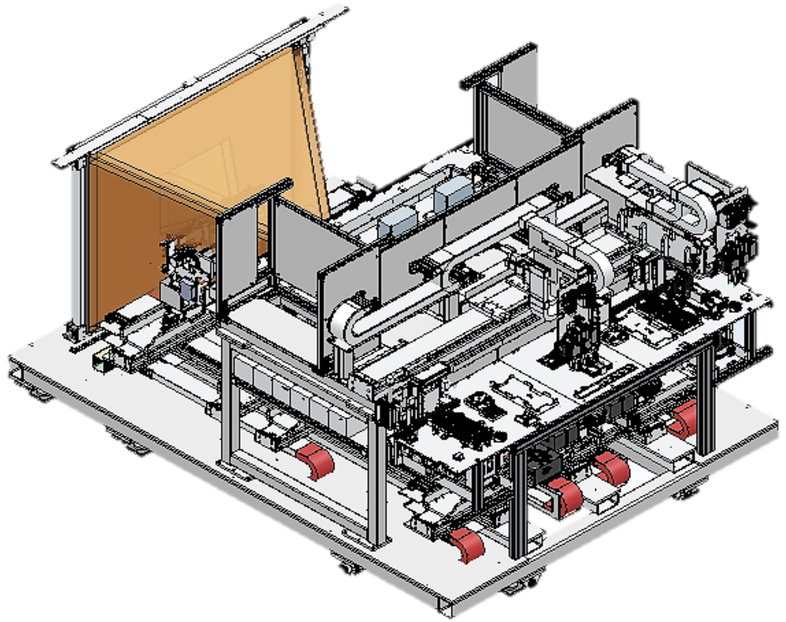


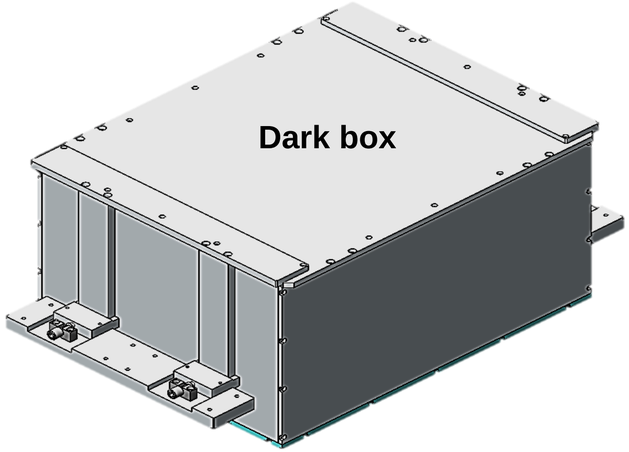
TDC Data buffering (Reference SP)

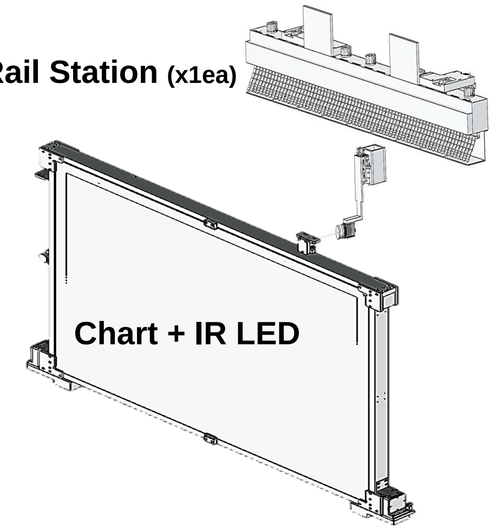


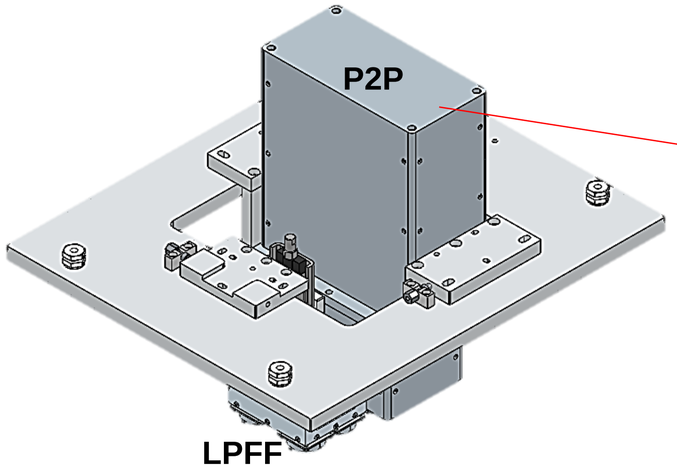


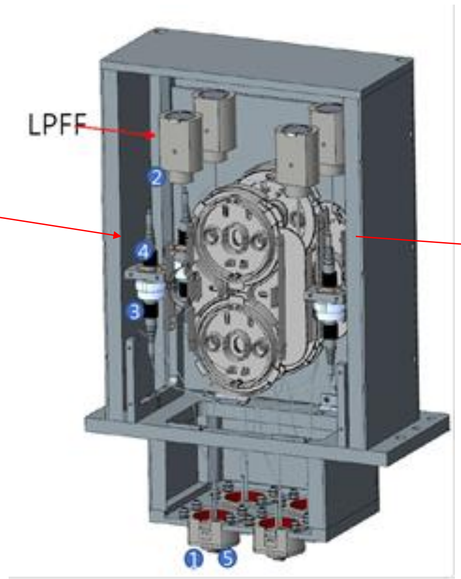
6. CALU 장비 구성

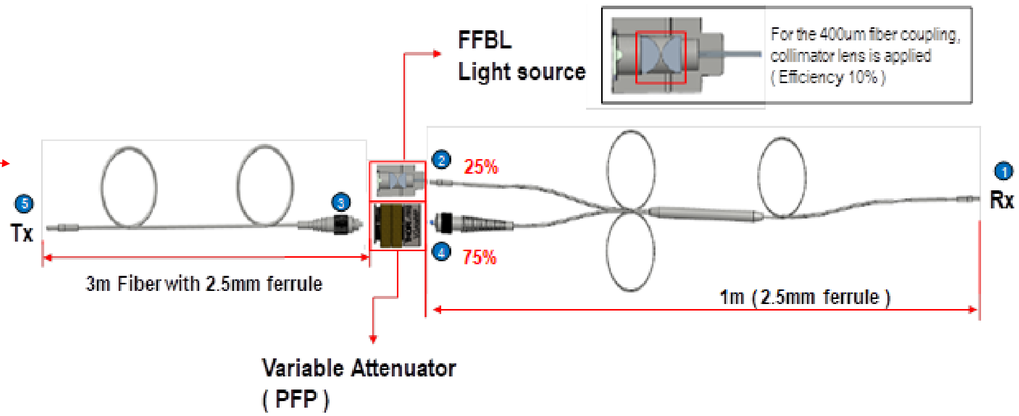












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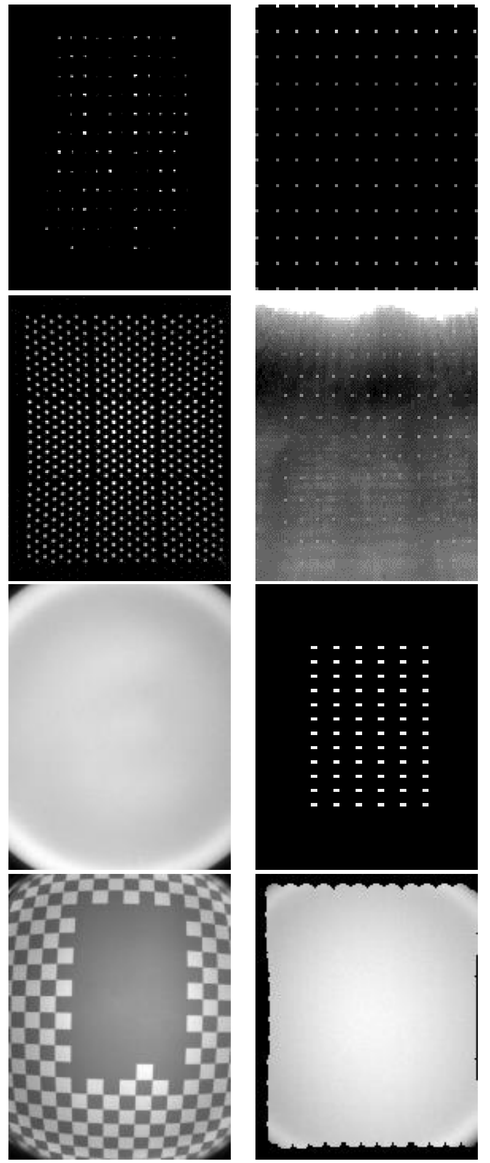
Unified Calibration

7. CALU Test Flow

Test Flow

Dark Box	Reference scan
	Image X4(Spot Finder)
	Gate timing scan
	TOF 30cm
LPFF (Liquid Pipe Flat Field)	DNL_Short mode
	DNL_Normal/Long mode
Rail	TOF 60cm
	TOF 100cm
	Image 80cm/90cm/100cm
	Image X4 100cm
P2P	P2P Scan



X4 : Bank 4개를 전부 사용하면서 180 frame 을 측정(default : 45frame 씩 측정)

8. Stored Items in the NVM(256Kbyte)

- CALU Machine 으로부터 Calibration process 가 끝나면, NVM 에 Cal parameter 가 저장되고, depth 측정 시 보정 (Calibration)에 사용 됨
- NVM에 저장된 정보 중 일부는 Sensor 부팅시에 initial setting 값으로 register 에 복사 됨

NVM Item	Station	Description	Bit 수	참조
PDE 평균, 표준편차		PDE 평균과 표준 편차가 저장되어 있음	16x2	
High & Low temperature VBD model polynomial coefficient		고온/저온에서의 SPAD의 VBD 트렌드를 다항식 fitting 하여 계산하여 적용(polynomial fitting)	32x3x2	Ref-1
Zefram S/W version		이미지처리 s/w 이름(matlab 기반)		
JLPS_VERSION		DLL Version		
pulse shape wide_bin1~64 bank1~4	Dark box	Wide LASER pulse(1.2ns) 인가 시 64bin 까지의 histogram data(Total # of bin = 104) LASER Bank별 performance 가 일정한지 확인 하기 위해 측정	16x64x4	Ref-2
tail_paremeter_wide_amp_A_Bank1~4		30cm black box에서 반사되어 돌아온 LASER의 pulse shape 를 파라미터화 하여 NVM에 저장 (ambient light 없는 이상적인 환경에서의 Pulse shape 획득 목적)	16x4x4	Ref-3
tail_paremeter_wide_decay_B_Bank1~4				
tail_paremeter_wide_amp_C_Bank1~4				
tail_paremeter_wide_decay_D_Bank1~4				
tail_paremeter_narrow_amp_A_Bank1~4				
tail_paremeter_narrow_decay_B_Bank1~4				
tail_paremeter_narrow_amp_C_Bank1~4				
tail_paremeter_narrow_decay_D_Bank1~4				
JLNM_VERSION		DLL Version		
SpotCalibDistance		Dark box 30cm		
SPX001~144, SPY001~144_Bank1~4		Image Super Pixel 좌표(Image X4 를 통해 반사되어 돌아온 LASER Spot Finder	13x144x4	Ref-4
RSPX0, RSPY0, Bank1~4		Reference_0pixel 좌표(stray 분석을 통한 RSPX0 Reference pixel 선정)	8x2x4	Ref-5
RSPX1, RSPY1, Bank1~4		Reference_1pixel 좌표(stray 분석을 통한 RSPX1 Reference pixel 선정)	8x2x4	Ref-5
TRGOUTDLY_wide_Bank1~4		Wide 에서 F-Sync 와 Bank별 LVDS 신호사이의 시간 간격	8x4	Ref-6

