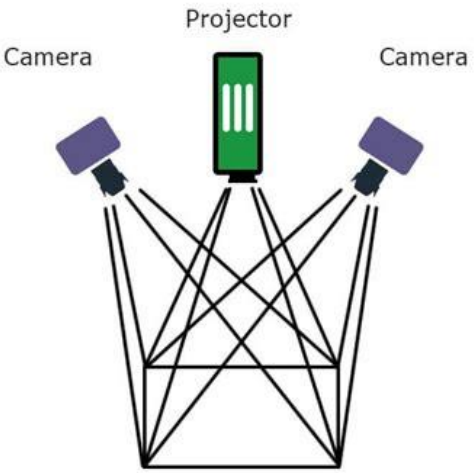
DXOMARK DEPTH MAP CAMERA EVALUATION REPORT

--Sample report v1.0--

StereoCamera vs ToF AD-96TOF1-EBZ

corp.dxomark.com



StereoCam 1

3D System	Active stereovision
Pattern projector	Textured pattern
Camera size	192 x 50 x 52 mm
Working distances	270 – 3000mm
Max resolution	1936 x 1216
Frame rate at max resolution	5 fps
Lens FOV (H)	67°
Field of View max	3970mm
Interface	Ethernet

Testing Conditions

Mode ssesosor	Full resolution
SW version	
Output	Depth Map
Room temperature	21°C

Image resolution	1280 x 1024
Illumination	0 to 7750 lux

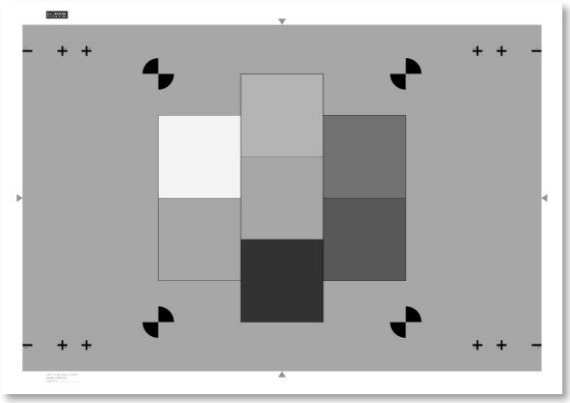
AD-96TOF1-EBZ

3D System	Time of Flight
Pattern projector	940nm Vertical-Cavity Surface-Emitting Laser
Camera size	60 x 40 x 20 mm
Working distances	250 – 6000mm
Max resolution	640 x 480
Frame rate at max resolution	30 fps
Lens FOV (H)	90°
Field of View max	12000mm
Interface	Ethernet, WiFi or USB

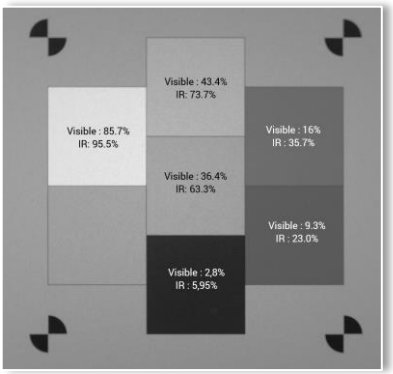
Testing Conditions

Mode sensor	Full resolution
SW version	
Output	Depth Map
Room temperature	21°C

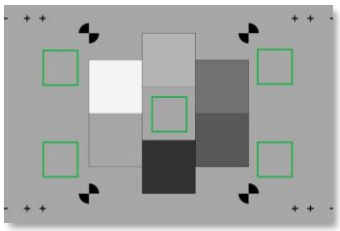
Image resolution	640 x 480
Irradiance	0 to 0.065 W/m²/nm
Wavelength	940nm



Visual noise chart



Reflectances in visible and IR of each patch



Setup for Uniformity measures

- **Measurement conditions**
  - Chart is VNU0002_140_P. The grey background is 860mm height.
  - Shooting distance is adjusted to have 850mm height framing:
    - For AD-96TOF1-EBZ : at 700 mm from the chart
    - For StereoCam 1: at 1013 mm from the chart
  - Illumination is provided by DXOMARK MLS (multispectral lighting system) using many light intensities and, for StereoCam 1, exposure time :
    - For AD-96TOF1-EBZ : MLS NIR 940 nm, from 0 to 0.065 W/m²/nm (equivalent to 0 to 28510 lux in sunlight)
    - For StereoCam 1 : MLS Blackbody 6500K, from 0 to 7750 lux, changing the exposure time from 5 to 0.5 ms
  - 30 pictures are taken for each condition

- **KPI's:**
  - Spatial noise (relative)

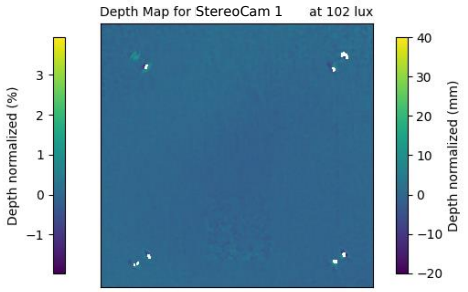
    Is measured by the standard deviation of the error distance between the temporal averaged image and the plan that best fit the data in the considered ROI. Is divided by the distance from the chart to get a relative spatial noise.
  - Temporal noise (relative)

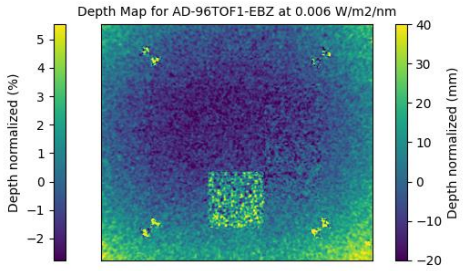
    Is measured by the average of the standard deviation of each pixel over time in the considered ROI. Is divided by the distance from the chart to get a relative temporal noise.
  - Depth map fill rate

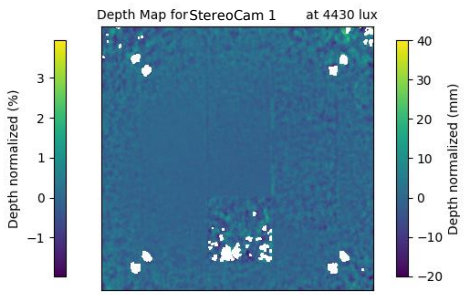
    Is measured by the percentage of pixel with a valid depth value over all the pixels of the image.
  - Uniformity : Corners vs center

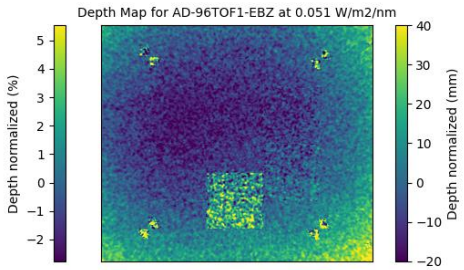
    Is measured by the ratio (expressed in percentage) of the total standard deviation (spatial and temporal) in the 4 corners vs the center.

