DXOMARK DEPTH MAP CAMERA EVALUATION REPORT

--Sample report v1.0--

Stereocam 1
vs
Stereocam Intel RealSense D435

corp.dxomark.com

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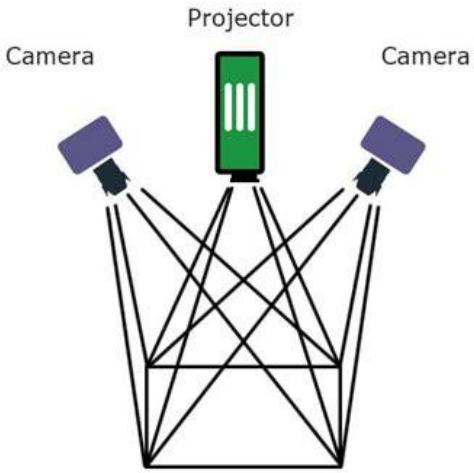

StereoCam 1

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

Image resolution	1280 x 1024
Illumination	0 to 7750 lux

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Intel RealSense D435

3D System	Active stereovision
Pattern projector	Static infrared pattern projector 850nm +- 15nm
Camera size	90 x 25 x 25mm
Working distances	280 – 3000mm
Max resolution	1280 x 720
Frame rate at max resolution	90 fps
Lens FOV (H)	87°
Field of View max	5694mm
Interface	USB-C* 3.1 Gen 1*

Testing Conditions

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

Image resolution	1280 x 720
Illumination	0 to 7770 lux

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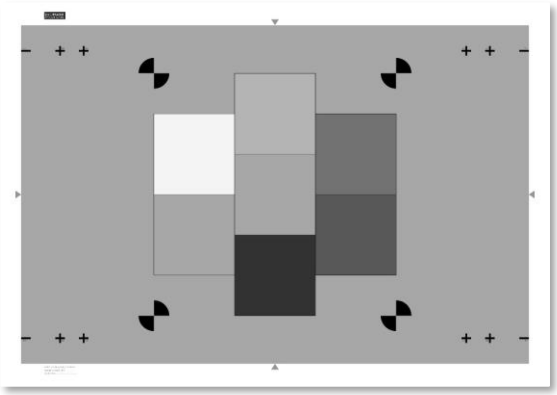
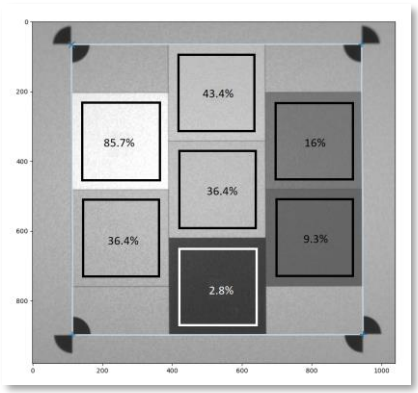
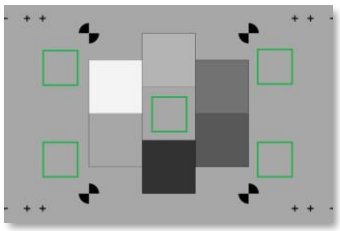


Visual noise chart



Reflectances in visible 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 Intel RealSense D435 device : at 672 mm from the chart
    - For StereoCam 1 device : at 1013 mm from the chart for noise measures
  - Illumination is provided by DXOMARK MLS (multispectral lighting system) using many light intensities and, for StereoCam 1, exposure time :
    - For Intel RealSense D435 device : MLS Blackbody 6500K, from 0 to 7770 lux
    - For StereoCam 1 device : 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 : Corner 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.

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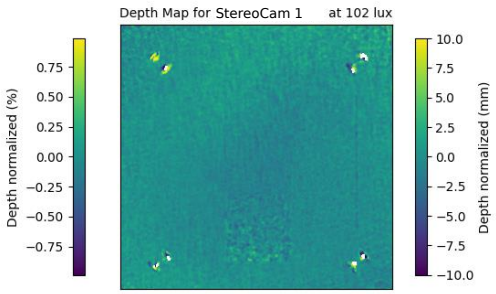
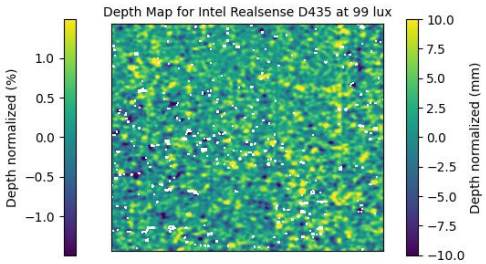
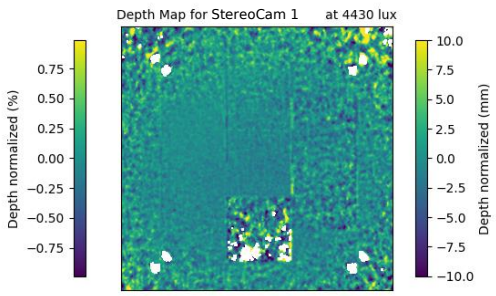
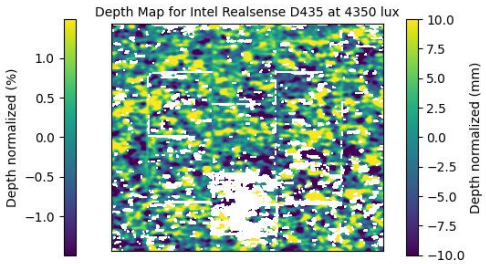
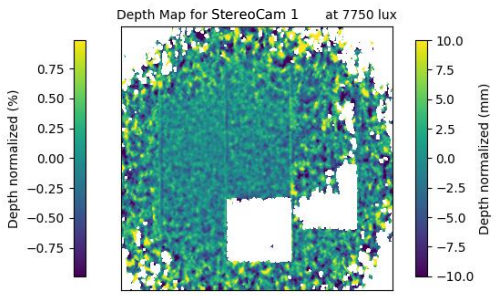
- **Depth maps for 3 intensities of illuminance/irradiance for each device**

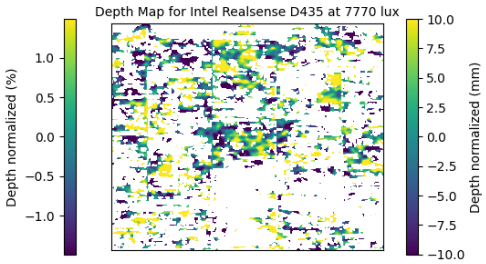












Depth maps of Intel RealSense D435 are noisier than StereoCam 1's, and in a more random way (it is not necessarily the darkest patch that is the noisiest).
Besides, we observe a lot of invalid pixels for both devices for high illuminance, especially for Intel Realsense D435.

Note that 0 is the position of the chart.