8. Stored Items in the NVM(256Kbyte)

NVM Item	Station	Description	Bit 수	참조
TDCTR1C_wide_Bank1~4	Dark box	Wide mode 에서 TDC_ON_Time	16x4	Ref-7
TMINTOF_WPSG_Bank1~4		No idea	8x4	
SETPLSCG_WPSG_Bank1~4		No idea	8x4	
TGDDLY_WPSG_Bank1~4		No idea	8x4	
TDCTR1C_WPSG_bank1~4		WPSG mode 에서 TDC_ON_Time	8x4	Ref-7
gateDelay_Bank1~4		WPSG 에서 SPAD gate_off 시간	16x4	Ref-8
REF_STRAY_DELAY_Bank1~4		WPSG mode 에서 Reference pixel 에서의 bank별 stray light의 delay	16x4	Ref-9
IMG_STRAY_DELAY_Bank1~4		WPSG mode 에서 Image pixel 에서의 bank별 stray light의 delay	16x4	Ref-9
spot_skew_offset_wide		Wide mode 에서의 spot shift 가 있는지 skew 측정	16	Ref-10
Spot 001~144 skew_wide_Bank1~4		Bank1~4 의 Super pixel 의 좌표가 항상 일정한 곳에 오는지 skew 를 통해 확인한다.	Packed 10	Ref-10
spot_skew_offset_narrow		Narrow mode 에서의 spot shift 가 있는지 skew 측정	16	Ref-10
Spot 001~144 skew_narrow_Bank1~4		Bank1~4 의 Super pixel 의 좌표가 항상 일정한 곳에 오는지 skew 를 통해 확인한다.	Packed 10	Ref-10

8. Stored Items in the NVM(256Kbyte)

NVM Item	Station	Description	Bit 수	참조
Temperature - P2P cal mean sensor temp	P2P	Sensor 에 내장된 온도센서에서 측정한 현재 온도 값		
Temperature - P2P cal mean NTC temp		Jasper module NTC 온도센서에서 측정한 현재 온도 값		
Temperature - P2P cal mean driver temp		Jasper module RIKER 에서 측정한 현재 온도 값		
P2P scale - tdc skew		1ps - TDC 의 skew 측정 스케일	8	Ref-11
P2P scale - imaging pixels skew		1ps - Image pixel 의 skew 측정 스케일	8	Ref-11
P2P scale - reference pixels skew		1ps – reference pixel 의 skew 측정 스케일	8	Ref-11
E to A TDC skew - SP 001~SP144		Image super pixel 0~144의 E 와 A TDC 간의 skew	8+128	Ref-12
S to A TDC skew - SP 001~SP144		Image super pixel 0~144의 S 와 A TDC 간의 skew	8+128	Ref-12
SE to A TDC skew - SP 001~SP144		Image super pixel 0~144의 SE 와 A TDC 간의 skew	8+128	Ref-12
West reference (ref 0) TDC skew - E to A		Reference pixel 0 의 Anchor 와 East 간 TDC skew	8+128	Ref-13
East reference (ref 1) TDC skew - E to A		Reference pixel 1 의 Anchor 와 East 간 TDC skew	8+128	Ref-13
Patch 000~ Patch142 skew (A to mean of patch), pixel index 1~217		Anchor pixel과 각 patch zone 의 평균과의 skew	8x425	Ref-12
Ref pixel 0~13 skew - RSPX0 - bank 1~4 - wide pulse		Wide pulse 를 bank별로 가동하면서 Reference pixel-0 의 0~13pixel 간 skew 측정	(8+128)x4	Ref-13
Ref pixel 126~139 skew - RSPX1 - bank 1~4 - wide pulse		Wide pulse 를 bank별로 가동하면서 Reference pixel-1 의 126~139pixel 간 skew 측정	(8+128)x4	Ref-13
Ref pixel 0~13 skew - RSPX0 - bank 1~4 - narrow pulse		Narrow pulse 를 bank별로 가동하면서 Reference pixel-0 의 0~13pixel 간 skew 측정	(8+128)x4	Ref-13
Ref pixel 126~139 skew - RSPX1 - bank 1~4 - narrow pulse		Narrow pulse 를 bank별로 가동하면서 Reference pixel-1 의 126~139pixel 간 skew 측정	(8+128)x4	Ref-13

8. Stored Items in the NVM(256Kbyte)

NVM Item	Station	Description	Bit 수	참조
EFL	Rail	Sensor lens effective focal length	32	Ref-14
PPX, PPY			32	
coeffData p1~p4			32	
Distortion X,Y		Rx lens distortion X,Y	32	

9. NVM Item 참조 설명

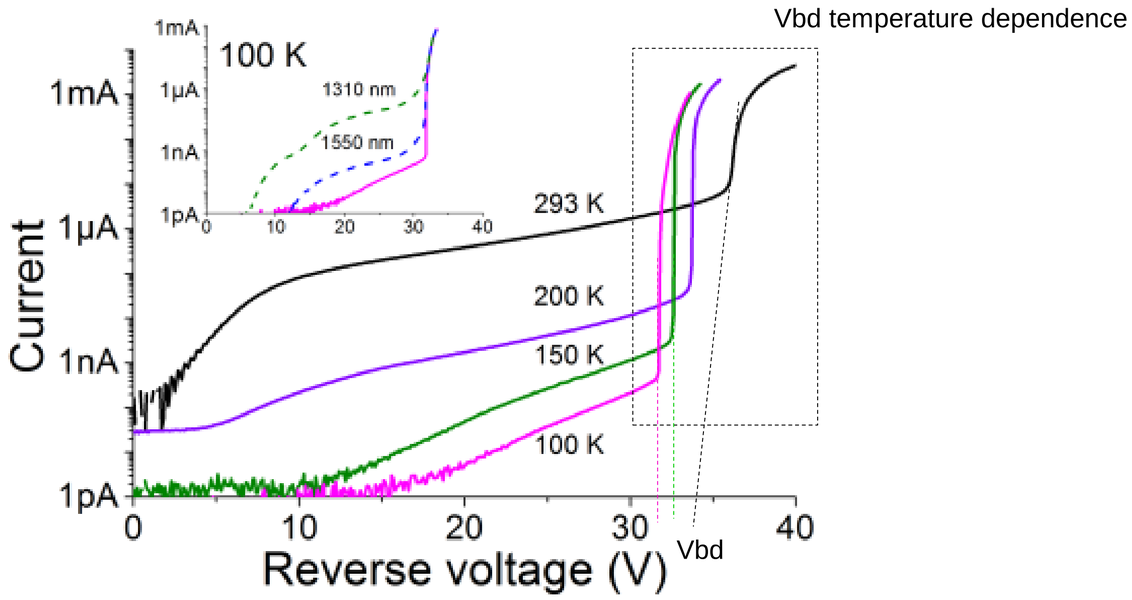
Ref-1 : High & Low temperature VBD Model

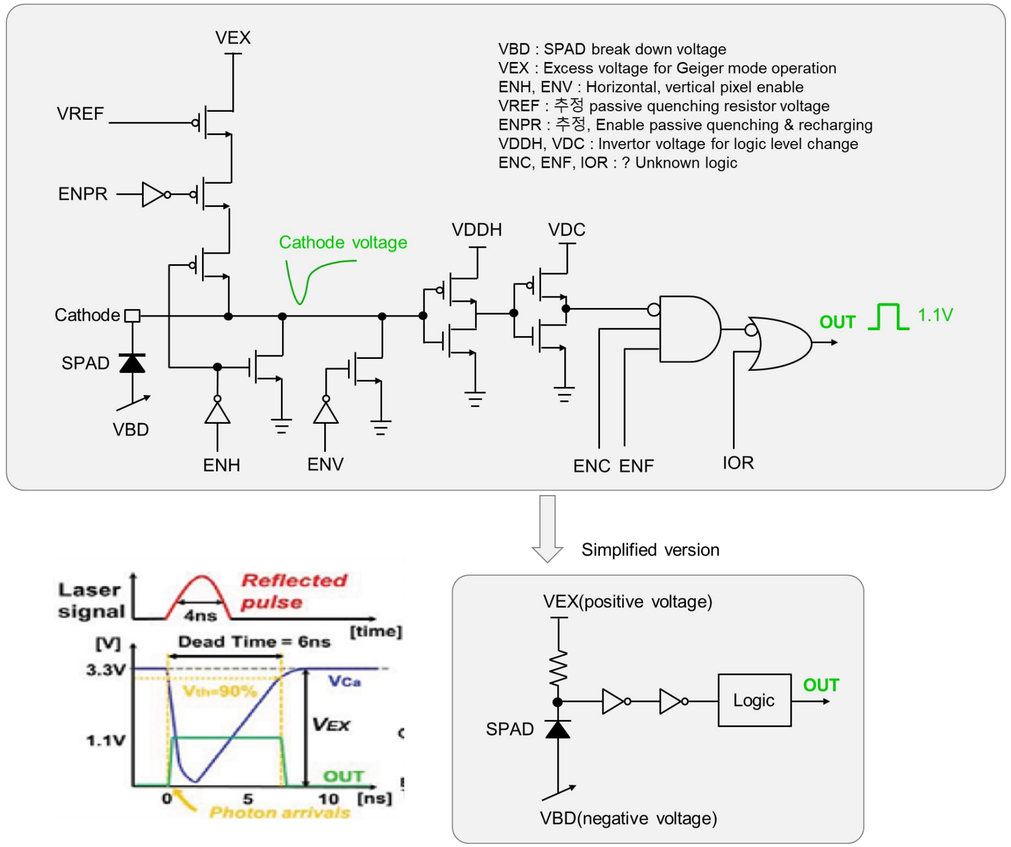
- VBD (SPAD breakdown 전압) 설정 시 Sensor 내부에 있는 온도센서로 부터 Sensor 온도를 읽고 이를 SPAD VBD 다항식에 넣어 최종적으로 인가할 VBD 전압을 설정 함, 다항식의 계수들은 NVM에 저장되어 있음

  전압 설정 예시

VBD(V) : - 20.159113V (pTempCoeff[2]:0.000000, pTempCoeff[1]:0.020866, pTempCoeff[0]:19.202517, fPeriscopeTemp:40.116463, periscope_temperature:134)

Example Graph





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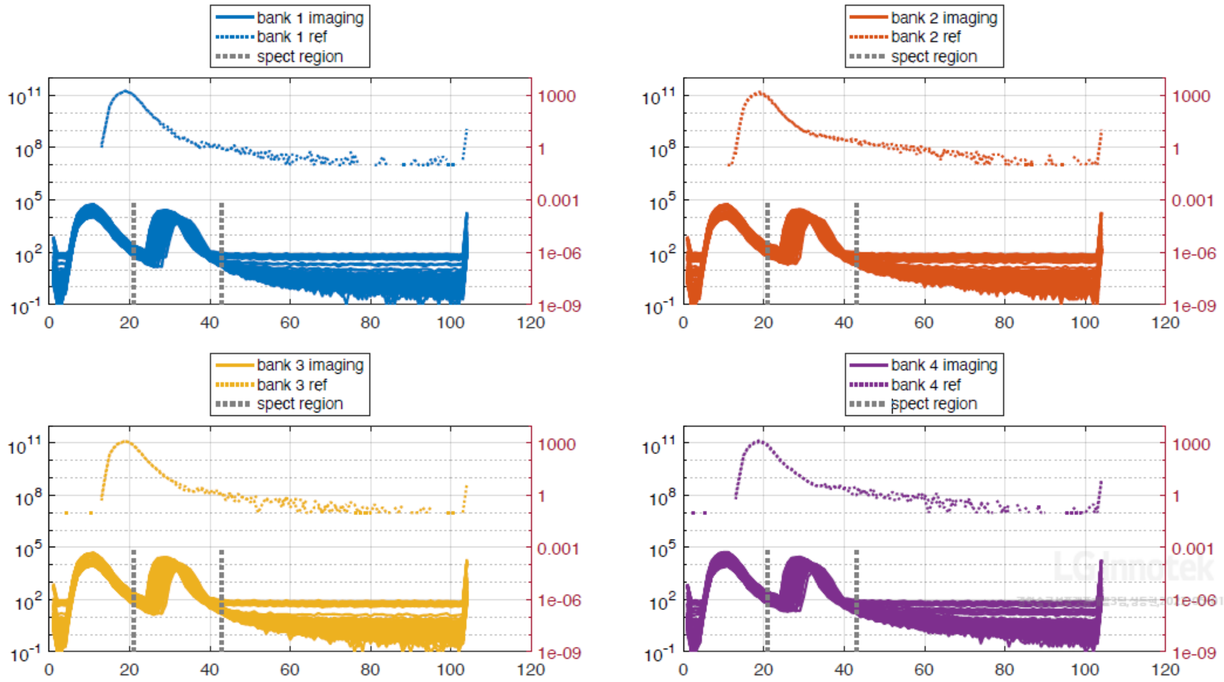
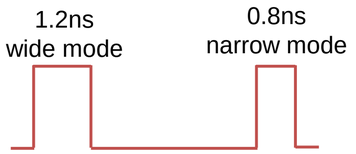
Unified Calibration