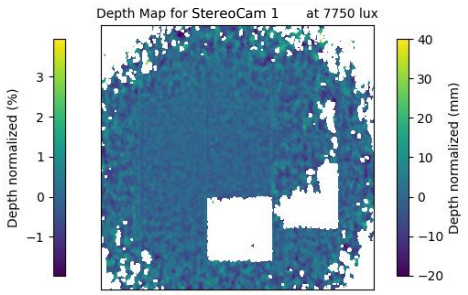
- **Depth maps for 3 intensities of illuminance/irradiance for each device**

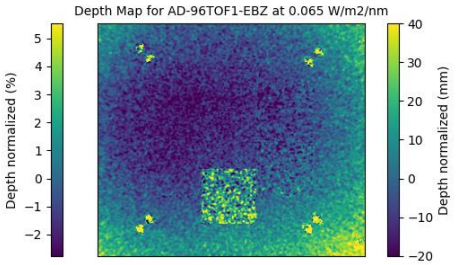












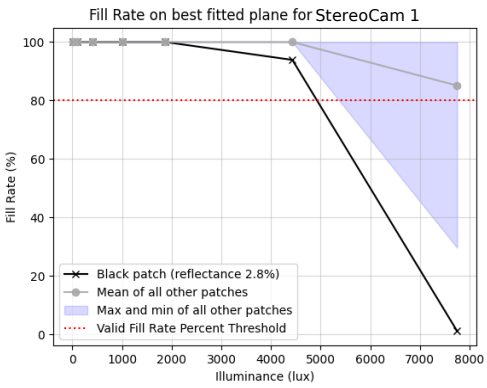
AD-96TOF1-EBZ's noise is way more important than StereoCam 1's one.
We notice that the darkest patches of the VNU chart are poorly seen (a lot of invalid pixels) by StereoCam 1 under high illuminance. For AD-96TOF1-EBZ, the darkest patch is seen really noisy in a similar way for all irradiance.

Note that the 0 is the position of the chart.

AD-96TOF1-EBZ

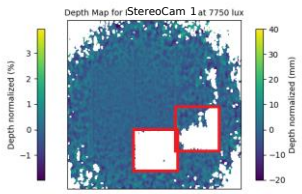
For AD-96TOF1-EBZ device, the depth map fill rate is at 100% for <u>any</u> irradiance and <u>any</u> reflectance, which is expected because these devices are 100% efficient on any plane surface opaque and non-shrinking.

StereoCam 1



Fill Rate	ambient light (lux)	object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
	0	100	100	100	100	100	100
	102	100	100	100	100	100	100
	409	100	100	100	100	100	100
	1000	100	100	100	100	100	100
	1870	100	100	100	100	100	100
	4430	93.9	100	100	100	100	100
	7750	1.14	28.5	95.9	100	100	100

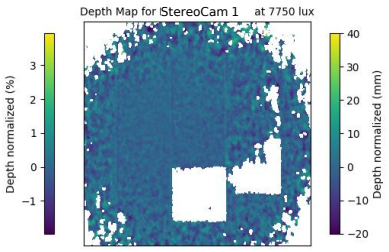
The StereoCam 1 device has a 100% fill rate for high reflectance patch under any illuminance. However, for low reflectance patches, the fill rate drops when increasing the illuminance.

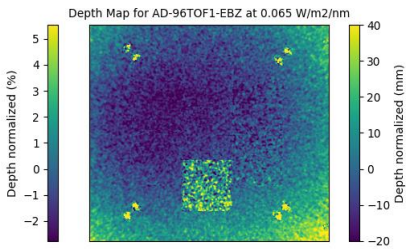


The two patches in red have less than 80% of fill rate

→ We consider that the measures taken in conditions where the fill rate is under 80% are invalid : we will plot graphs zoomed on what we call the “valid measures” (excluding the measures for StereoCam 1 taken with 7750 lux for patch of reflectance 2.8% and 9.3%).

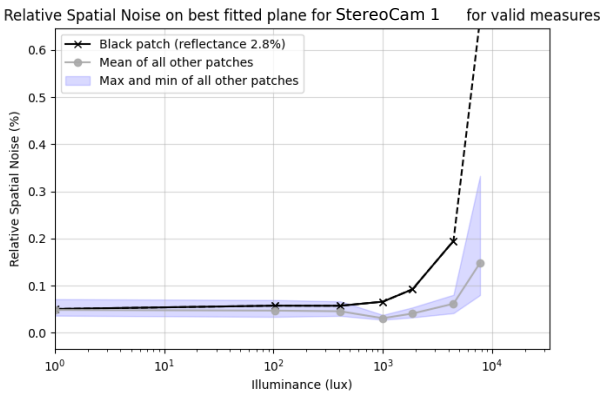
Depth maps under highest illuminance/irradiance:



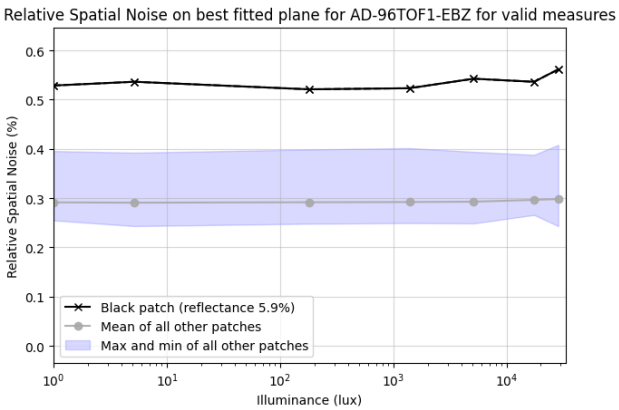


- **Spatial Noise**

StereoCam 1



AD-96TOF1-EBZ

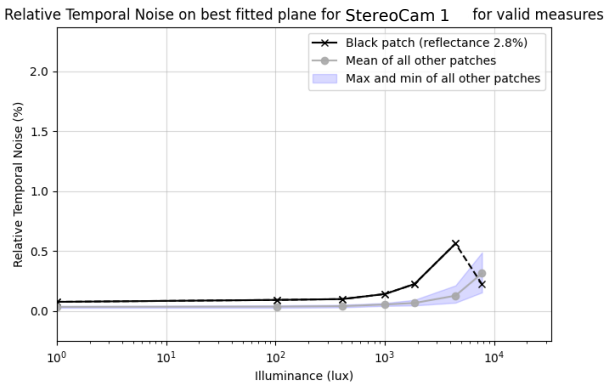


StereoCam 1 has negligible spatial noise in the nominal operating range (ambient light less than 1000 lux) whereas AD-96TOF1-EBZ has higher spatial noise at all illuminances, especially for low reflectances.