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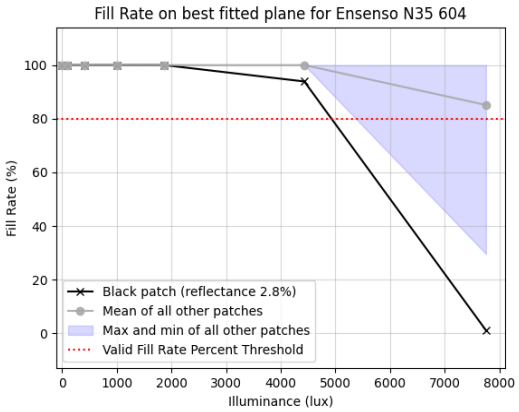
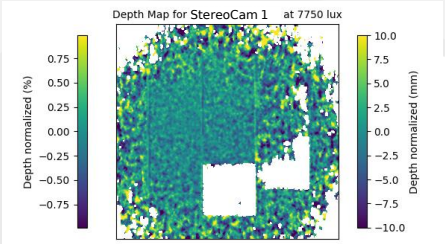
StereoCam 1

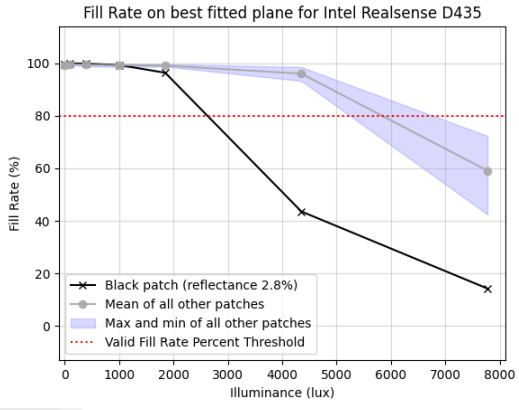
Fill Rate	ambient light (lux)	object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
	0	100	100	100	100	100	100
	102	100	100	100	100	100	100
	409	100	100	100	100	100	100
	1000	100	100	100	100	100	100
	1870	100	100	100	100	100	100
	4430	93.9	100	100	100	100	100
	7750	1.14	28.5	95.9	100	100	100

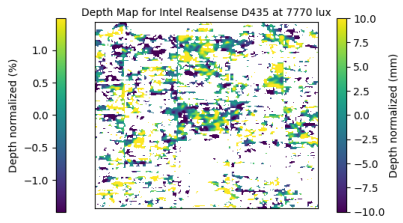




Intel RealSense D435

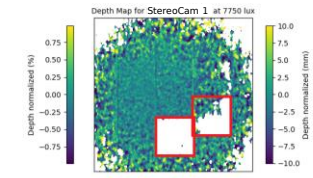
Fill Rate	ambient light (lux)	object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
	0	99.54	99.04	99.44	99.75	99.04	99.58
	99	99.95	99.81	99.84	99.34	99.63	99.35
	402	99.83	99.70	99.78	98.99	99.70	98.86
	1007	99.27	99.49	99.74	98.83	99.65	98.56
	1850	96.34	98.92	99.30	98.73	99.63	98.85
	4350	43.73	93.25	95.65	95.38	98.53	97.28
	7770	14.41	42.27	48.46	62.74	72.26	69.50





Depth maps under highest illuminance

Both stereo cameras have a fill rate that drops at high light intensities : the cameras are no longer able to see the pattern projected by their projector, making it more difficult to match points of interest between the right and left camera images. The fill rate is particularly affected for dark patches of reflectance 9.3% and 2.8% for the StereoCam 1, while all patches are affected for the Intel RealSense D435

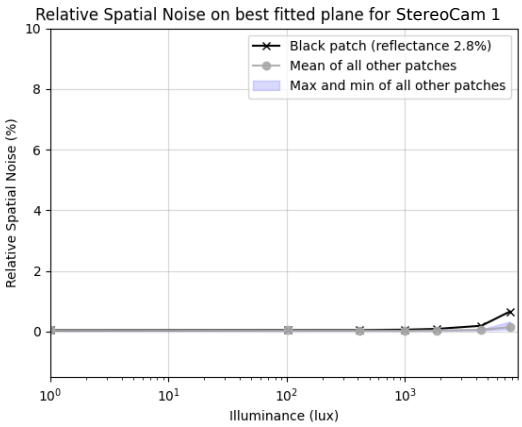


The two patches in red have less than 80% of fill rate

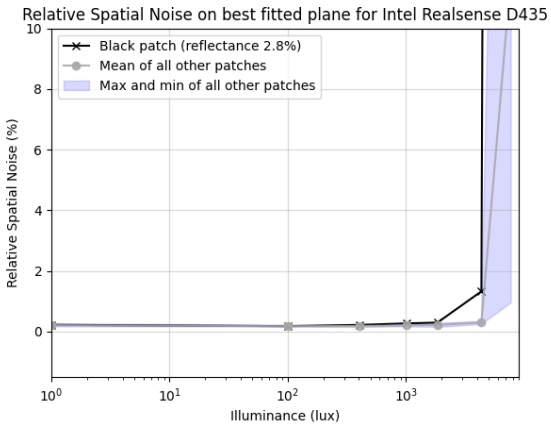
→ We consider that the measures taken in conditions where the fill rate is under 80% are invalid : we will plot graphs zoomed on what we call the “valid measures” (excluding the measures for StereoCam 1 taken with 7750 lux for patch of reflectance 2.8% and 9.3% and all measures taken with 7770 lux for RealSense plus the one taken at 4350 lux for darker patch).

- **Spatial Noise**

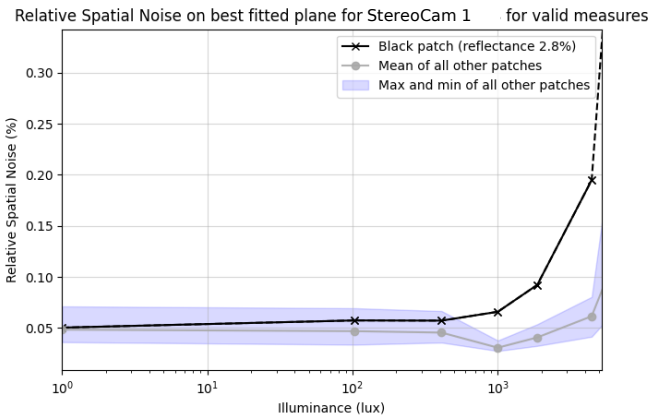
StereoCam 1

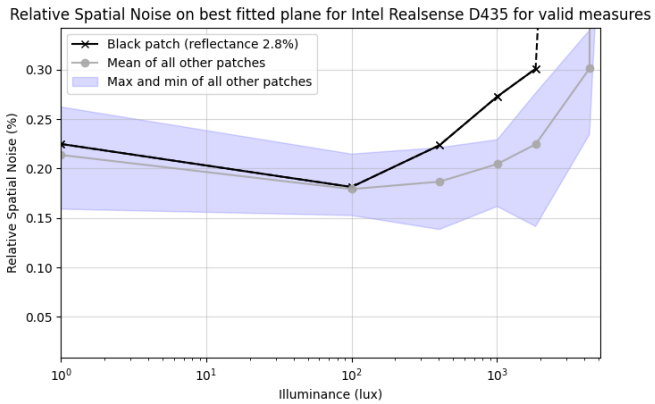


Intel RealSense D435



Considering only the “valid measures” (the values captured when the conditions allowed more than 80% fill rate), we get the graphs below:



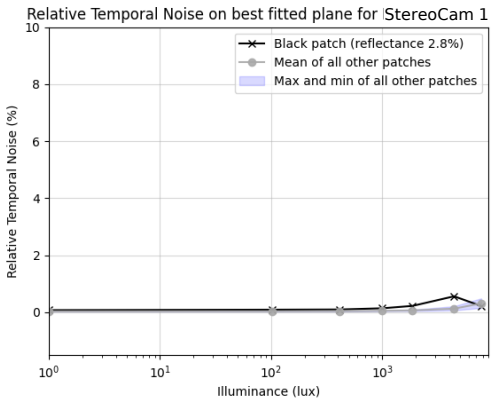


The spatial noise increases with the reflectance and the luminance, for both devices. However, comparing at same scale, we see that the noise is more stable and lower with StereoCam 1 device

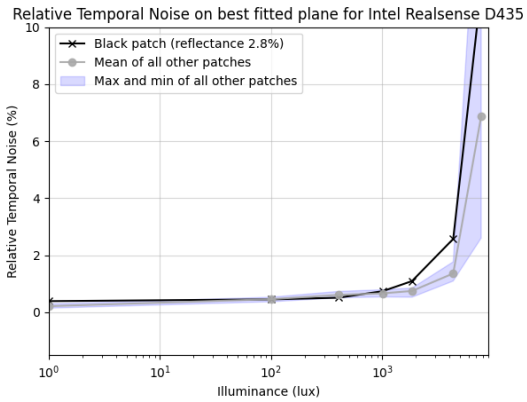
(See exact values in Appendix)

- **Temporal Noise**

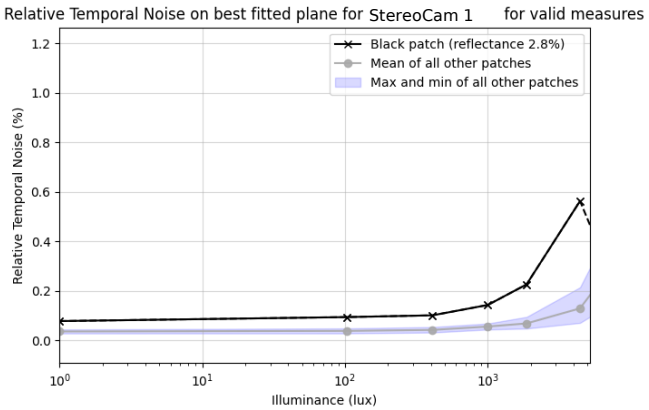
StereoCam 1

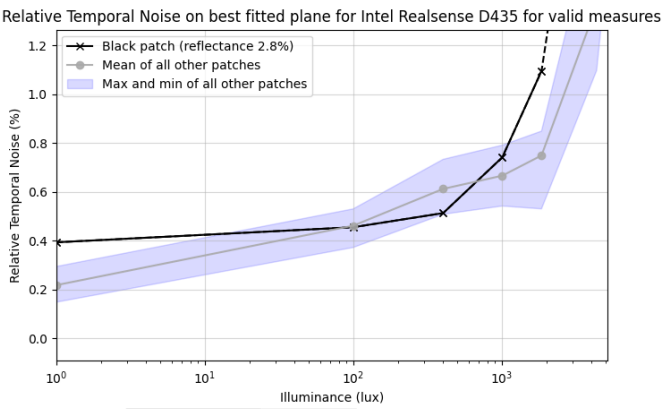


Intel RealSense D435



Considering only the “valid measures” (the values captured when the conditions allowed more than 80% fill rate), we get the graphs below:



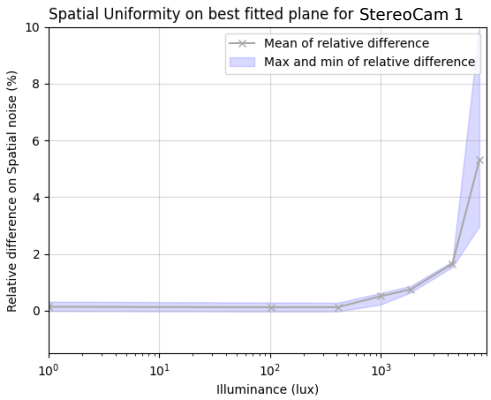


The temporal noise increases with the reflectance and the luminance, for both devices. However, comparing at same scale, we see that the noise is way more stable and lower with StereoCam 1 device.

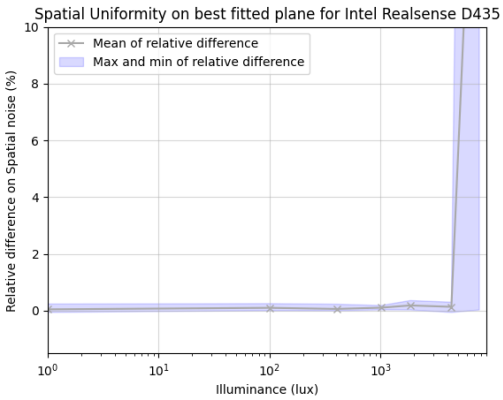
(See exact values in Appendix)

- **Spatial Uniformity**

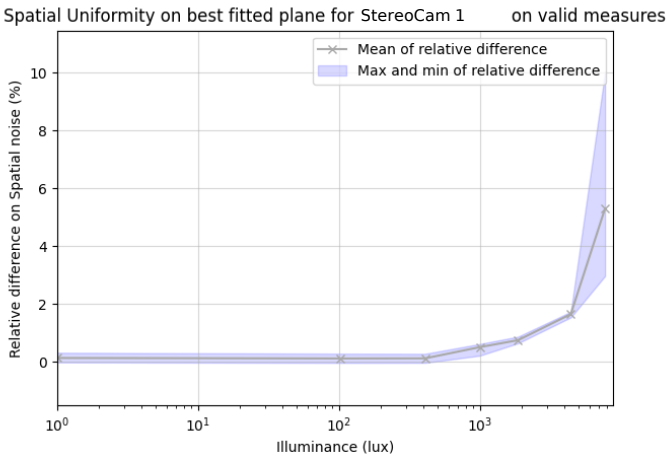
StereoCam 1

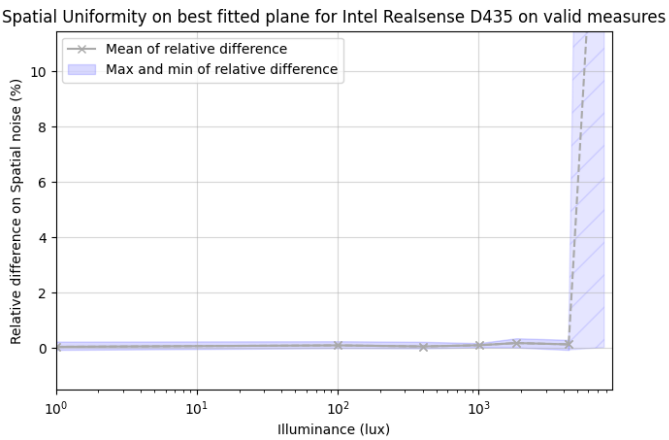


Intel RealSense D435



The uniformities were computed for the patch of reflectance 34.6%. For Intel RealSense D435, under 7770 lux this patch has a fill rate below 80% : these conditions are considered invalid. Zooming on only valid values we get the graphs below:

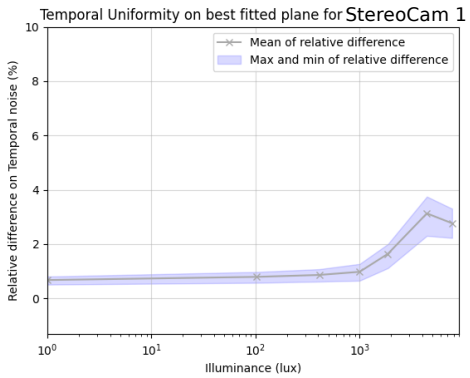




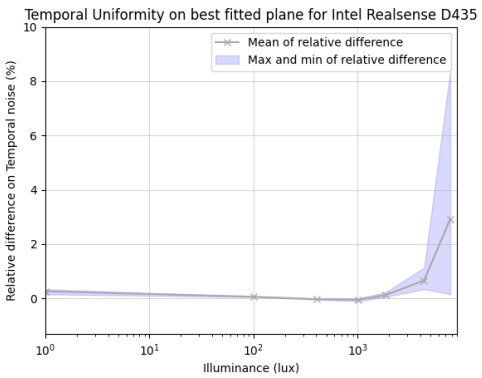
The spatial uniformity for the two devices is pretty similar : for low illuminances, the relative difference is a bit above zero, with the same min/max envelope. However, for high illuminances, the relative difference for Intel RealSense D435 can be up to 8 times higher than StereoCam 1's one.

- **Temporal Uniformity**

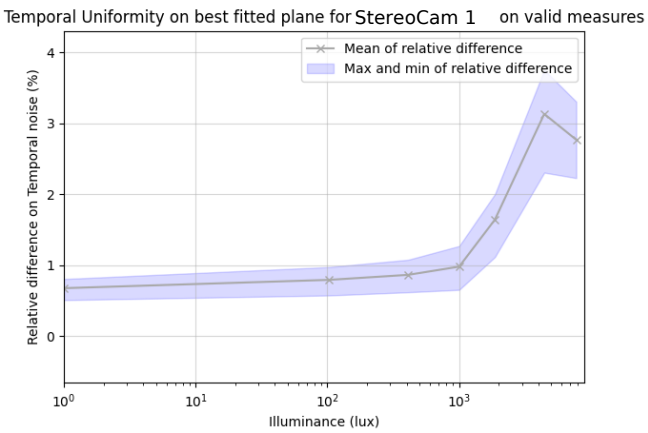
StereoCam 1

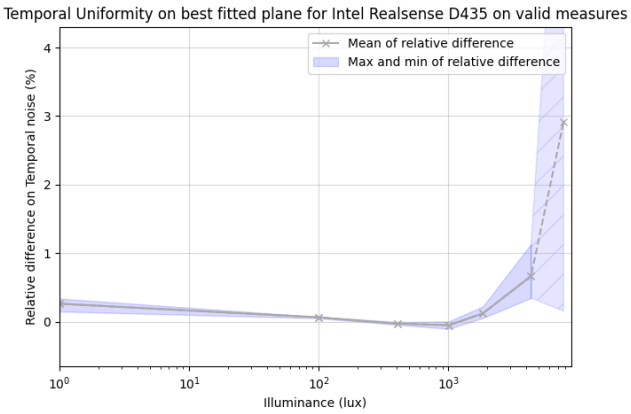


Intel RealSense D435



The uniformities were computed for the patch of reflectance 34.6%. For Intel RealSense D435, under 7770 lux this patch has a fill rate below 80% : these conditions are considered invalid. Zooming on only valid values we get the graphs below:





The temporal uniformity for the two devices is pretty similar : for low illuminances, the relative difference is a bit above zero, though StereoCam 1 is a bit less uniform than Intel RealSense D435. However, when getting into high illuminances, the temporal uniformity of StereoCam 1 worsens before Intel RealSense D435's one,. It should be noted that the relative difference of the Intel RealSense D435 is up to twice as high, but this happens for invalid values.

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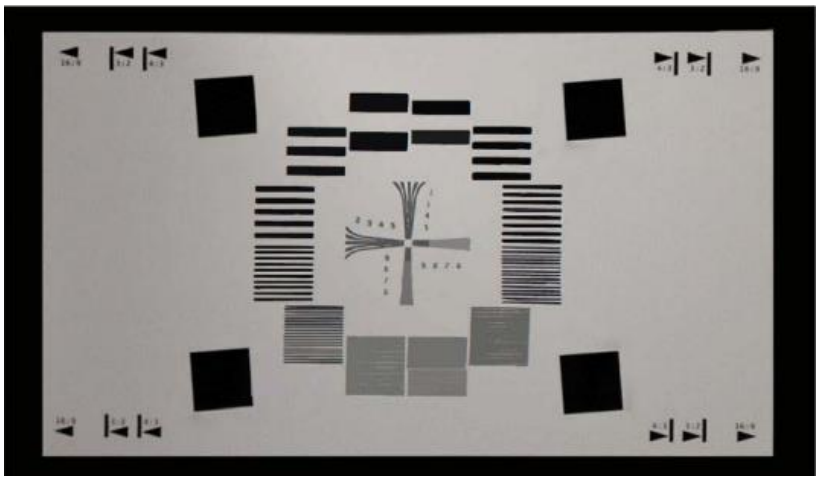
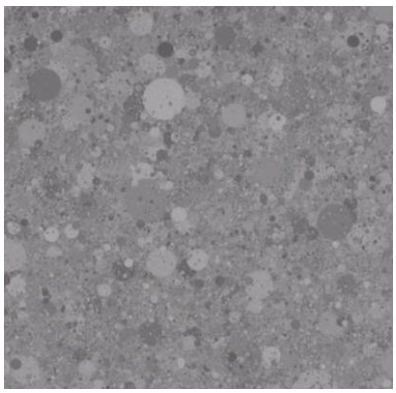


Spatial resolution 3D chart



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.
  - 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)
  - 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 slit which has a detection rate higher or equal to 80%. Detection rate is defined as the number of detected slits over the theoretical number, expressed in % (can be higher than 100% if more slits are detected than theory).