Ref-2 : pulse shape wide bank1~4

- Per bank 특성이 일정한지 확인, bank 별 144 super pixel 중 maximum histogram 을 frame 별로 비교하여, 갑작스러운 drop 이나 이상점이 있는지 확인하기 위함
- Ambient light 가 없는 30cm 에서 stray 와 TOF 파형 확보





WPSG & NPSRF

WPSG - Wide Pulse, Soft Gating
"Wide pulse" indicates a nominal Tx pulse width.
"Soft-gating" indicates Periscope is operating in gated mode where the pixels are disabled for a short amount of time after the Tx fires to avoid triggering arrival events from the module's internal stray.

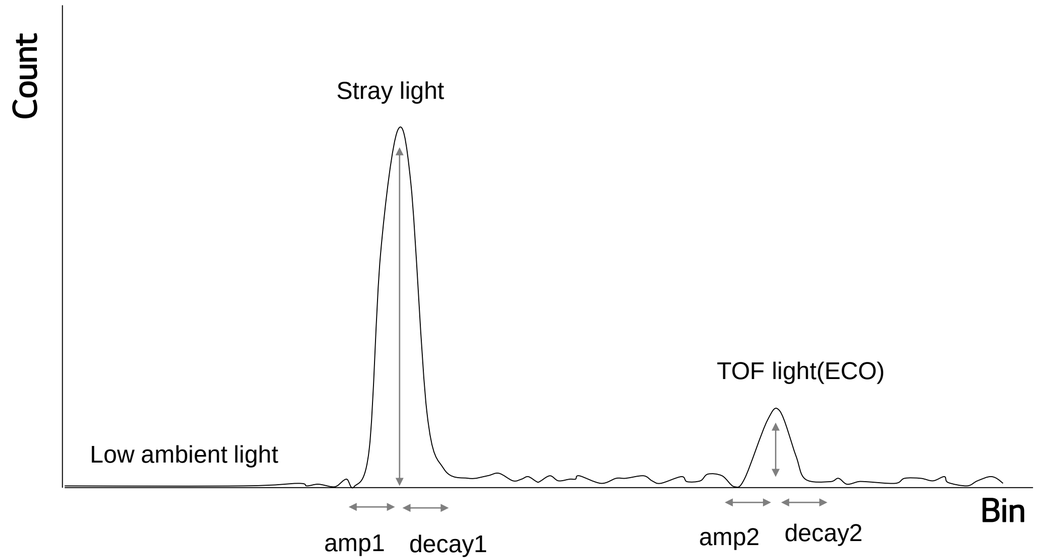
NPSRF - Narrow Pulse, Short Range, Free-running

- Narrow pulse indicates a shorter Tx pulse width nominal width. The reduced pulse width helps to provide additional separation between the signal caused by internal stray reflections and an echo from a target at close range
- Short Range refers the to distribution of Periscope's TDC bin widths. In short- range mode, all bins are uniform in duration of a certain range in ps. This is opposed to the long range modes where higher TDC bins have long ps. This provides allows for greater temporal resolution of targets at close range, but limits to the maximum detection range.
- Free-running indicates Periscope is not gating the pixel on time. They are always active and will trigger detection events from close range echos as well as the internal stray.1

Unified Calibration

Ref-3 : tail_parameter amp, decay bank1~4

- 30cm Dark box 에서의 Stray light 와 TOF light 측정하여, amplitude(rising) 와 decay light 의 기울기를 측정, Ambient light 가 없는 이상적인 상황에서의 Stray light, TOF light 의 특성 파라미터 추출 목적



Test Items	Upper Limit	Lower Limit	DUT No.1
CALU_PS_wide_tail_param_amp1_per_bank_1	4	0	0.540297
CALU_PS_wide_tail_param_amp1_per_bank_2	4	0	0.265291
CALU_PS_wide_tail_param_amp1_per_bank_3	4	0	0.371159
CALU_PS_wide_tail_param_amp1_per_bank_4	4	0	0.211838
CALU_PS_wide_tail_param_decay1_per_bank_1	-0.1	-1.5	-0.642087
CALU_PS_wide_tail_param_decay1_per_bank_2	-0.1	-1.5	-0.547873
CALU_PS_wide_tail_param_decay1_per_bank_3	-0.1	-1.5	-0.58513
CALU_PS_wide_tail_param_decay1_per_bank_4	-0.1	-1.5	-0.528699
CALU_PS_wide_tail_param_amp2_per_bank_1	0.04	0	0.000657
CALU_PS_wide_tail_param_amp2_per_bank_2	0.04	0	0.000142
CALU_PS_wide_tail_param_amp2_per_bank_3	0.04	0	0.000381
CALU_PS_wide_tail_param_amp2_per_bank_4	0.04	0	0.000068
CALU_PS_wide_tail_param_decay2_per_bank_1	-0.002	-0.4	-0.070492
CALU_PS_wide_tail_param_decay2_per_bank_2	-0.002	-0.4	-0.057036
CALU_PS_wide_tail_param_decay2_per_bank_3	-0.002	-0.4	-0.068052
CALU_PS_wide_tail_param_decay2_per_bank_4	-0.002	-0.4	-0.050775

Unified Calibration

Ref-4 : SPX SPY 1~144, Bank1~4

- Image X4 측정으로 180 frame 의 TOF Data 를 측정, Spot finder 기능을 통해 Image pixel 영역에서 super pixel detection, super pixel 좌표를 NVM 에 저장

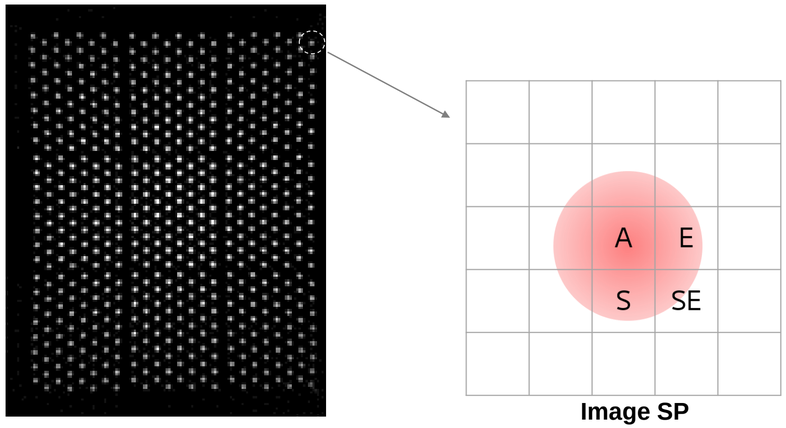
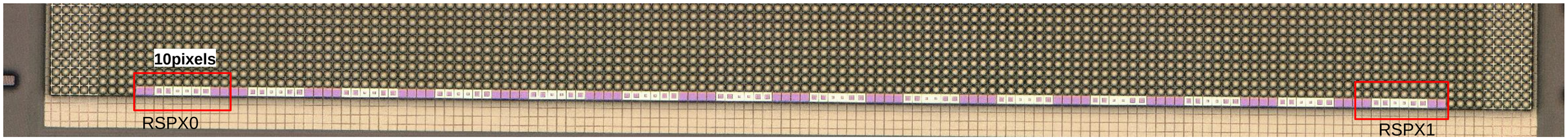
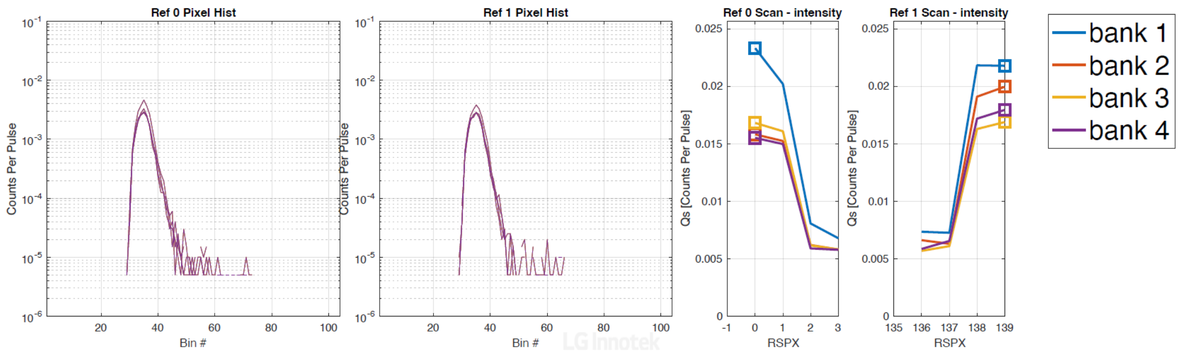


Image SP

Ref-5 : RSPX0, RSPX1

- Bank별로 LASER 를 켜면서 Reference pixel 에 들어오는 stray light 의 histogram 을 분석하여 최적의 reference pixel 을 선정