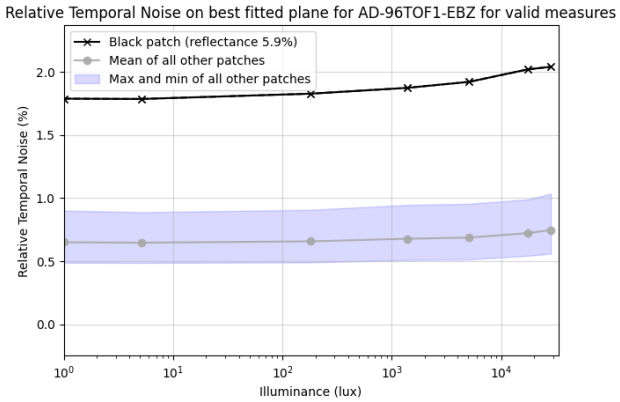
(See exact values in Appendix)

- **Temporal Noise**

StereoCam 1



AD-96TOF1-EBZ



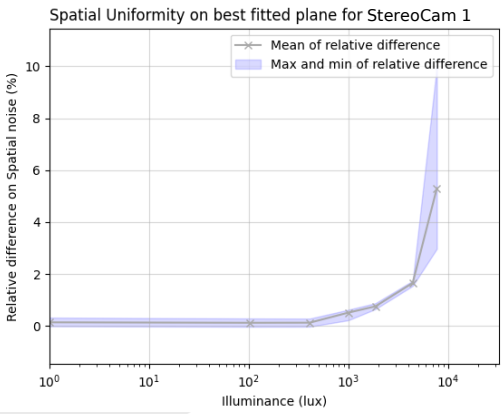
The conclusions that can be drawn from these graphs are similar to the ones for the spatial noise. Worse, the temporal noise of AD-96TOF1-EBZ is very high for all values (higher than its spatial noise), and for low reflectances it is extremely high.

(See exact values in Appendix)

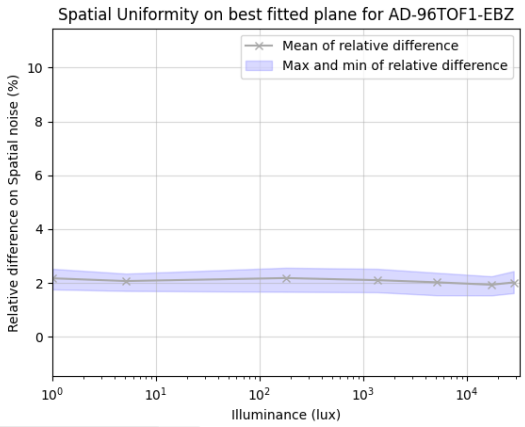
- **Spatial Uniformity**

We only computed the uniformity over the patch of reflectance of 36.4% in visible and of 63.3% in IR. We compare the noise on the center with the noise on the 4 corners (what we call the “relative difference” on the below graphs).
All values were taken in valid conditions according to the table displayed page 8.

StereoCam 1



AD-96TOF1-EBZ

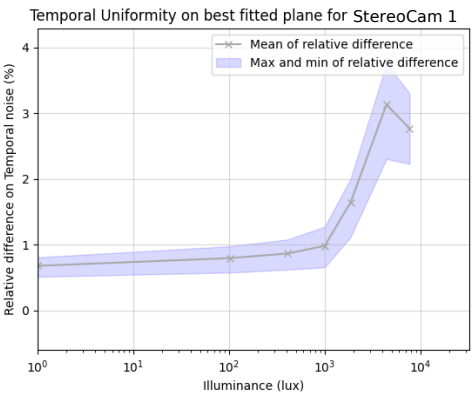


We notice that StereoCam 1 has a better Spatial Uniformity for all low illuminances. Then, as the illuminance increases, around 4000 lux, the uniformity gets worse for StereoCam 1. The relative difference on Spatial Noise of StereoCam 1 exceeds AD-96TOF1-EBZ one at 7770 lux. For one corner patch, it even reaches 10%.
StereoCam 1 is well uniform for nominal operating range although it is less consistent than AD-96TOF1-EBZ.

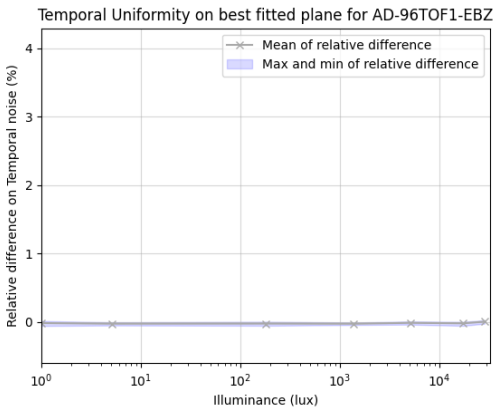
- **Temporal Uniformity**

We only computed the uniformity over the patch of reflectance of 36.4% in visible and of 63.3% in IR. We compare the noise on the center with the noise on the 4 corners (what we call the “relative difference” on the below graphs).
All values were taken in valid conditions according to the table displayed page 8.

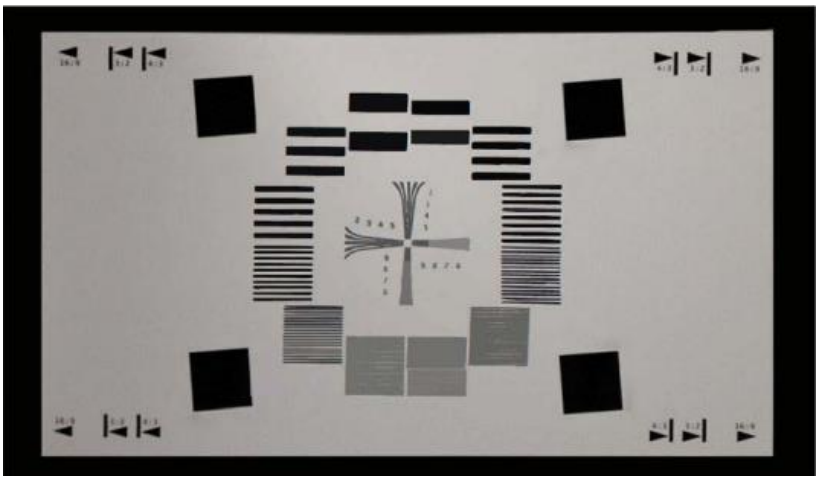
StereoCam 1



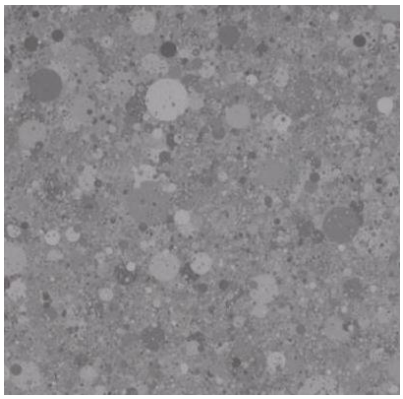
AD-96TOF1-EBZ



The temporal uniformity is way better, almost perfect (because the relative difference is centered around 0 which is the ideal value) for AD-96TOF1-EBZ device. StereoCam 1 has a similar behavior than for Spatial Noise: a good uniformity at nominal operating range worsening from 2000 lux.