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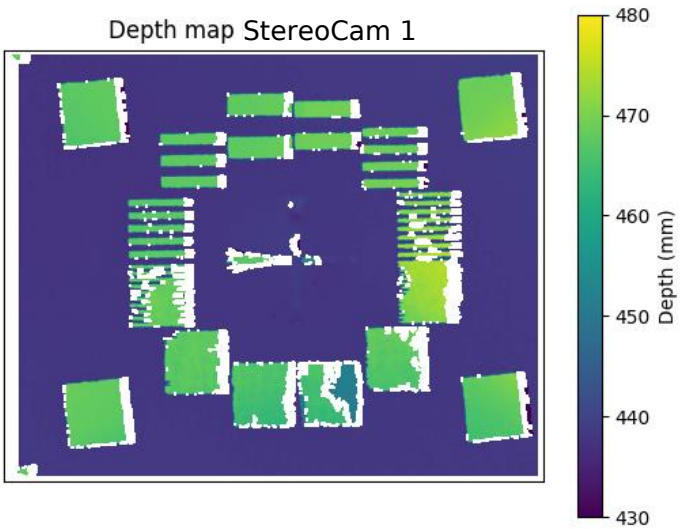
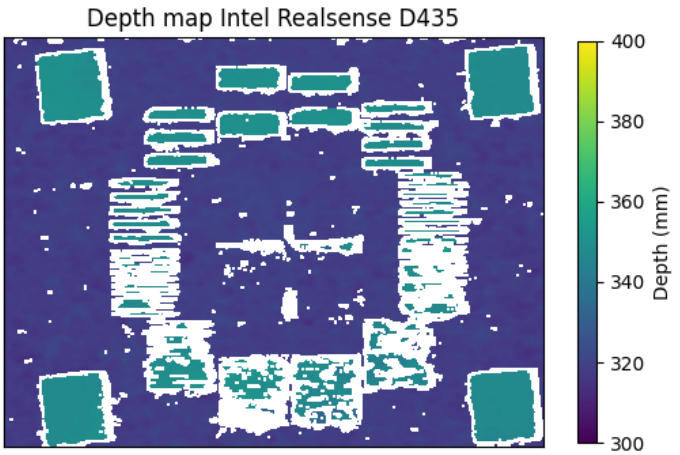
- **Deadleaves background 3cm behind the chart**





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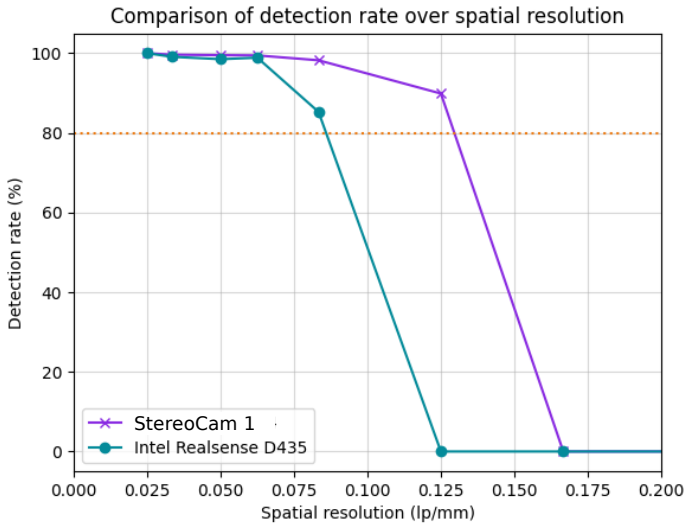
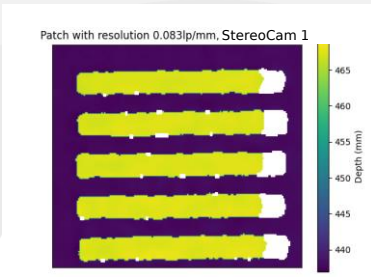
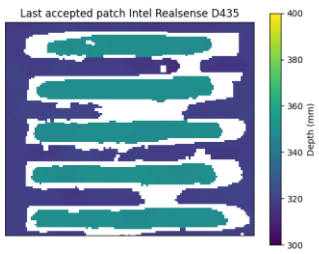


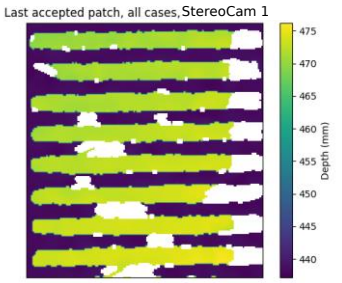
If we define a threshold at 80% for detection rate, we deduce that the spatial resolution of the Intel RealSense D435 device is 0.083 lp/mm.
And the spatial resolution of the StereoCam 1 device is 0.125 lp/mm.

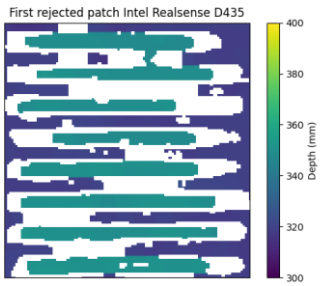
Below, the last patch detected by Intel RealSense D435, also detected by StereoCam 1:



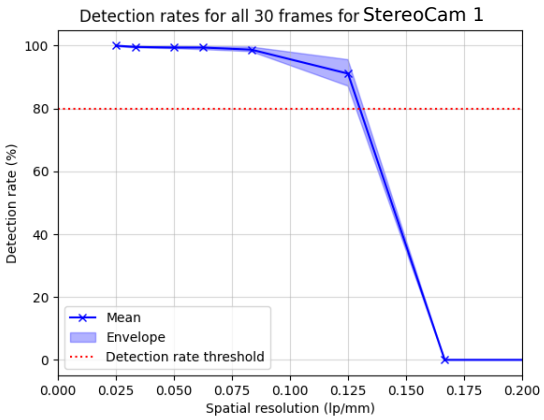


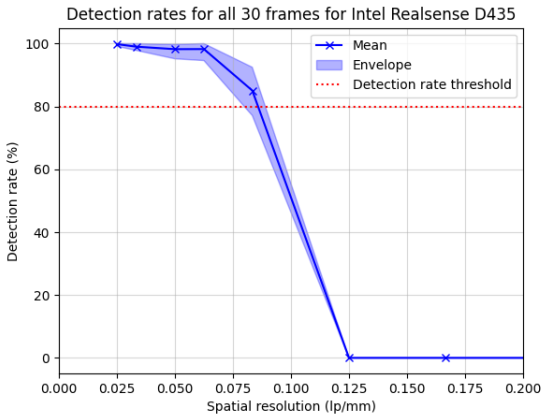
Below, the patch with small slit (patch of spatial resolution 0.125 lp/mm) that StereoCam 1 detects well and Intel RealSense D435 does not:





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





Over 30 shoots, the detection rate for each patch of the chart can vary. By displaying the envelop of its possible values over frames, we see that the spatial resolution is not always the same for Intel Realsense D435 (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

Intel RealSense D435	Spatial resolution : minimum slit size detected		
	Min	Average	Max
In line pairs per millimeter	0.063	0.081	0.083
In % of image height	0.017	0.023	0.023

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

In few rare frames, the detection rate over 0.083 lp/mm patch by Intel RealSense D435 goes slightly below 80%, making the patch invalid.

If we keep strictly to the 80% fill rate threshold, in these rare cases, the spatial resolution can be reduced to 0.063 lp/mm.

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 both devices
  - 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.