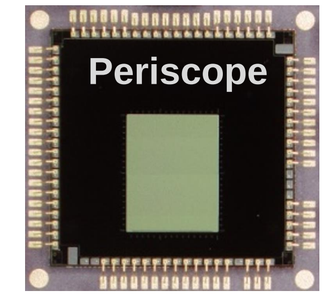


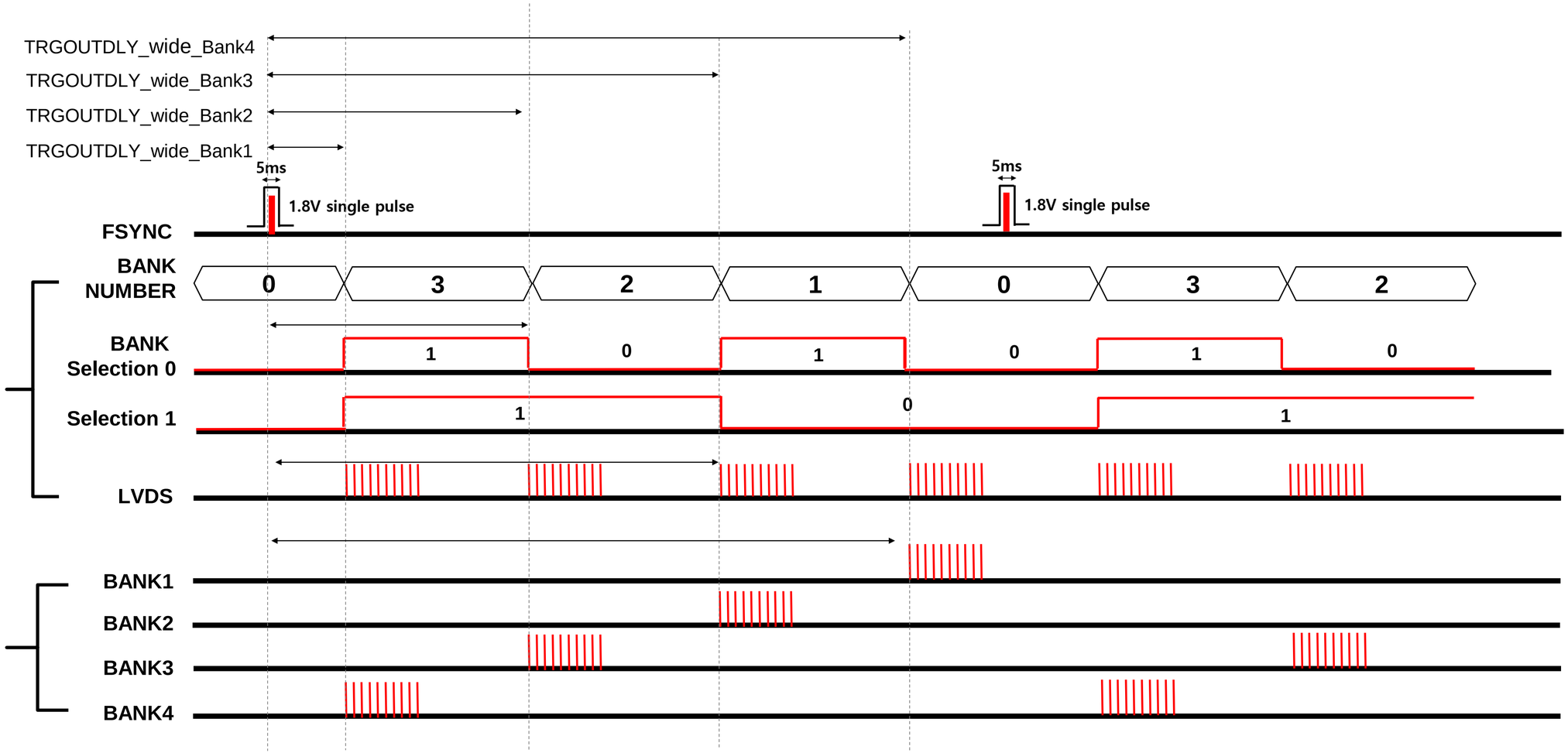
Test Items	Values
CALU_RefSel_RSPX0_1	0
CALU_RefSel_RSPX0_2	0
CALU_RefSel_RSPX0_3	0
CALU_RefSel_RSPX0_4	0
CALU_RefSel_RSPX1_1	139
CALU_RefSel_RSPX1_2	138
CALU_RefSel_RSPX1_3	138
CALU_RefSel_RSPX1_4	138

Unified Calibration

Ref-6 : TRGOUTDLY

- Wide pulse(1.2ns) 인가 시 Fsync 와 TRGOUT(LVDS) 사이의 Time delay



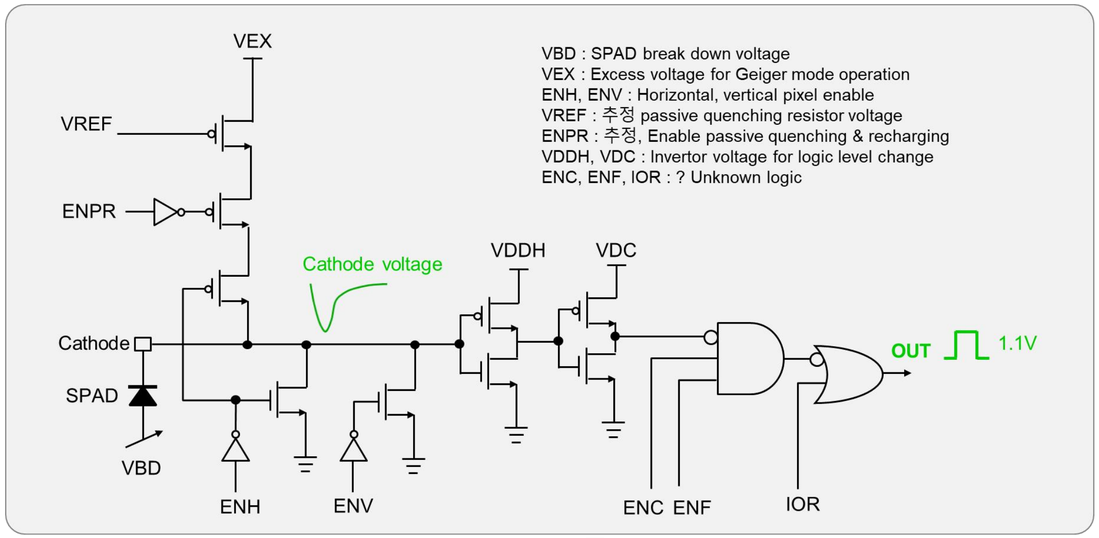


Unified Calibration

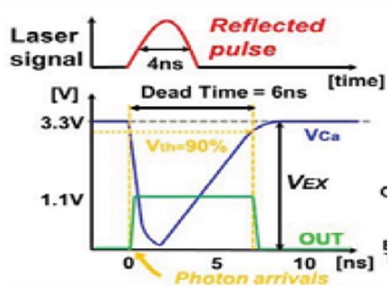
Ref-7 : TDCTR1C in WPSG, Wide mode

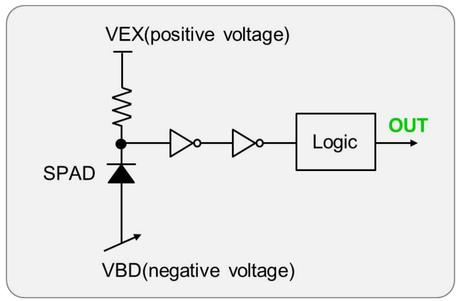
- TDCTR1 설정을 통해 TDC ON Time(duration) 제어

Test Items	unit	Value
CALU_WPSG_TDCTR1C_1	[LSBmin]	35
CALU_WPSG_TDCTR1C_2	[LSBmin]	35
CALU_WPSG_TDCTR1C_3	[LSBmin]	35
CALU_WPSG_TDCTR1C_4	[LSBmin]	34



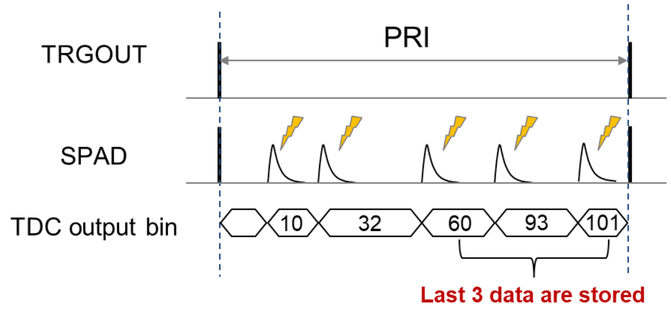
Simplified version



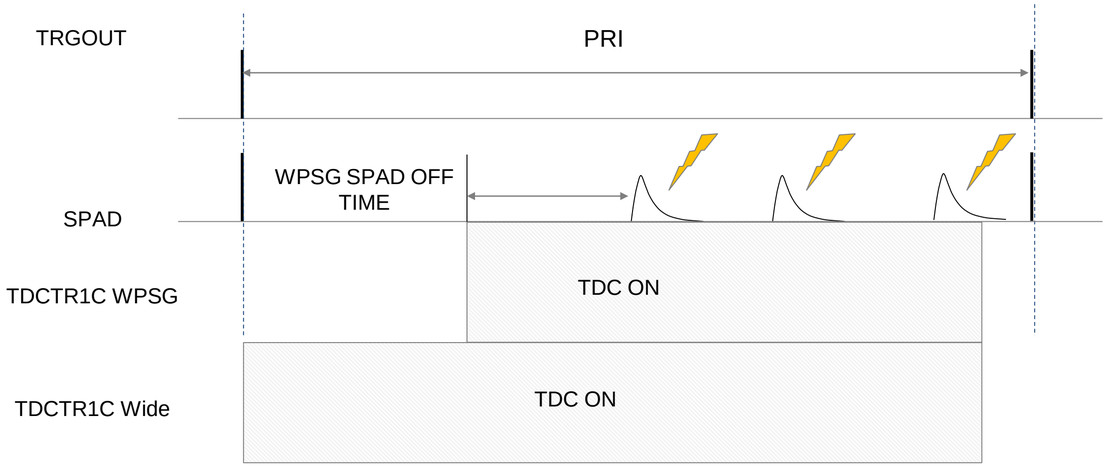


Spot Position Estimation Counter(SPEC)

TDC Data buffering (Image SP)



TDC Data buffering (Image SP)



Unified Calibration

Ref-8 : gateDelay

- WPSG mode 에서 image pixel SPAD gate off 시간

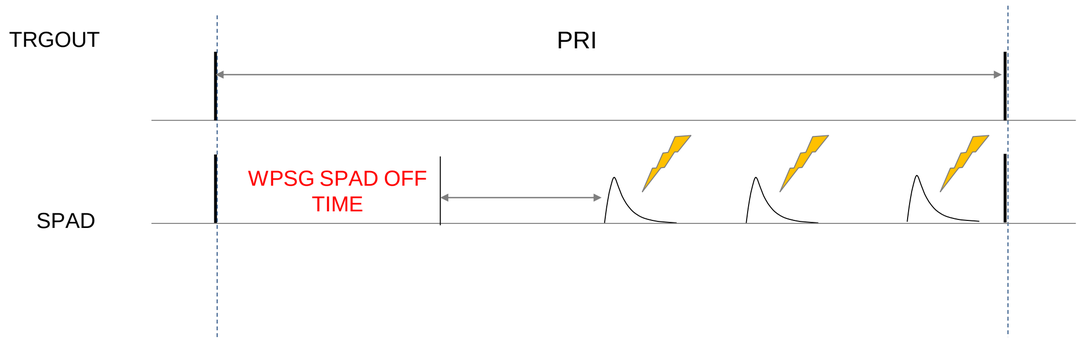
Test Items	unit	Value
CALU_WPSG_gateDelay_1	[ps]	3958
CALU_WPSG_gateDelay_2		3958
CALU_WPSG_gateDelay_3		3958
CALU_WPSG_gateDelay_4		3958

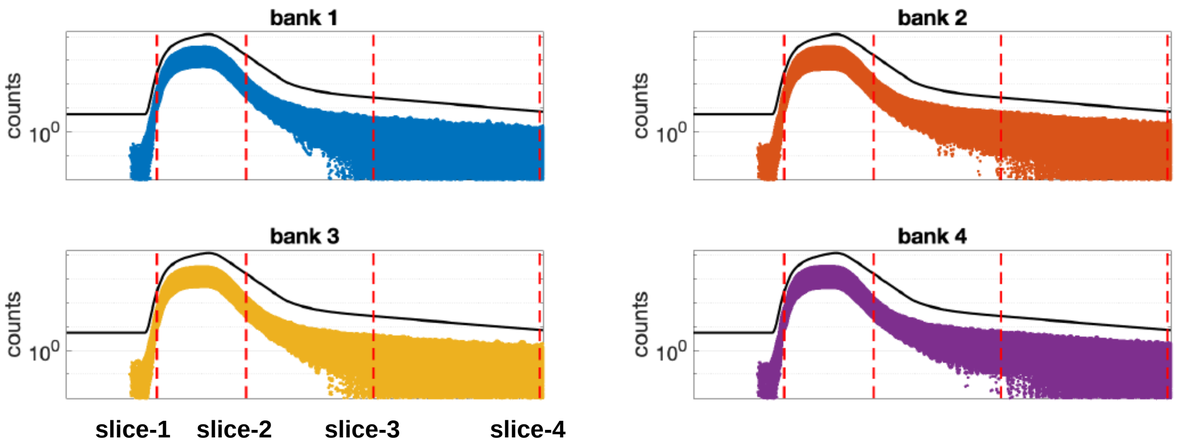
Ref-9 : Reference & Image pixel Stray delay