Spatial resolution 3D chart



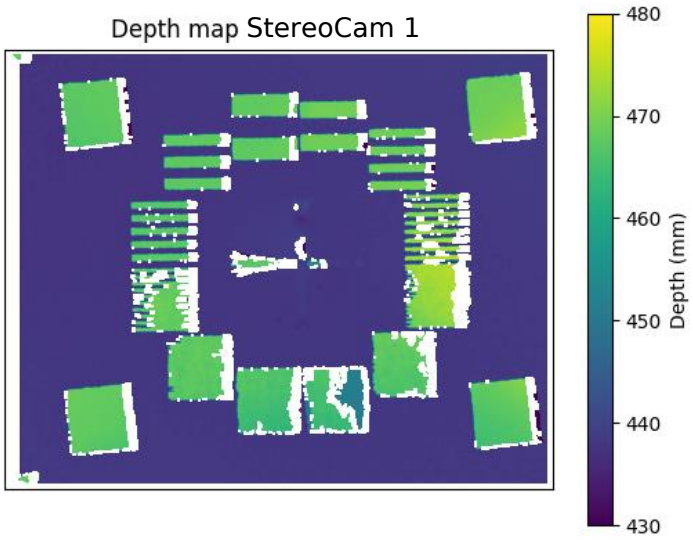
Deadleaves background

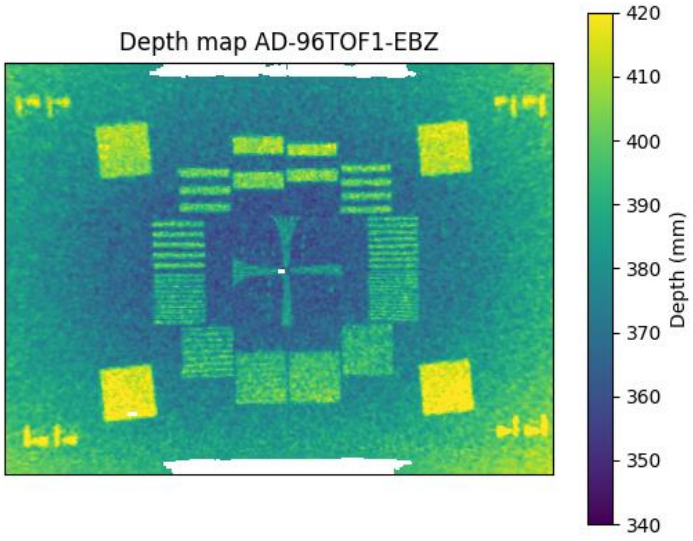
- **Measurement conditions**
  - Chart is Depthmap_resolution. This chart is made of a plan of reflectance 18% with holes of different sizes (0.6mm to 20mm) . The background is placed 3 cm behind the chart.
  - The distance of the foreground chart is defined by the distance used during the spatial and temporal noise test.
  - A Deadleaves background is placed at this distance to avoid occlusion of the stereo cameras as much as possible occlusions of stereo cameras, the background can be placed further away, e.g. 30 cm from the target for ToF cameras, as this technology does not produce occlusions.
  - Illumination is provided by DXOMARK MLS (multispectral lighting system) using the following conditions:
    - Warm white LED 2700K - 1950 lux (exposure time = 1ms for StereoCam 1)
    - For AD-96TOF1-EBZ device : 0.028 W/m²/nm
  - 30 pictures are taken

- **KPI's:**
  - Spatial resolution

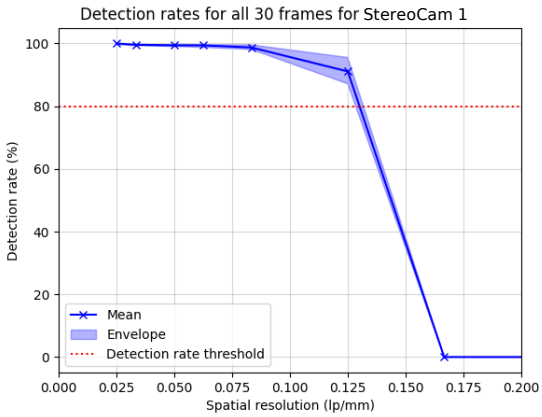
    Is defined by the minimum hole size the camera can detect. Is expressed in line pairs per millimeter. Is defined as the spatial resolution of the patch with the smaller slits which has a detection rate higher or equal to 80%. Detection rate is defined as the number of detected slits over the theoretical one, expressed in % (can be higher than 100% if more slits are detected than theory).

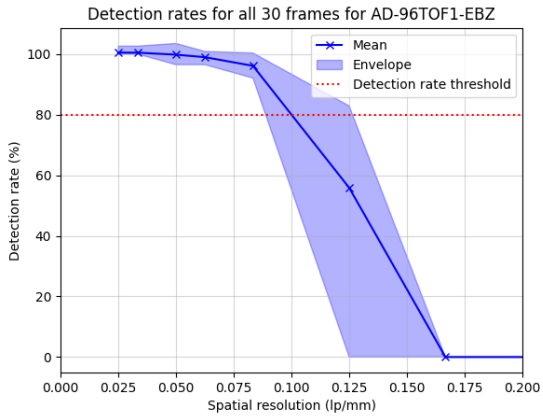
- **Deadleaves background 3cm behind the chart**





- Spatial resolution at 634mm distance- statistics in 30 frames





Over 30 shoots, the detection rate for each patch of the chart can vary. By displaying the envelope of its possible values over frames, we see that the spatial resolution is not always the same for AD-96TOF1-EBZ (with detection rate threshold being at 80%).

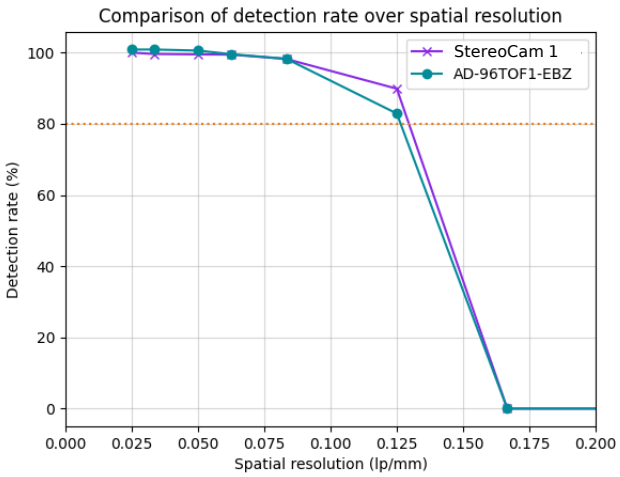
StereoCam 1	Spatial resolution : minimum slit size detected		
	Min	Average	Max
In line pairs per millimeter	0.125	0.125	0.125
In % of image height	0.024	0.024	0.024

AD-96TOF1-EBZ	Spatial resolution : minimum slit size detected		
	Min	Average	Max
In line pairs per millimeter	0.083	0.100	0.125
In % of image height	0.035	0.042	0.052

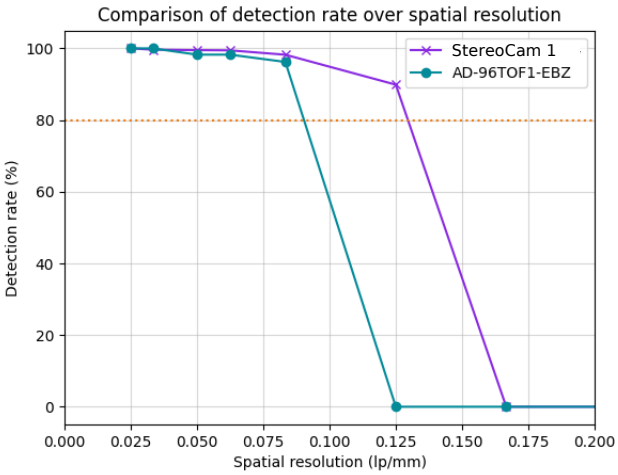
The detection rate for StereoCam 1 device is always 0.125 lp/mm

On most frames, the spatial resolution of AD-96TOF1-EBZ is 0.083 lp/mm. We call that situation "average case".