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

Acrylic paint tubes

Chalks and pencils

Brushes and slate

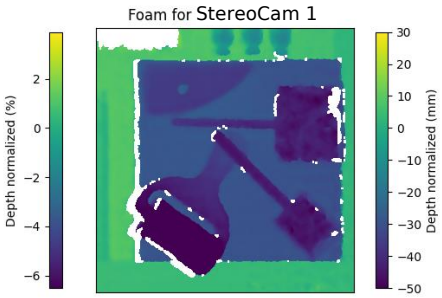
Black rectangle over white rectangle

Yellow and black foam

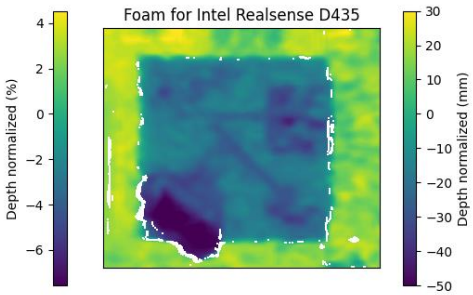
- **Foam texture**

StereoCam 1

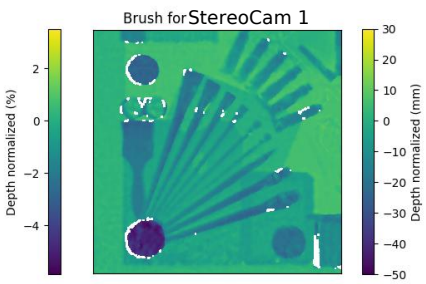
Intel RealSense D435



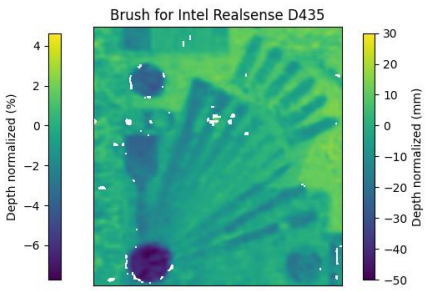
Estimated shooting distance : 767 mm



Estimated shooting distance : 661 mm



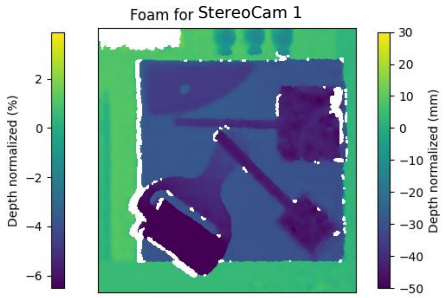
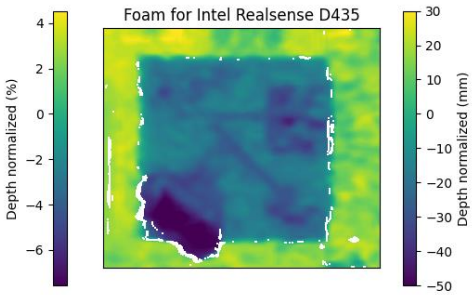
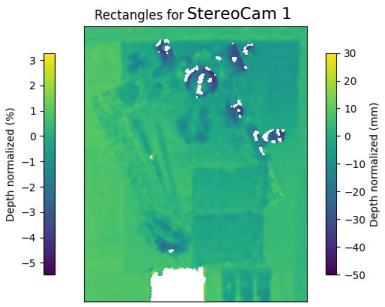
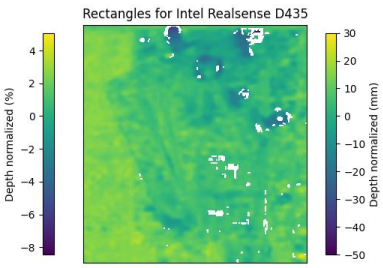
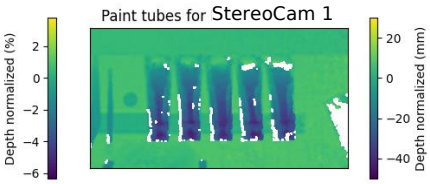
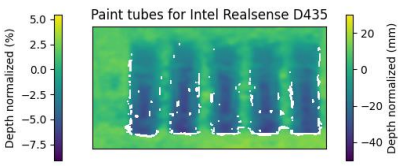
Estimated shooting distance : 852 mm



Estimated shooting distance : 647 mm

The black foam for Intel RealSense D435 is really noisy. The noise is due to the color, but also to the foam texture, as the yellow foam is noisy but to a lesser extent.

- **Black parts**

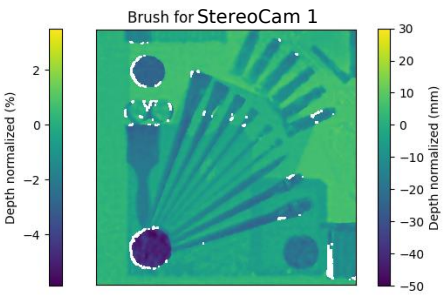
	StereoCam 1	*Intel RealSense D435*
		
	Estimated shooting distance : 767 mm	*Estimated shooting distance : 661 mm*
		
	Estimated shooting distance : 915 mm	*Estimated shooting distance : 591 mm*
		
	Estimated shooting distance : 788 mm	*Estimated shooting distance : 550 mm*

Both devices can barely tell the black and white rectangles apart, but since the black rectangle is thin, it was expected. However, the black part is way noisier than the white part, especially for StereoCam 1.

For every surface, the noise of StereoCam 1 seems lower than Intel RealSense D435.

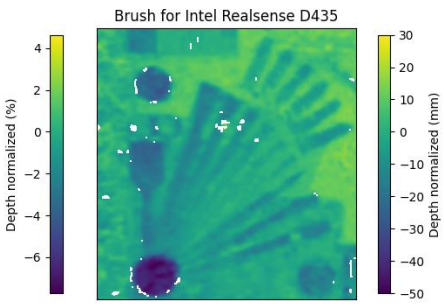
- **Perceptual spatial resolution**

StereoCam 1



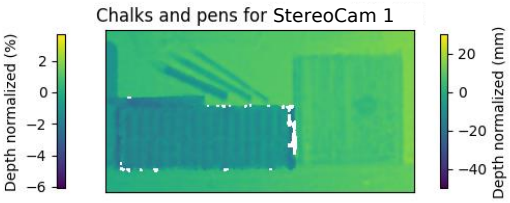
Estimated shooting distance : 852 mm

Intel RealSense D435

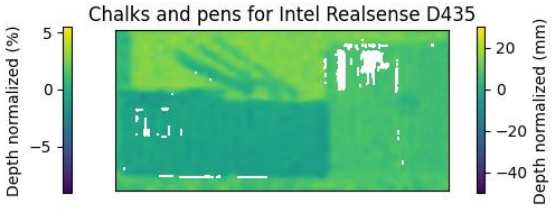


Estimated shooting distance : 647 mm

- The Intel RealSense D435 struggles to detect the thinnest brushes unlike the StereoCam 1 that can correctly detect them.
- This is expected since the Intel RealSense D435 has a lower spatial resolution than the StereoCam 1.