- Slice-4 이후에 image & ref pixel 에서 stray light 가 완전히 decay 하여 소멸할 때 까지 delay time

Test Items	unit	Value
CALU_WPSG_imgStrayDelay_1	[ps]	1436
CALU_WPSG_imgStrayDelay_2		1446
CALU_WPSG_imgStrayDelay_3		1442
CALU_WPSG_imgStrayDelay_4		1457
CALU_WPSG_refStrayDelay_1		1531
CALU_WPSG_refStrayDelay_2		1507
CALU_WPSG_refStrayDelay_3		1504
CALU_WPSG_refStrayDelay_4		1503

TDC Data buffering (Image SP)

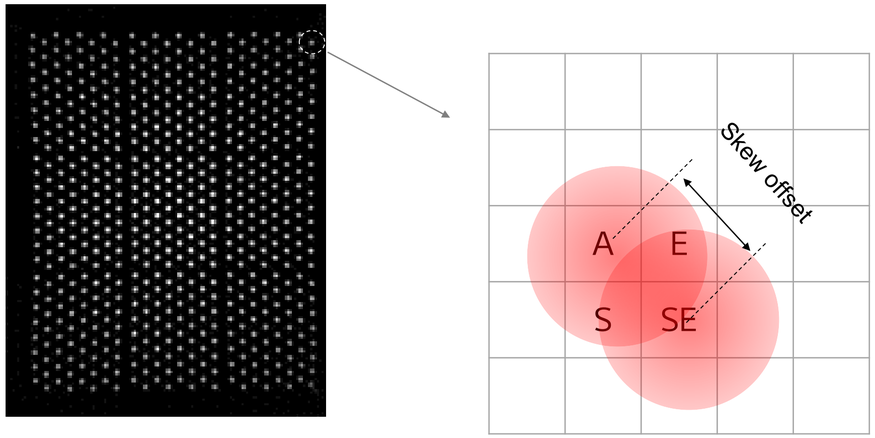




Unified Calibration

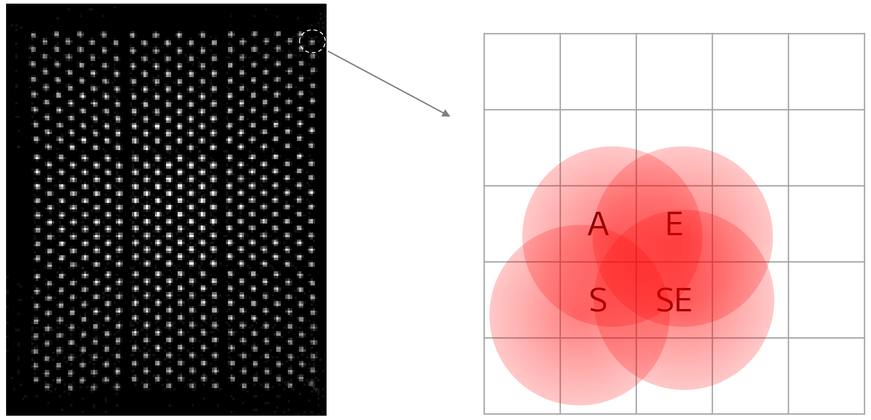
Ref-10(spot skew offset wide & narrow)

- Wide, Narrow mode 에서 spot anchor pixel shift 가 있는지 skew 계산



Ref-10(spot skew offset wide & narrow)

- Wide, Narrow mode 에서 spot 의 위치 변화가 있는지 skew 계산

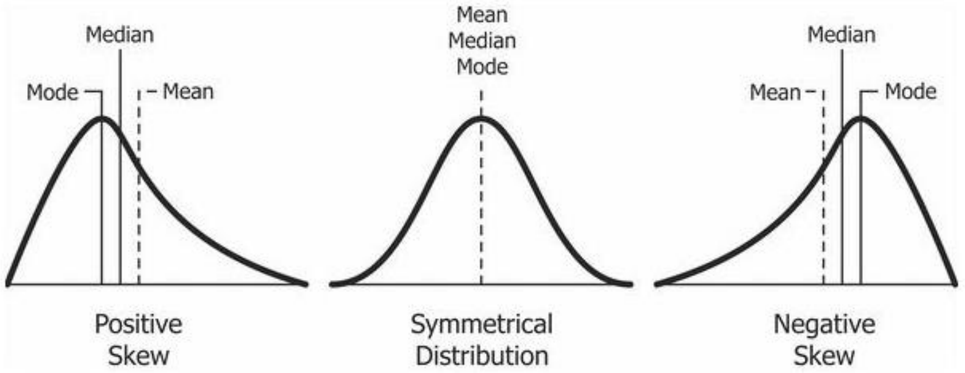


Ref-11 TDC, Image, Ref skew scale

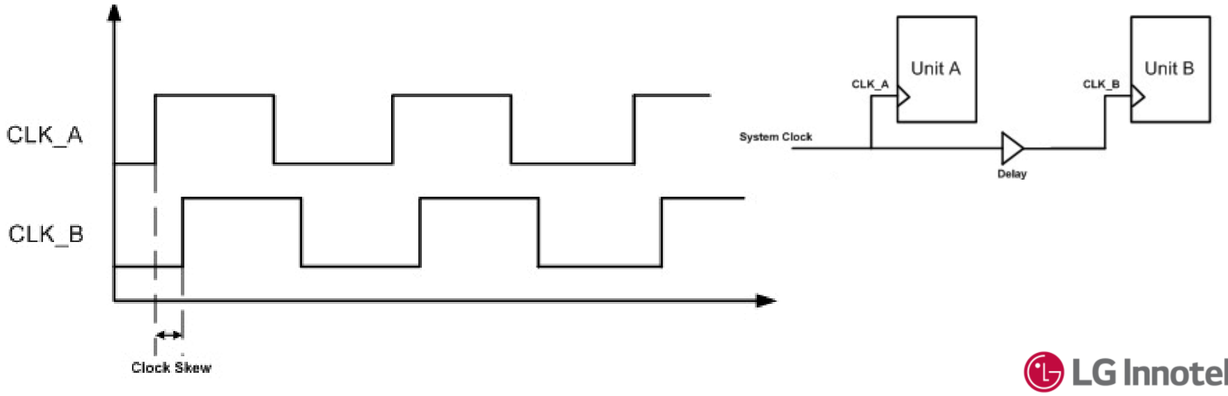
- P2P skew 측정 시 측정 scale 설정 값 – 1ps 로 설정 됨

Test Items	USL	LSL	unit	Value
CALU_P2P_img_skew_scale	4.9	0.1	[ps]	1
CALU_P2P_ref_skew_scale	4.9	0.1	[ps]	1
CALU_P2P_tdc_skew_scale	4.9	0.1	[ps]	1