On some frames, its spatial resolution reaches 0.125 lp/mm. We call that situation "best case".



Best case for AD-96TOF1-EBZ

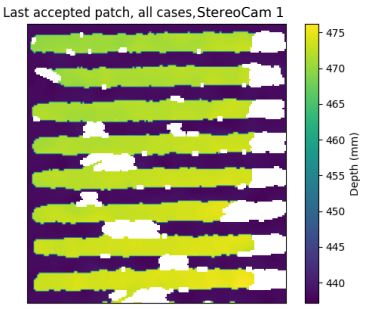


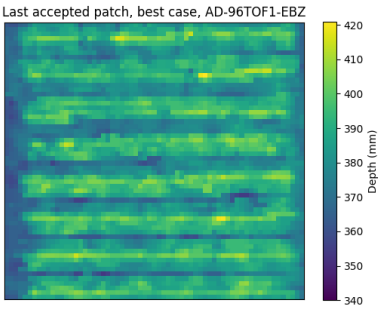
Average case for AD-96TOF1-EBZ

In most cases, AD-96TOF1-EBZ has lower spatial resolution than StereoCam 1 (what we call “average case”).
However, in best cases, AD-96TOF1-EBZ’s spatial resolution can be equal to StereoCam 1’s one.

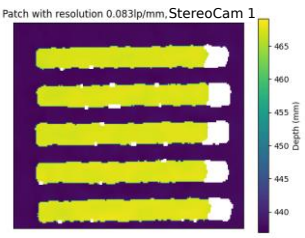
The depth maps below are the last patches that AD-96TOF1-EBZ will detect with over 80% detection rate, viewed by both devices.

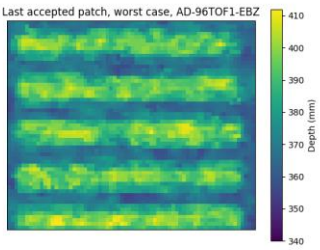
Best case for AD-96TOF1-EBZ :





Average case for AD-96TOF1-EBZ :





DMC (DXOMARK chart)

DMC (DXOMARK chart)

- **Measurement conditions**
  - Chart is DXOMARK chart
  - Shooting distance is adjusted to have the same vertical framing
  - Illumination is provided by DXOMARK MLS (multispectral lighting system) using 2 illuminants and several light intensities:
    - Daylight simulation D65 at 1000 lux for StereoCam 1
    - No IR lighting for TOF
  - 1 picture is taken for each light conditions

- **KPI's:**
  - The analysis is done by an expert that will point the filtering artefact and defects in the depth map.
  - Relative spatial noise:

  Is expressed in %. Is measured on many surfaces, put in relative thanks to distance to the chart measure

- **Comparisons on different parts of the chart**

Brushes and slate

Metallic spatulas

Acrylic paint tubes

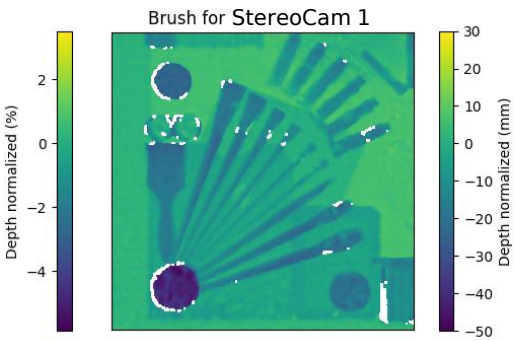
Chalks and pencils

Black rectangle over white rectangle

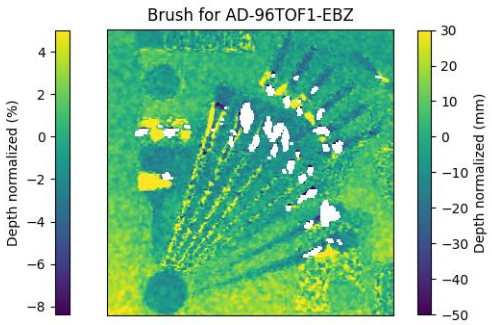
Yellow and black foam

- **Reflective parts**

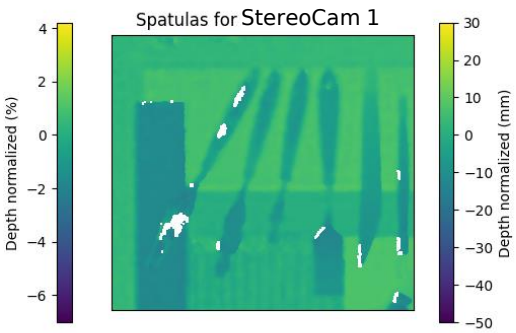
StereoCam 1 ***AD-96TOF1-EBZ***



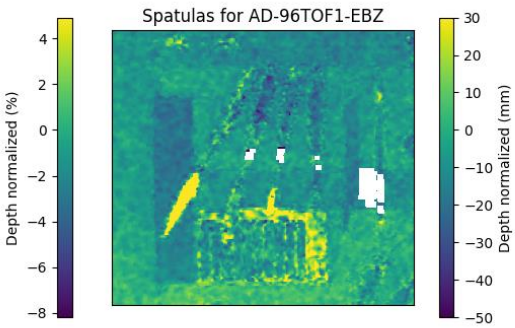
Estimated shooting distance : 852 mm



Estimated shooting distance : 596 mm



Estimated shooting distance : 712 mm



Estimated shooting distance : 610 mm

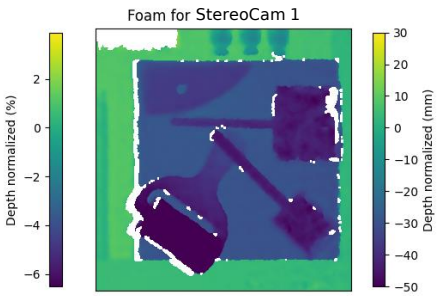
The metallic parts (coming from spatulas or brushes parts) are noisy for AD-96TOF1-EBZ, but most importantly they are seen as farther away than the chart itself.

Fill rate for smaller spatula is bad for StereoCam 1, the rest is well seen.