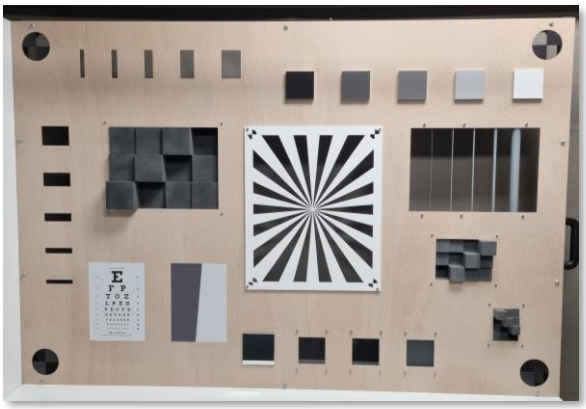
Estimated shooting distance : 820 mm



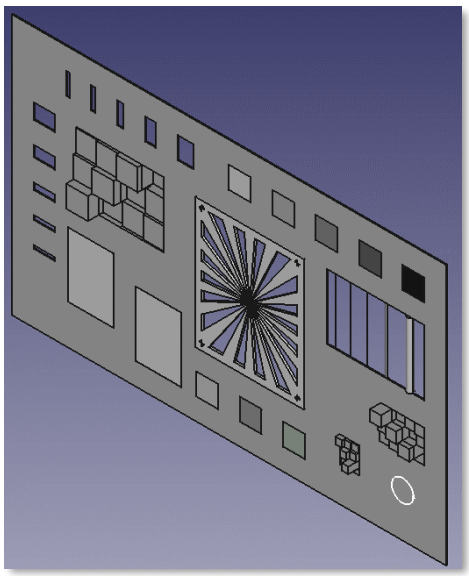
Estimated shooting distance : 551 mm

Vertical chalks and pencils can be used to compare spatial resolution

- The Intel RealSense D435 can barely see the chalks and cannot differentiate the pencils
- The StereoCam 1 sees the chalks slightly better but the pencils also cannot be distinguished.



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 framing of the different parts
    - Daylight simulation D65 at 200 lux for full framing
  - 1 picture is taken for each light conditions.

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

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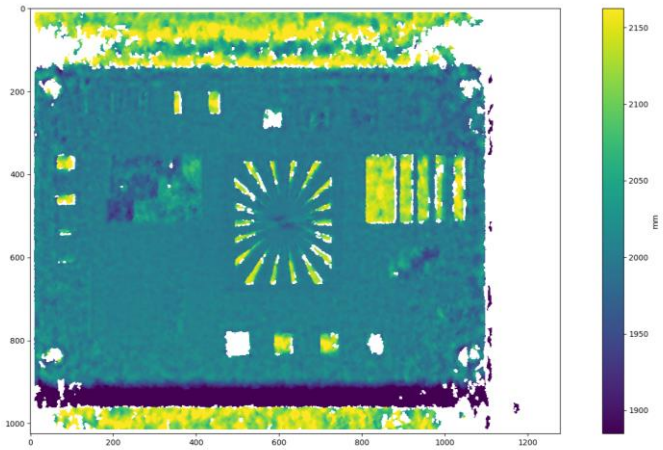
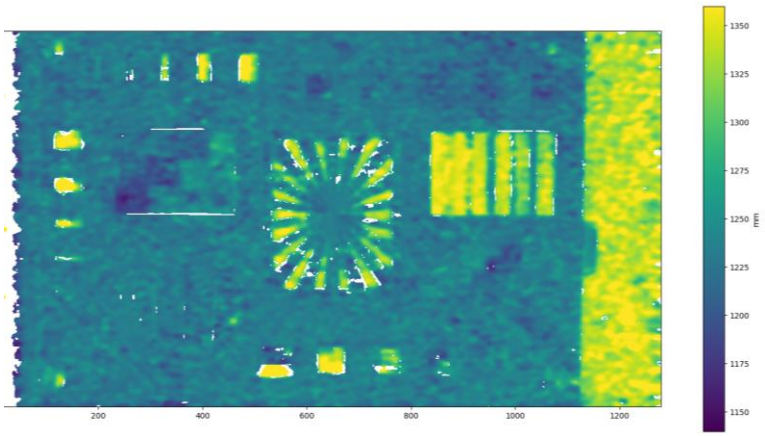
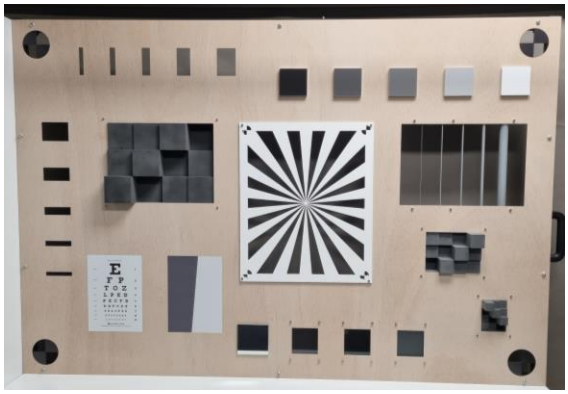
- **Comparisons on global chart**