통계적인 의미에서의 skew



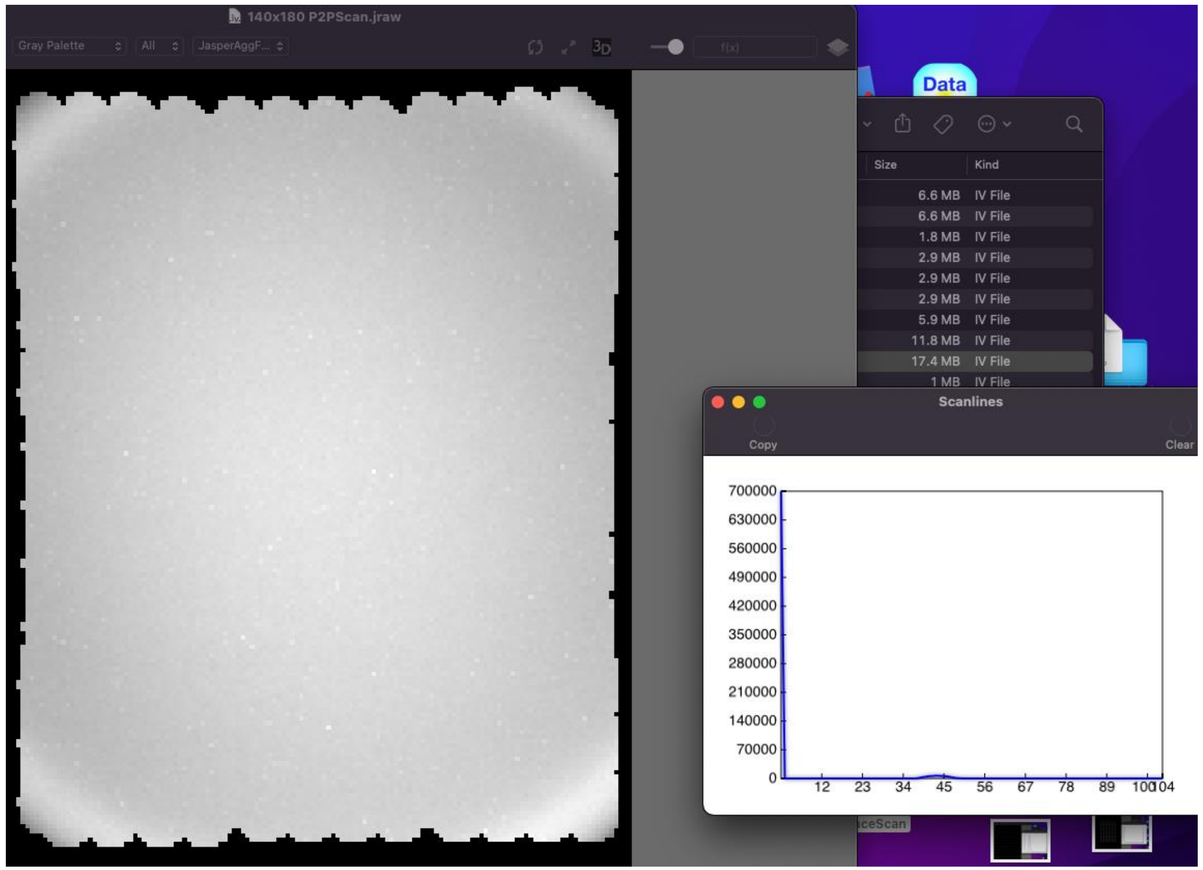
Digital 회로에서의 skew



Unified Calibration

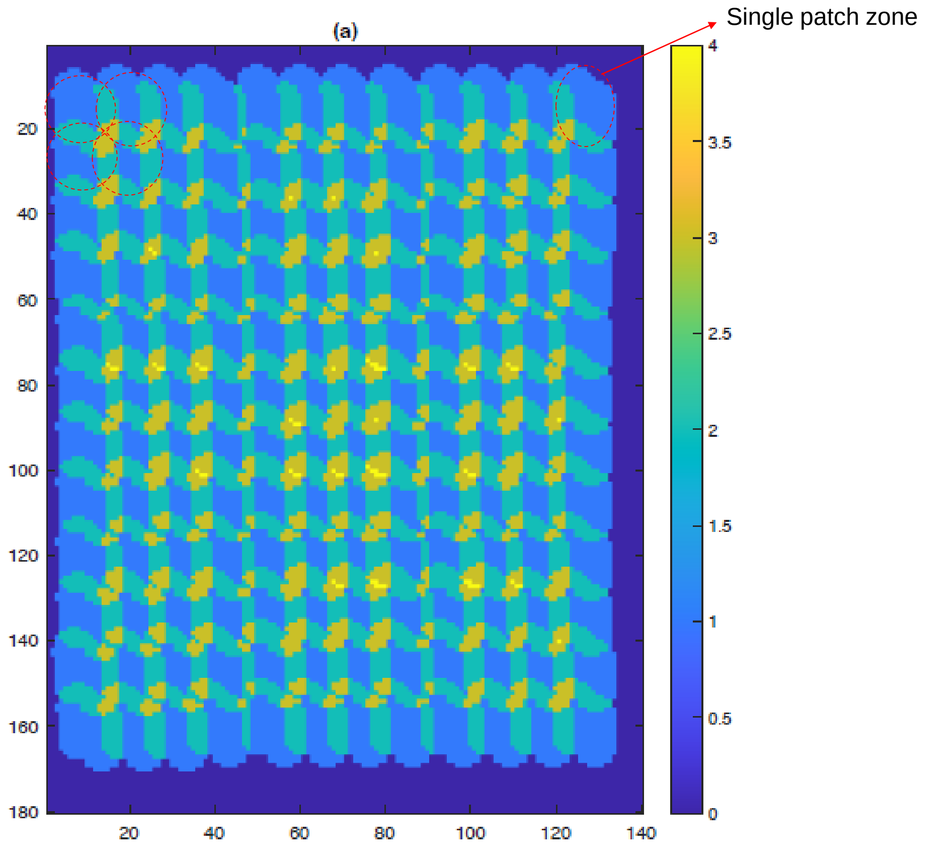
Ref-12 TDC A to E, A to S, A to SE skew

- P2P 측정 시 bank 1개만 사용하여 diffuser 를 통해 dot 을 확대하여 전체 영역에 퍼지게 함(전체 pixel 에 동일 시간에 photon 이 도달하도록 함)
- 동일시간에 도달한 photon 에 대해 TDC 에서 ADC 진행
- Anchor to East, Anchor to South, Anchor to SouthEast 간의 TDC skew 계산
- P2P 에서는 super pixel 외에 전체 pixel 에 대해 TDC 진행(262 frame 소요 됨)



P2P Image

Test Items	USL	LSL	unit	Value
CALU_P2P_tdc_sigma_E2A	15	0.1	[ps]	2.45655
CALU_P2P_tdc_sigma_SE2A	15	0.1	[ps]	2.53951
CALU_P2P_tdc_sigma_S2A	15	0.1	[ps]	2.51052



Total 144 개 patch zone

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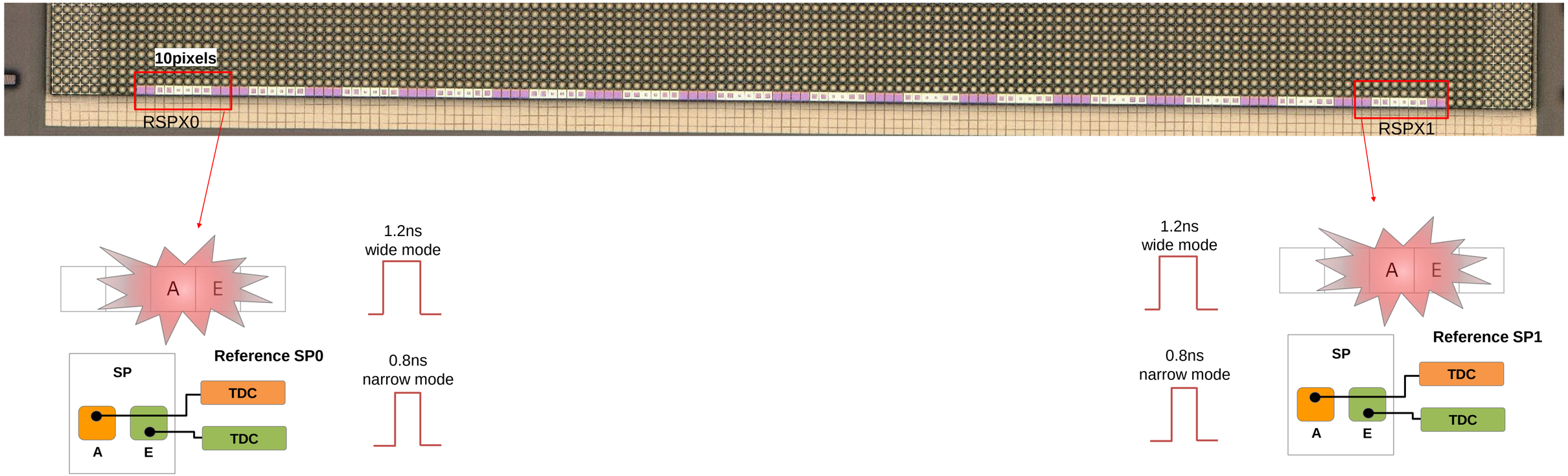
Unified Calibration

Test Items	Unit	Value
CALU_P2P_img_skew_sigma_patch_maxVal	[ps]	11.024
CALU_P2P_img_skew_sigma_patch_minVal		7.80781
CALU_P2P_img_skew_99p_patch_maxVal		29.3341
CALU_P2P_img_skew_99p_patch_minVal		18.2994
CALU_P2P_img_skew_sigma_frame		9.14164
CALU_P2P_img_skew_99p_frame		23.4036
CALU_P2P_img_skew_99p7_superpixel		38.137
CALU_P2P_img_skew_range_1pix_single_95p		34.219
CALU_P2P_img_skew_range_1pix_single_max		41.939
CALU_P2P_img_skew_range_1pix_super_95p		16.3674
CALU_P2P_img_skew_range_1pix_super_max		21.9583
CALU_P2P_img_skew_range_2pix_single_95p		40.9072
CALU_P2P_img_skew_range_2pix_single_max		48.3223
CALU_P2P_img_skew_range_2pix_super_95p		21.7616
CALU_P2P_img_skew_range_2pix_super_max		26.1174
CALU_P2P_img_skew_range_3pix_single_95p		46.3922
CALU_P2P_img_skew_range_3pix_single_max		59.1056
CALU_P2P_img_skew_range_3pix_super_95p		27.6425
CALU_P2P_img_skew_range_3pix_super_max		39.993
CALU_P2P_img_skew_range_4pix_single_95p		50.4424
CALU_P2P_img_skew_range_4pix_single_max		59.1056
CALU_P2P_img_skew_range_4pix_super_95p		31.9474
CALU_P2P_img_skew_range_4pix_super_max		43.6193

Unified Calibration

Ref-13 Reference pixel skew

- Wide mode bank 별로 VCSEL 가동하면서 RSPX0-0~13pixel, PSPX1-126~139pixel 의 TDC skew 측정
- Narrow mode bank 별로 VCSEL 가동하면서 RSPX0-0~13pixel, PSPX1-126~139pixel 의 TDC skew 측정

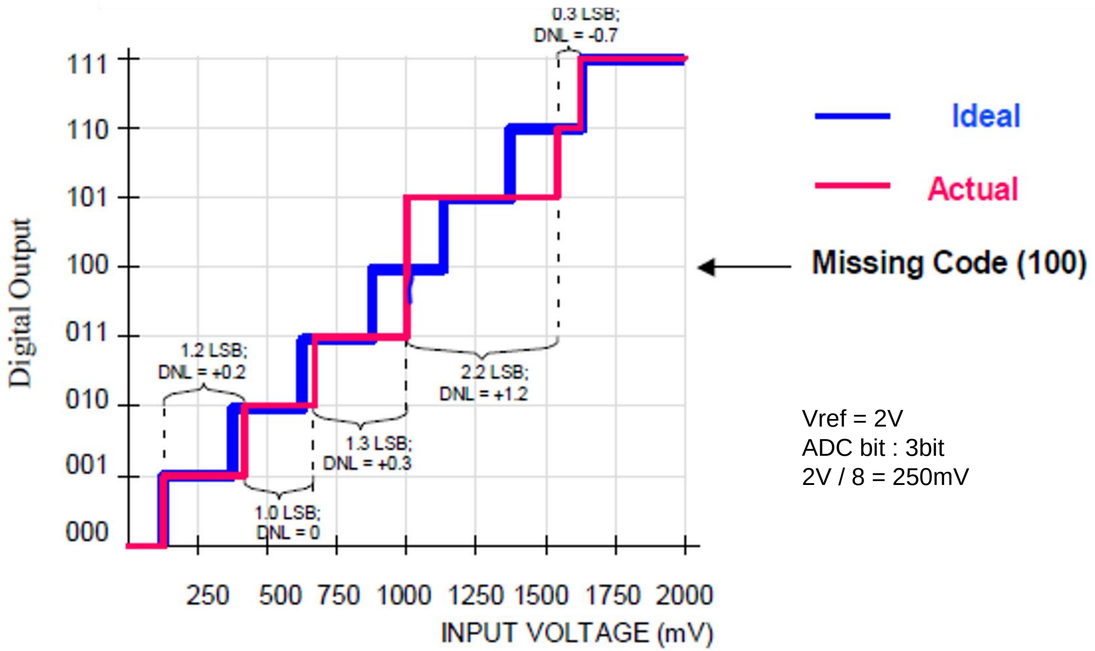


Unified Calibration

ADC-DNL/INL

- DNL/INL : Analog to Digital Convertor(ADC) 에서 임의의 입력 신호를 디지털화 하는 과정에서 발생하는 오차

DNL(Differential nonlinearity)

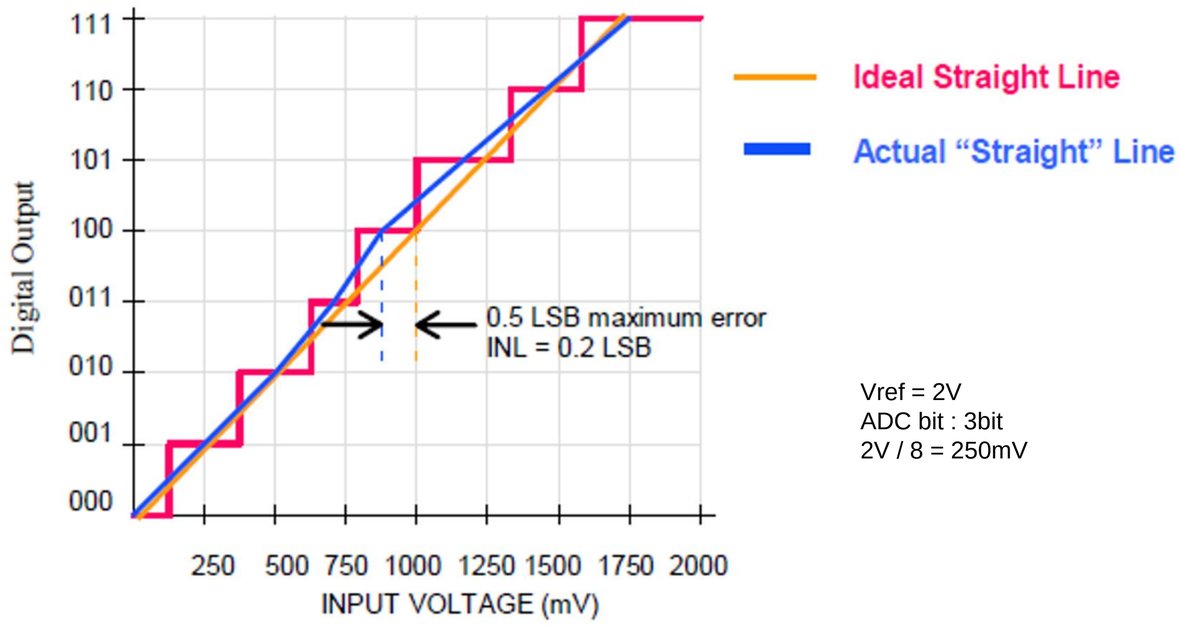


Vref = 2V
ADC bit : 3bit
2V / 8 = 250mV

$$DNL = \frac{(V_{measure} - V_{ideal}) - LSB}{LSB} - 1$$

DAC가 1증가시 변화하는 실측값과 이상적인 값의 차이를 LSB로 나누었을때의 비율(%)