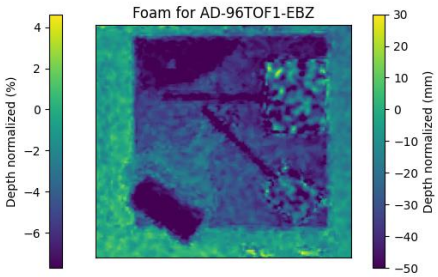
- **Black/dark parts**

StereoCam 1

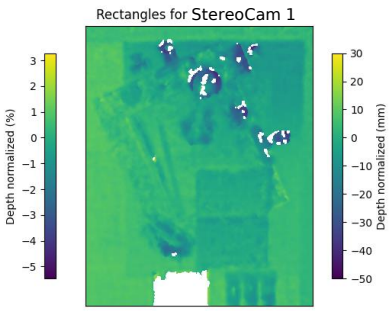
AD-96TOF1-EBZ



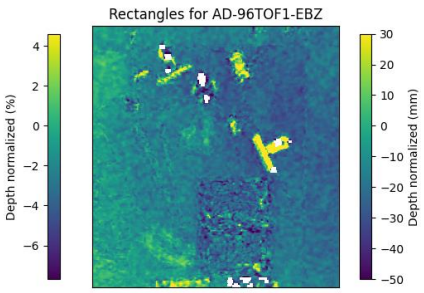
Estimated shooting distance : 767 mm



Estimated shooting distance : 648 mm



Estimated shooting distance : 915 mm



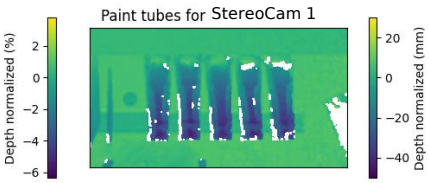
Estimated shooting distance : 650 mm

Useful to see how the noise changes for different textures and darker color

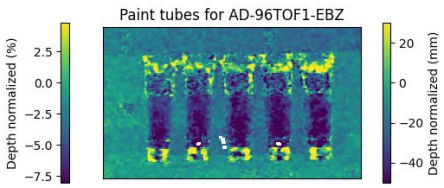
- The black foam and black rectangle are a bit noisy for StereoCam 1. It also has a bit of fill rate issues.
- The black foam and black slate have a lot of noise for AD-96TOF1-EBZ

- **Black/dark parts**

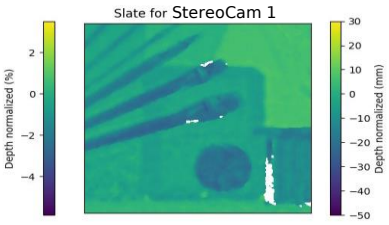
StereoCam 1 ***AD-96TOF1-EBZ***



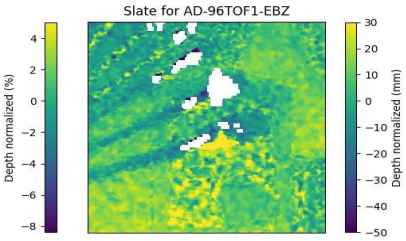
Estimated shooting distance : 788 mm



Estimated shooting distance : 624 mm



Estimated shooting distance : 852 mm

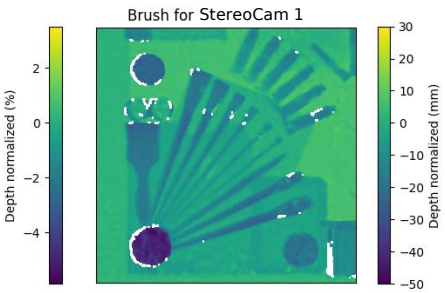


Estimated shooting distance : 596 mm

- For AD-96TOF1-EBZ, the slate seems seen as farther away than the chart itself, like the reflective parts.
- No fill rate issue for AD-96TOF1-BEZ on the black caps and black parts but they are really noisy
- StereoCam 1 : uniform noise but a lot of invalid pixels on black caps and parts, no problem with slate

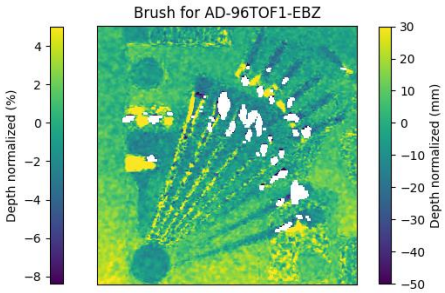
- **Perceptual spatial resolution**

StereoCam 1



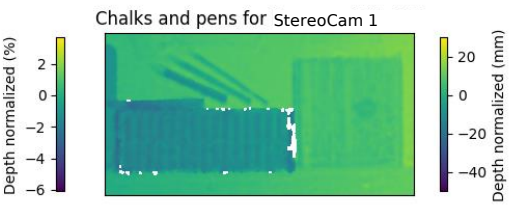
Estimated shooting distance : 852 mm

AD-96TOF1-EBZ

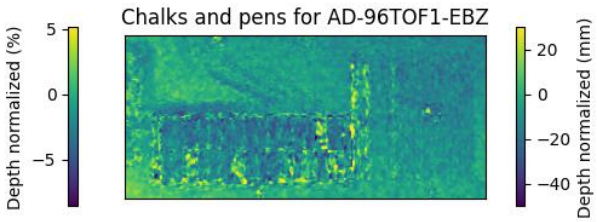


Estimated shooting distance : 596 mm

Both devices detect each paint brush.



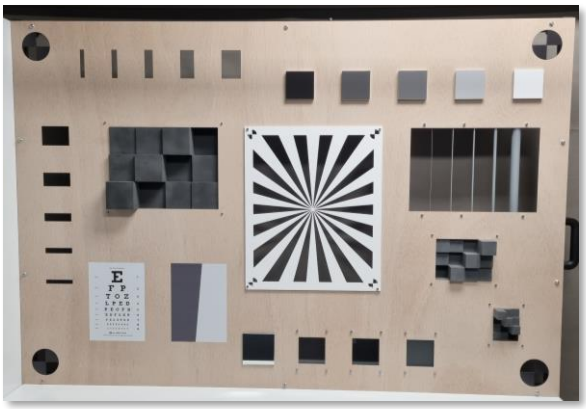
Estimated shooting distance : 820 mm



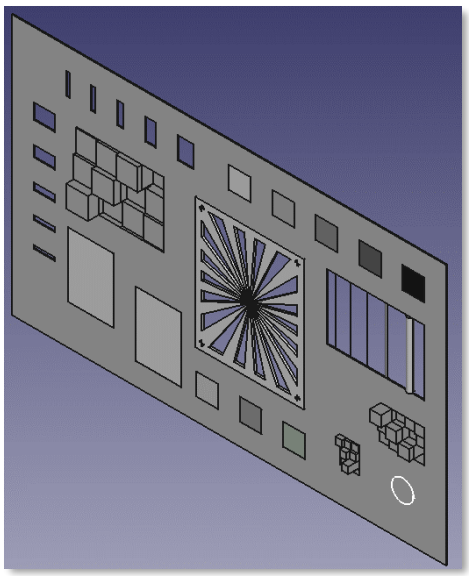
Estimated shooting distance : 585 mm

Vertical chalks and pencils can be used to compare spatial resolution

- AD-96TOF1-EBZ almost can't see the chalks, and has higher noise for some colors
- Worst spatial resolution for AD-96TOF1-EBZ than StereoCam 1 here → it is important to note that ToF device has better performances when the background is further away than 3cm, which is not the case for StereoCam 1 as it will create some occlusions. So the conditions were met for StereoCam 1 to have better results.