StereoCam 1 depthmap



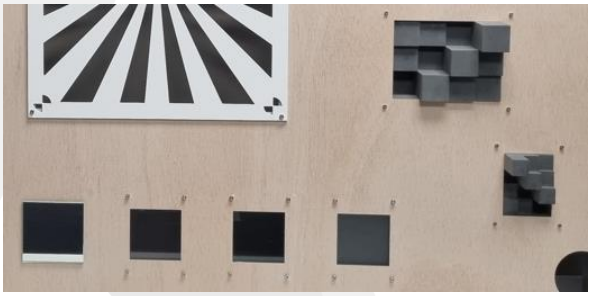
Intel RealSense D435 depthmap



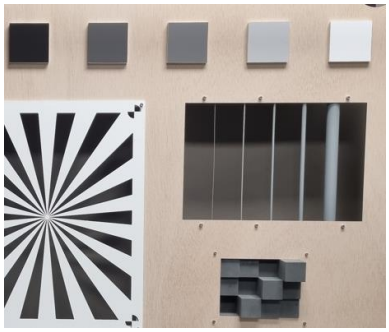
DXOMARK 3D chart

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

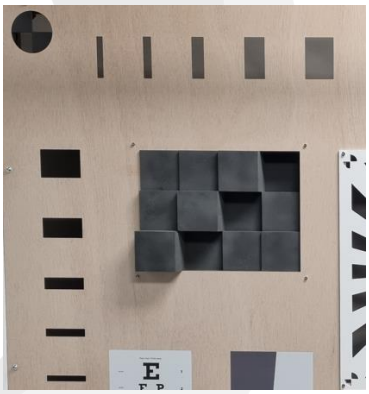
Boehler star



Mirror, transparent objects

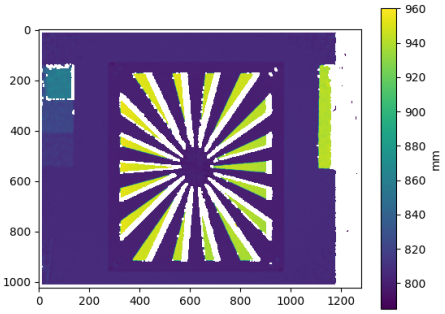


Poles and gray patches

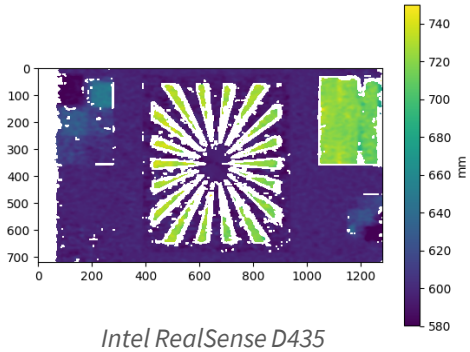


Large stair pattern and holes

- **Boehler star**



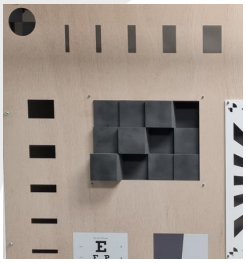
StereoCam 1

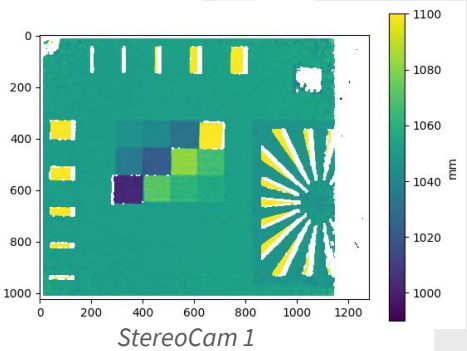


Intel RealSense D435

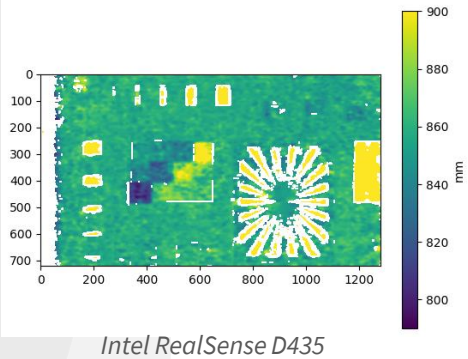
- Used to estimate the spatial resolution of cameras.
- Draw concentric circles from the center of the chart and keep the biggest circle that does not have any invalid pixel, or the smallest circle with at least one invalid pixel.
- Compute spatial resolution by dividing the number of white (or black)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

- **Large stair pattern and holes**





StereoCam 1

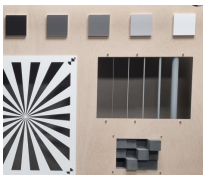


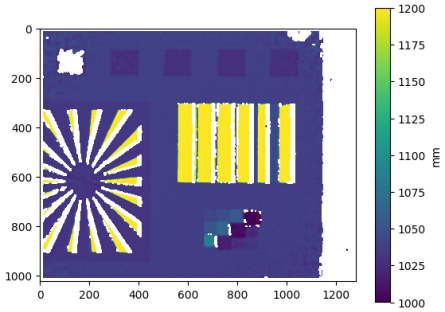
Intel RealSense D435

- 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.

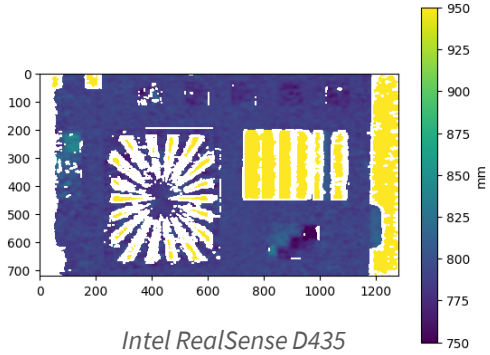
- The part with the vertical and horizontal holes could be used by defining two patches : one containing every vertical holes and one for the horizontal ones. Then count the number of holes seen by the cameras on each patch like on the spatial resolution 3D chart.

- **Poles and gray patches**

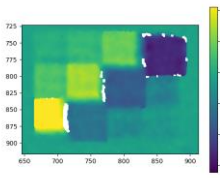




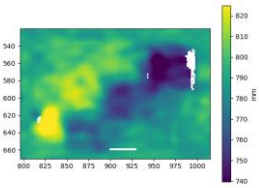
StereoCam 1



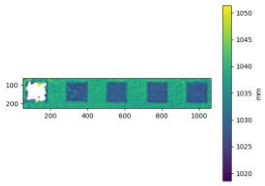
Intel RealSense D435



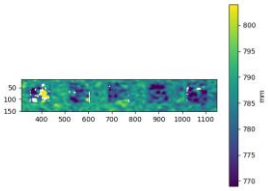
Medium stairs StereoCam 1



Medium stairs Intel RealSense D435



Gray patches StereoCam 1

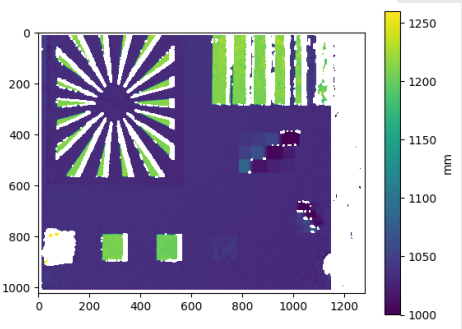


Gray patches Intel RealSense D435

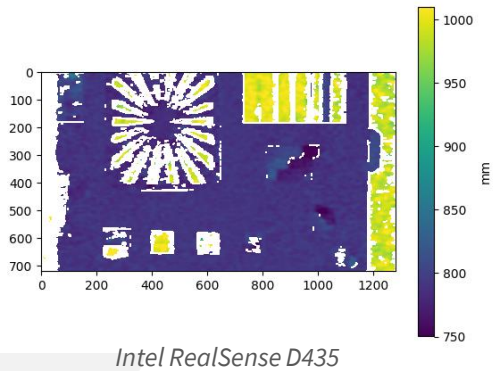
- Define a patch containing all the poles and read each row of the patch. Count the number of poles seen on the patch in a similar way as what is done for the patches of the spatial resolution 3D chart.

- 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



Intel RealSense D435

- 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

Spatial Noise

Relative Spatial noise	ambient light (lux)	object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
	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

Temporal Noise

Relative Temporal noise	ambient light (lux)	object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
	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

Intel RealSense D435

Spatial Noise

Relative Spatial noise	ambient light (lux)	object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
	0	0.225	0.262	0.212	0.222	0.106	0.211
	99	0.180	0.214	0.176	0.183	0.152	0.169
	402	0.224	0.222	0.190	0.192	0.138	0.191
	1007	0.275	0.221	0.186	0.230	0.162	0.223
	1850	0.302	0.276	0.209	0.237	0.141	0.258
	4350	1.29	0.347	0.288	0.311	0.238	0.298
	7770	268	47.9	9.14	1.19	0.421	0.946

Temporal Noise

Relative Temporal noise	ambient light (lux)	object reflectance					
		2.8%	9.3%	16%	36.4%	43.4%	85.7%
	0	0.396	0.295	0.223	0.238	0.149	0.186
	99	0.457	0.505	0.431	0.529	0.374	0.470
	402	0.514	0.606	0.553	0.732	0.509	0.661
	1007	0.743	0.653	0.568	0.777	0.544	0.789
	1850	1.08	0.831	0.707	0.814	0.528	0.827
	4350	2.34	1.35	1.21	1.24	0.875	1.06
	7770	9.88	13.1	5.58	2.54	1.79	2.04