INL(Integral nonlinearity)



Vref = 2V
ADC bit : 3bit
2V / 8 = 250mV

$$INL = \frac{V_{mesure} - V_{ideal}}{LSB}$$

이상적인 값과 실측값의 차이

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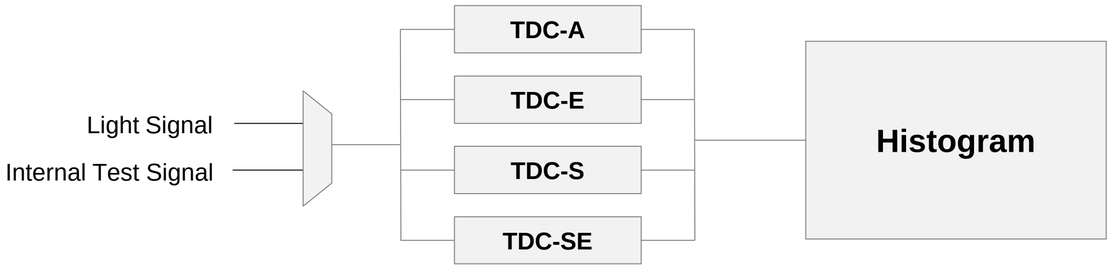
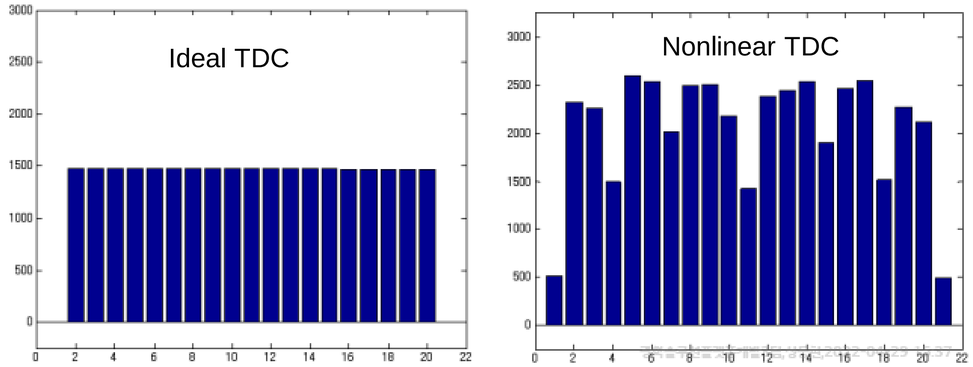
Unified Calibration

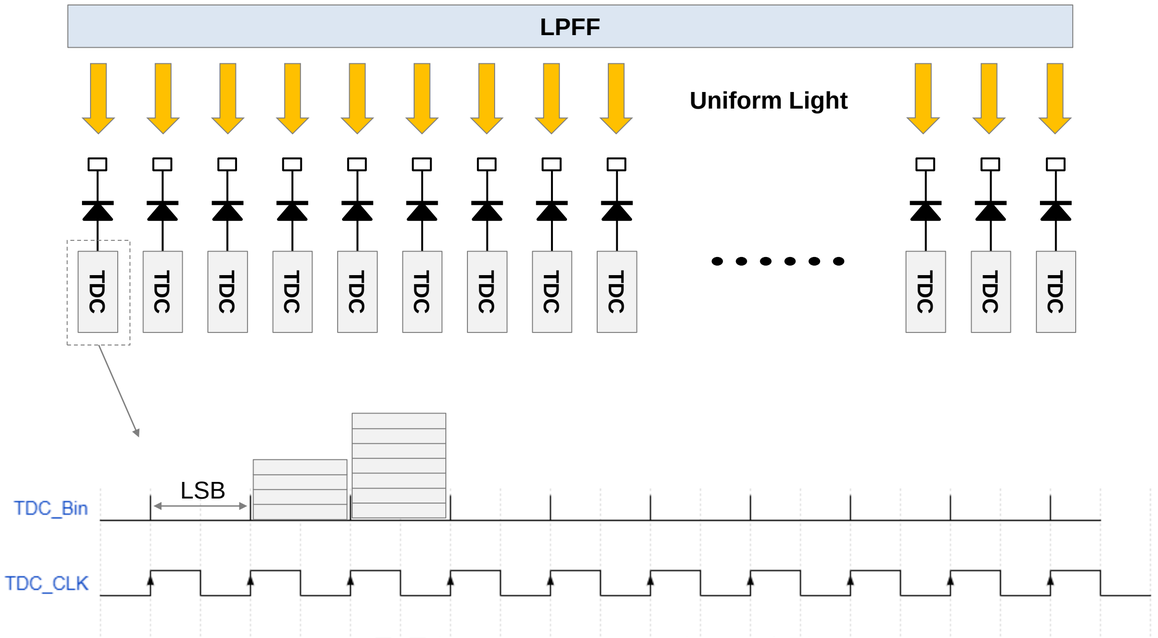
TDC Debug mode – DNL/INL Calibration

- TDC debug mode 를 통해 TDC 의 DNL(Differential nonlinearity) /INL(integral nonlinearity) Calibration 가능
- LPFF 를 통해 균일화 IR 광원을 CW(continuous wave) 형태로 Sensor 에 입사하면 TDC 에서 Digitized 하여 Histogram bin 에 accumulation 함

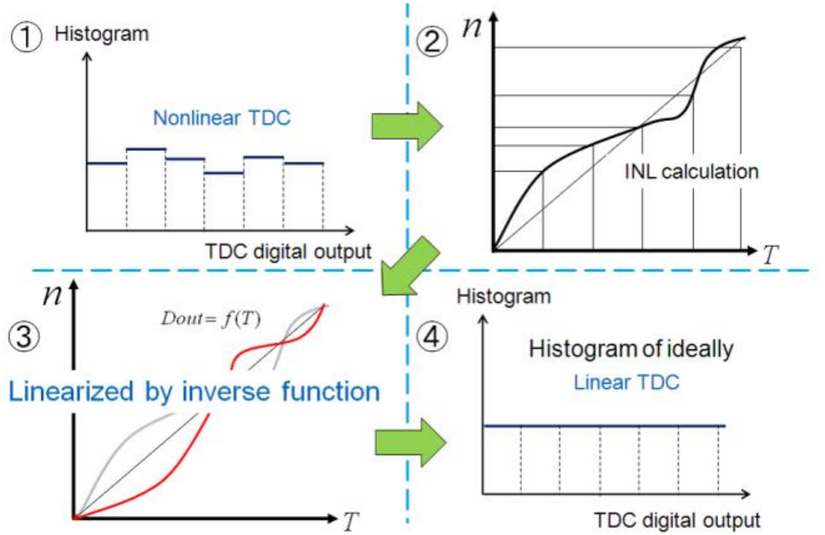


<TDC Debug mode>





<LPFF 를 통한 Super Pixel TDC의 DNL 측정>



<TDC Calibration >

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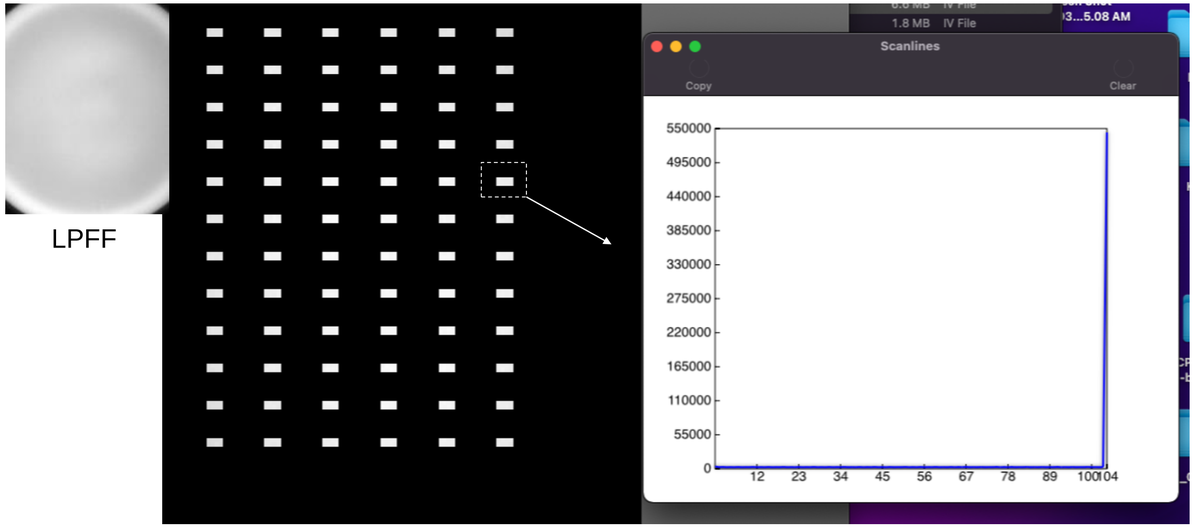
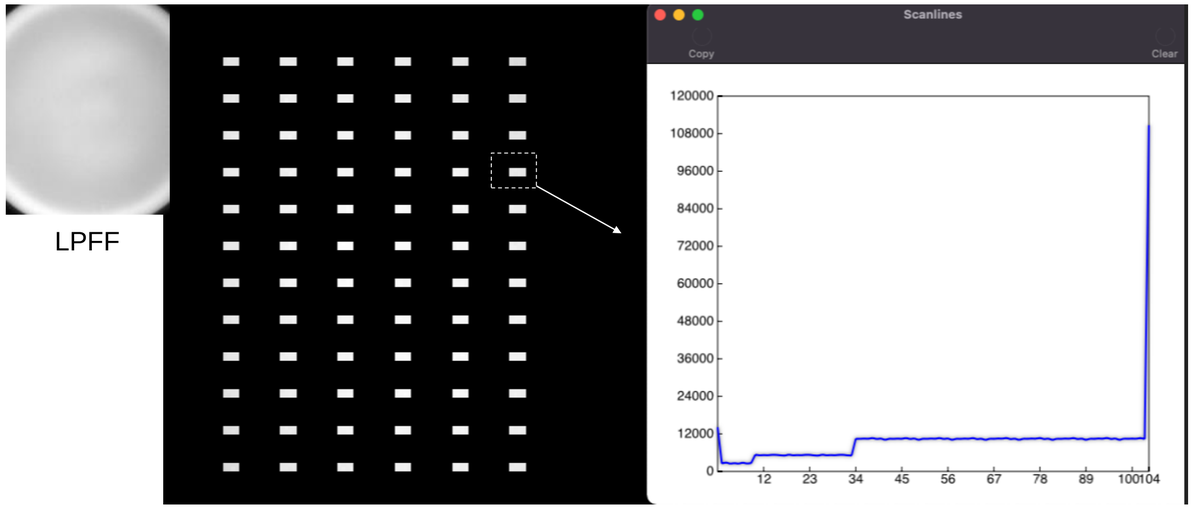
Unified Calibration