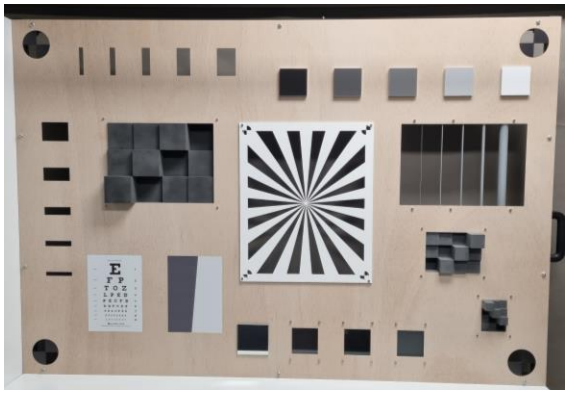
DXOMARK 3D chart in laboratory



DXOMARK 3D chart's structure

- **Measurement conditions**
  - Chart is DXOMARK 3D chart DM3D001. This chart is made of a plane with holes and 3D objects. A grey uniform background is placed 10 cm behind the chart.
  - Shooting distance is adjusted to have the same vertical framing.
  - Illumination is provided by DXOMARK MLS (multispectral lighting system) using 2 illuminants and several light intensities:
    - Daylight simulation D65 at 1000 lux for StereoCam 1 for framing of the different parts
    - Daylight simulation D65 at 200 lux for StereoCam 1 for full framing
    - No IR lighting for ToF
  - 1 picture is taken for each light conditions

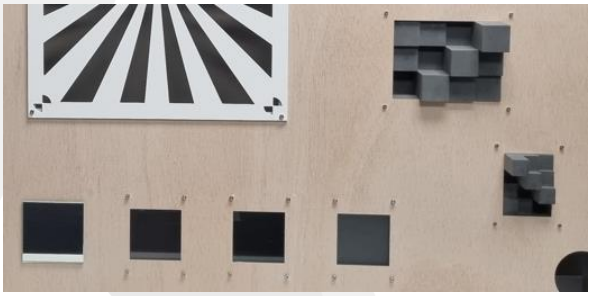
- **KPI's:**
  - Ideas of analysis that could be done by an expert to point the filtering artefact and defects in the depth map.



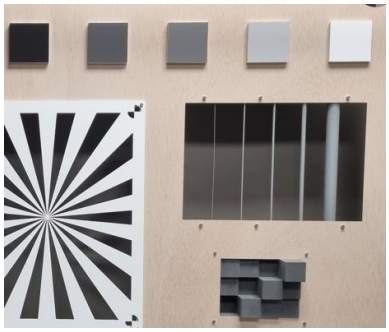
DXOMARK 3D chart

- **Comparisons on different parts of the chart**

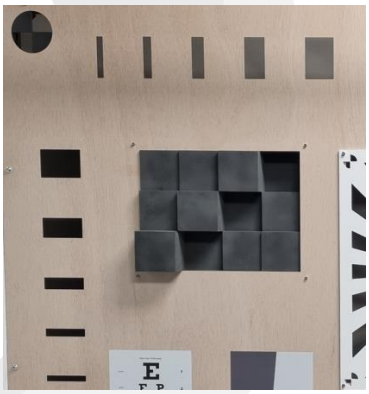
Boehler star



Mirror, transparent objects

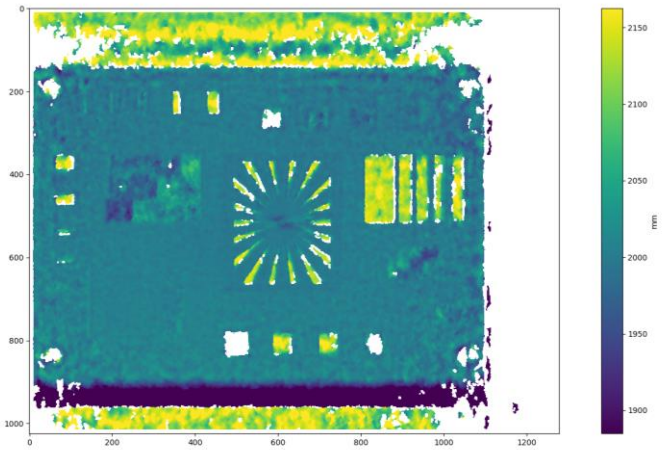


Poles and gray patches

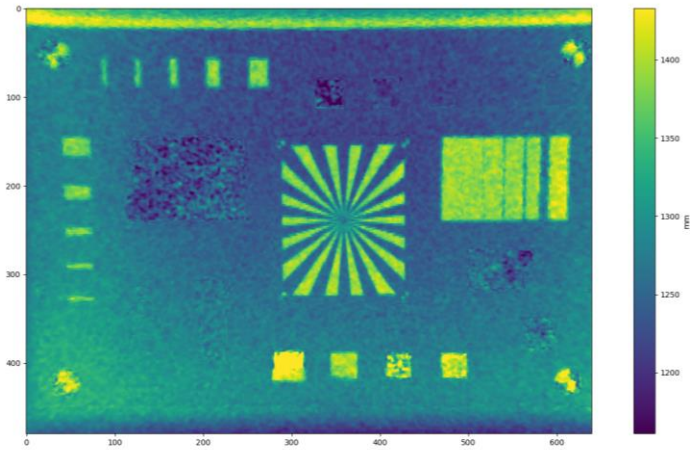


Large stair pattern and holes

- **Comparisons on global chart**

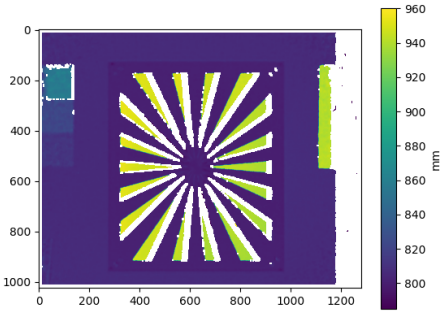


StereoCam 1 depthmap

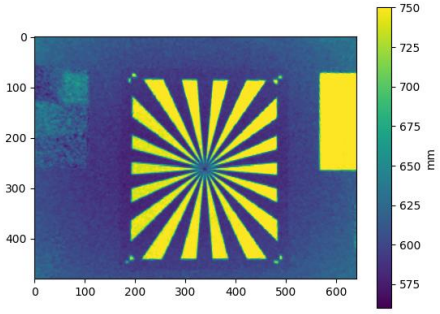


AD-96TOF1-EBZ depthmap

- **Boehler star**



StereoCam 1

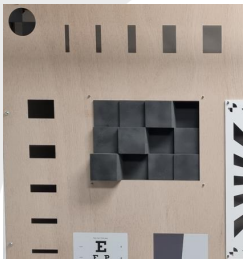


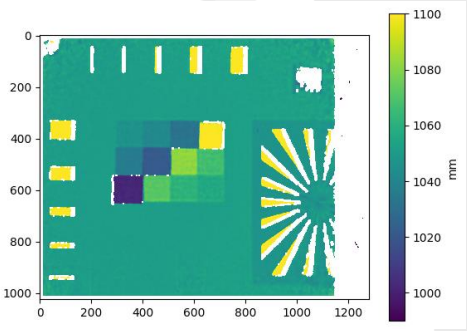
AD-96TOF1-EBZ

- Used to estimate the spatial resolution of cameras.
- Draw concentric circles from the center of the chart and keep the biggest circle that does not have any invalid pixel, or the smallest circle with at least one invalid pixel.
- Compute spatial resolution by dividing the number of white (or black) stripes by the length of the circle.

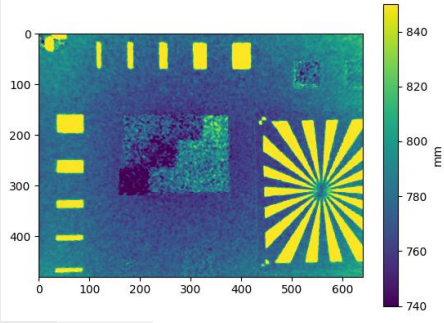
- For ToF cameras there probably will not be any invalid pixels → consider the biggest circle that does not have any pixel corresponding to a pixel on a hole (distance to the background)
- A thresholding would be needed at first like what is done for the spatial resolution on the spatial resolution 3D chart (see last section).