Jasper TDC measurement result

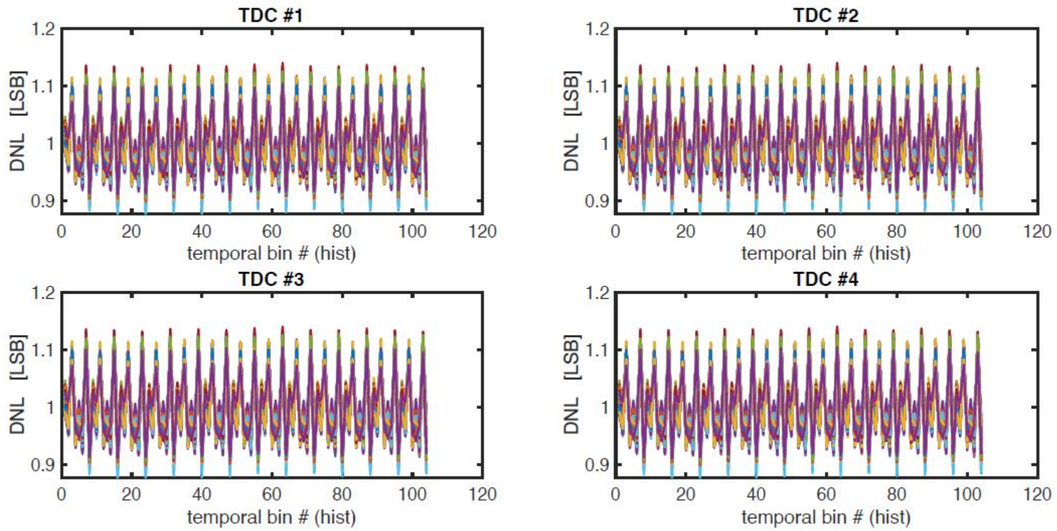
Short Rang Mode



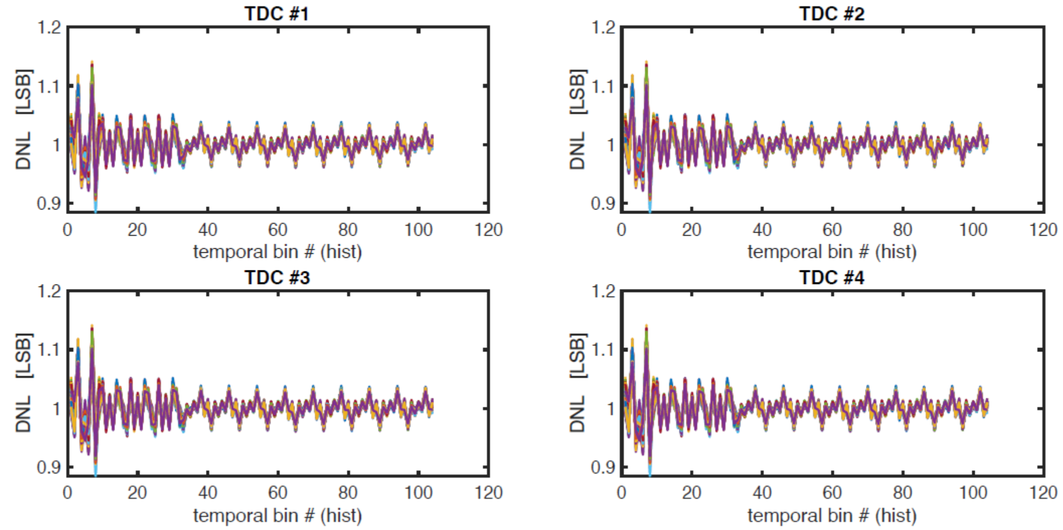
Normal/Long Rang Mode



DNL-Short Rang Mode



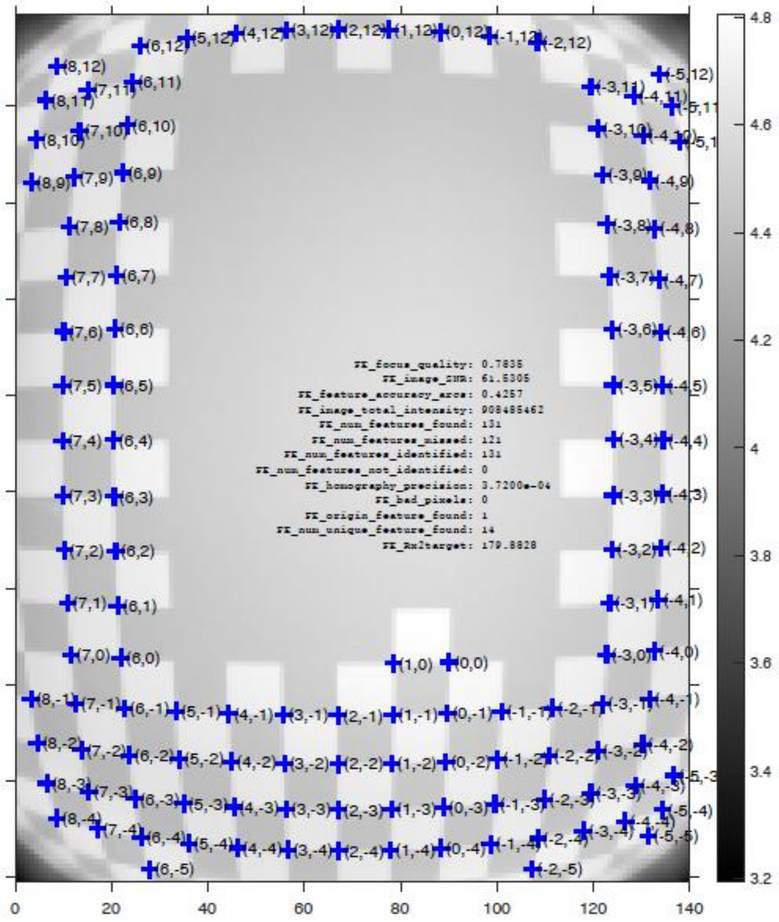
DNL-Normal/Long Rang Mode



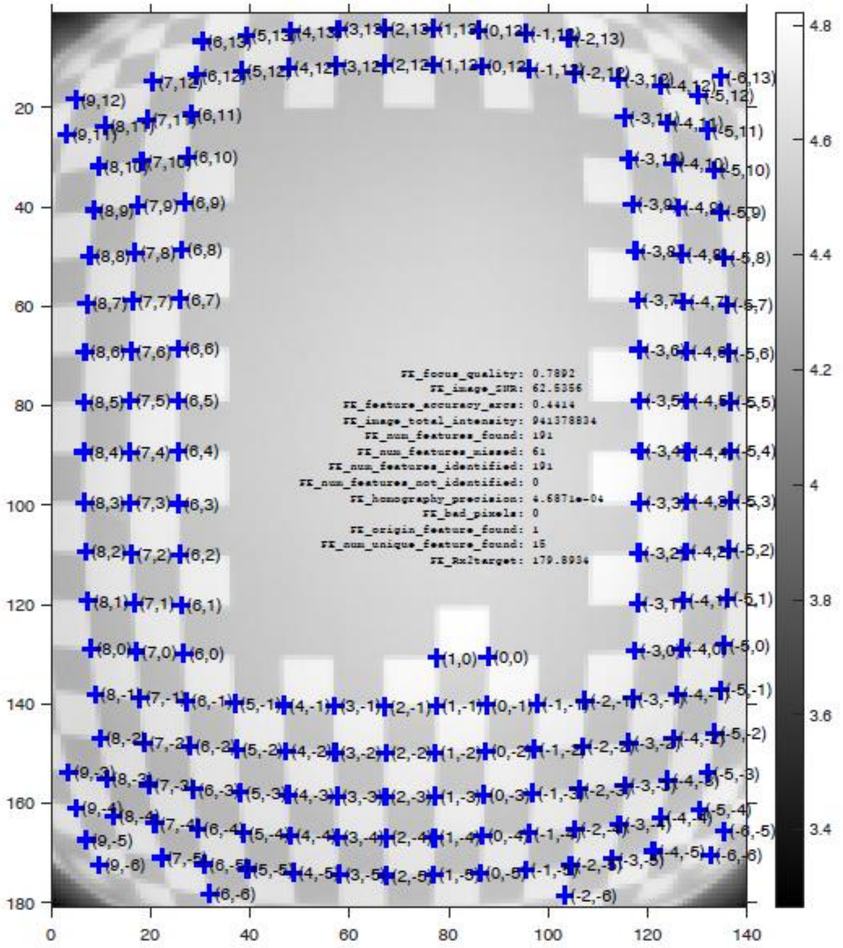
Unified Calibration

Ref-14 : Rx lens distortion

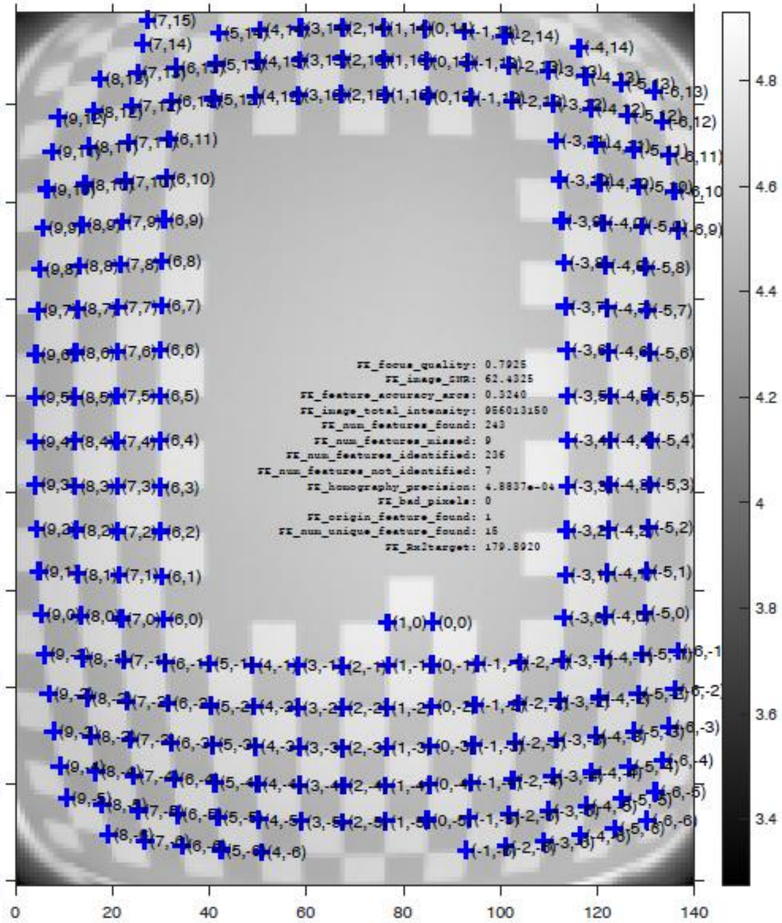
80cm



90cm



100cm



IMX459 Calibration

10. IMX459 Calibration process

Pre-Cal	1. Sony sensor 에 대한 full Register Map 필요 2. Full datasheet 필요 3. 온도별 SPAD Vbd 측정하여 Vbd trend polynomial fitting	Register 정보 업데이트 및 Vbd trend 측정
Dark	1. LASER Pulse delay 측정(Fsync to TRI_I, TRG_I to TRG_O, TRI_O to LD driver, LD driver to Pulse) 2. Trigger로 인한 offset parameter 산출 3. Sensor gate delay(Full datasheet 입수 후 구체화) 4. Reflected pulse waveform 측정(거리별 측정, target 반사율 10%) 5. Reflected pulse waveform parameter 계산 6. Spot finding 을 통한 Spot 좌표, Spot skew 측정 7. Super pixel 선정	Delay offset 측정 및 No ambient 에서의 pulse 파형 및 spot 특성 측정
DNL/INL	1. Uniform IR 광원을 Sensor 에 조사하면서 TDC debug mode 가동 2. DNL측정 / INL 계산 3. Inverse function 도출 4. Histogram 보정(Hardware correction 가능한지 Sony 에 문의 필요)	TDC Correction
P2P	1. Uniform IR 광원을 Sensor 에 조사하면서 P2P 2. Macro pixel histogram 분석을 통한 Pixel to Pixel skew 분석 3. Skew 분석을 통한 Histogram 보정	Pixel correction
Rail	1. Check box chart 측정 2. Sensor lens distortion 계산 3. 실거리 TOF 측정(30cm, 60cm, 100cm) 4. 실거리 측정을 통한 TDC offset parameter 산출	Lens distortion 보정 및 실거리 측정을 통한 TOF offset 보정