- **Large stair pattern and holes**





StereoCam 1

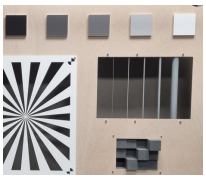


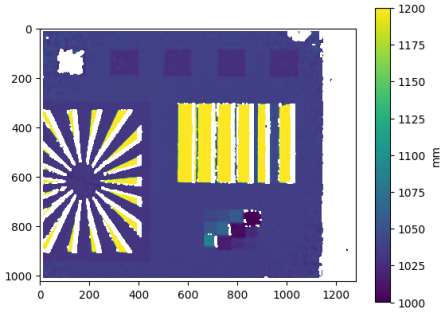
AD-96TOF1-EBZ

- Used to evaluate the depth resolution of the cameras.
- Define a patch for each cube (they all have different depths) and an additional patch on the flat part of the chart to be used as the reference.
- Compare the difference between the mean value of each patch and the mean value of the reference patch to the ground truth.

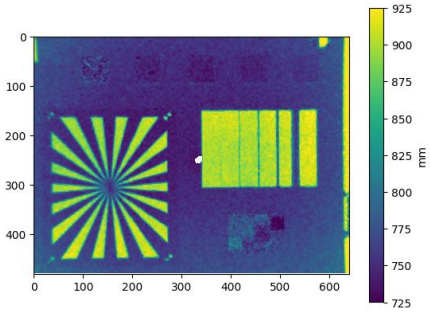
- The part with the vertical and horizontal holes could be used by defining two patches : one containing every vertical holes and one for the horizontal ones. Then count the number of holes seen by the cameras on each patch like on the spatial resolution 3D chart.

- **Poles and gray patches**

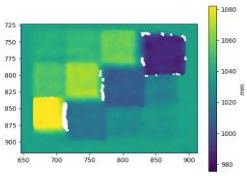




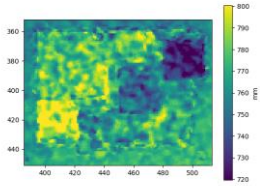
StereoCam 1



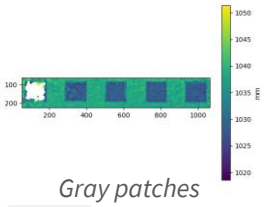
AD-96TOF1-EBZ



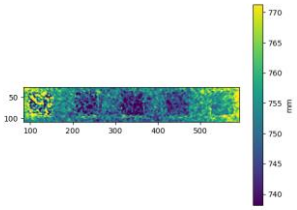
Medium stairs StereoCam 1



Medium stairs AD-96TOF1-EBZ



Gray patches StereoCam 1

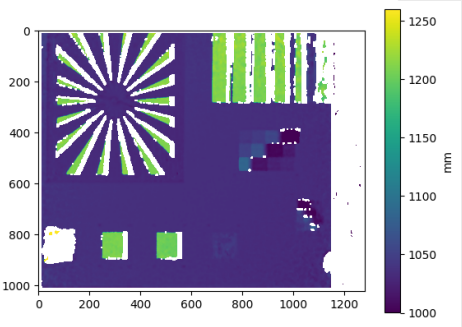


Gray patches AD-96TOF1-EBZ

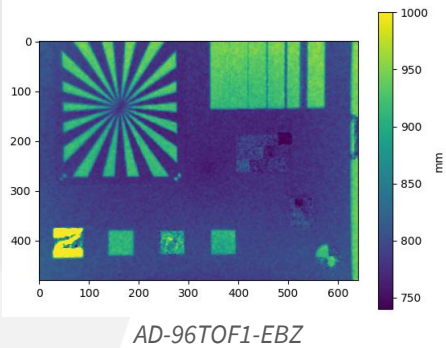
- Define a patch containing all the poles and read each row of the patches. Count the number of poles seen on the patch in a way similar as what is done for the patches of the spatial resolution 3D chart.

- The gray patches can be used the same way as the Visual Noise chart for the spatial noise, temporal noise and fill rate but not for the uniformity.

- **Mirror and transparent objects**



StereoCam 1



AD-96TOF1-EBZ

- In the best case scenario every element (mirror and transparent objects) is detected by the cameras and each patch is at about the same distance as the chart.

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- **Exact values of Spatial Noise and Temporal Noise**

StereoCam 1

AD-96TOF1-EBZ

Spatial Noise

Relative Spatial noise		object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
ambient light (lux)	0	0.510	0.366	0.428	0.042	0.071	0.050
	102	0.057	0.034	0.042	0.041	0.069	0.049
	409	0.057	0.036	0.038	0.040	0.067	0.047
	1000	0.066	0.029	0.028	0.027	0.038	0.032
	1870	0.935	0.418	0.378	0.329	0.543	0.039
	4430	0.195	0.081	0.071	0.042	0.070	0.044
	7750	0.667	0.338	0.133	0.085	0.111	0.080

Relative Spatial noise		object reflectance					
		5.95%	23.0%	35.7%	63.3%	73.7%	95.5%
Spectral radiance (W/m²/nm)	0	0.529	0.273	0.260	0.255	0.396	0.273
	0.002	0.536	0.283	0.243	0.258	0.392	0.278
	0.006	0.521	0.284	0.253	0.248	0.399	0.274
	0.015	0.523	0.280	0.254	0.249	0.402	0.276
	0.028	0.542	0.285	0.249	0.260	0.394	0.277
	0.051	0.536	0.287	0.266	0.266	0.388	0.275
	0.065	0.561	0.311	0.268	0.243	0.408	0.261

Temporal Noise

Relative Temporal noise		object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
ambient light (lux)	0	0.078	0.044	0.041	0.031	0.034	0.028
	102	0.094	0.048	0.046	0.032	0.036	0.028
	409	0.101	0.054	0.050	0.035	0.040	0.031
	1000	0.143	0.068	0.065	0.046	0.056	0.044
	1870	0.226	0.095	0.082	0.053	0.063	0.048
	4430	0.564	0.215	0.173	0.080	0.108	0.070
	7750	0.224	0.463	0.490	0.198	0.268	0.156

Relative Temporal noise		object reflectance					
		5.95%	23.0%	35.7%	63.3%	73.7%	95.5%
Spectral radiance (W/m²/nm)	0	1.79	0.901	0.735	0.573	0.555	0.488
	0.002	1.786	0.889	0.729	0.557	0.555	0.487
	0.006	1.83	0.907	0.756	0.576	0.558	0.490
	0.015	1.87	0.946	0.766	0.596	0.572	0.509
	0.028	1.92	0.955	0.771	0.608	0.587	0.514
	0.051	2.02	0.990	0.824	0.642	0.613	0.543
	0.065	2.04	1.04	0.843	0.658	0.638	0.559

We computed equivalent lux values of irradiance to compare ToF values with StereoCam 1 on same scale

Irradiance (in W/m²/nm)	0	0.002	0.006	0.015	0.028	0.051	0.065
Equivalent under sunlight (in lux)	0	4.16	179	1382	5103	17422	28510