DEPTH QUALITY DEFINITION AND MEASUREMENT

John Sweetser

RealSense Group, Intel Corp

DISCUSSION TOPICS

- WHAT IS DEPTH QUALITY AND WHAT MAKES A GOOD DEPTH CAMERA?
  - QUANTITATIVE & QUALITATIVE ASSESSMENT
- DEPTH QUALITY EVALUATION
  - PERFORMANCE METRICS (KPI'S)
  - TEST AND CHARACTERIZATION METHODS AND TOOLS
  - PERFORMANCE CRITERIA (STANDARDS)
- SAMPLE DEPTH QUALITY TEST DATA
- FACTORS THAT INFLUENCE DEPTH QUALITY
- KPI'S NOT CURRENTLY TESTED
- EFFECT OF CAMERA CALIBRATION ON DEPTH QUALITY

WHAT IS DEPTH IMAGE QUALITY?

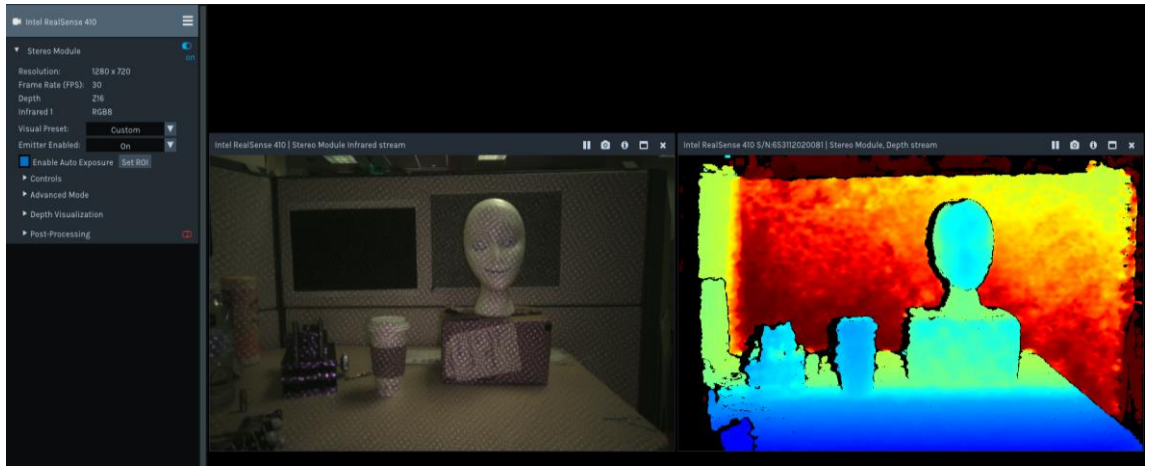
- **Depth Camera:** adds the distance (Z) dimension to traditional 2D RGB or B&W image. *attributes such as sharpness, distortion/uniformity, color fidelity, noise, and dynamic range, etc.*
- **Depth Image:** typically represented as 2D ‘depth map’ or 3D ‘point cloud’.
- **Depth Image Quality:** Evaluation of the depth image quantitatively (using predefined metrics) or qualitatively (using visual clues).

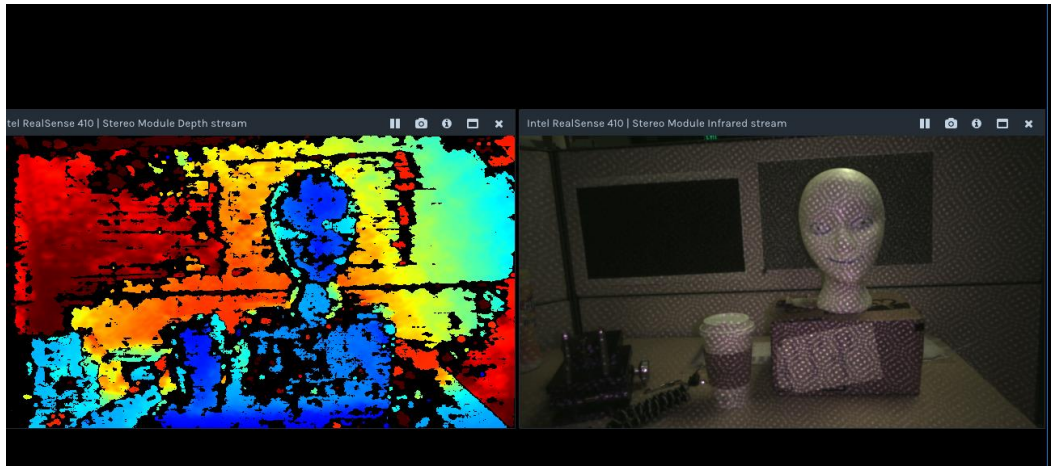
Typically, quantitative metrics are used in simplified scenes and controlled conditions and qualitative assessment is used in arbitrary or complex scenes

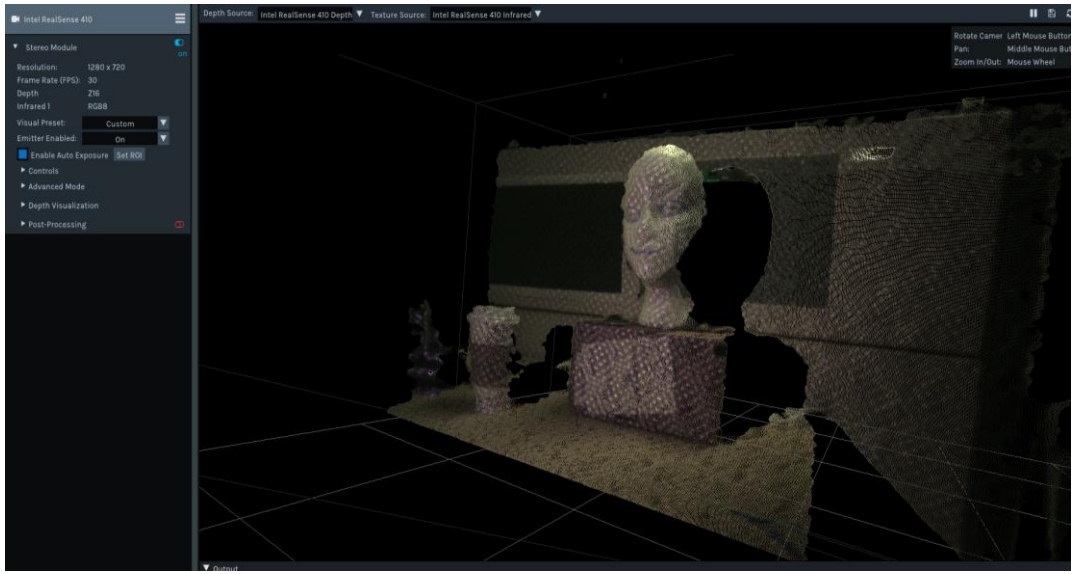
WHAT MAKES AN IDEAL DEPTH CAMERA?

1. **See everything:**
    a) All conditions: From darkness to bright sunlight
    b) All materials & objects
    c) All ranges
    d) No interference
2. **See it with little noise (high precision)**
3. **Get exact distance (high accuracy)**
4. **And cheap, small, low-power, wide field-of-view, high-speed, color…**

SAMPLE "GOOD" AND "BAD" DEPTH IMAGES







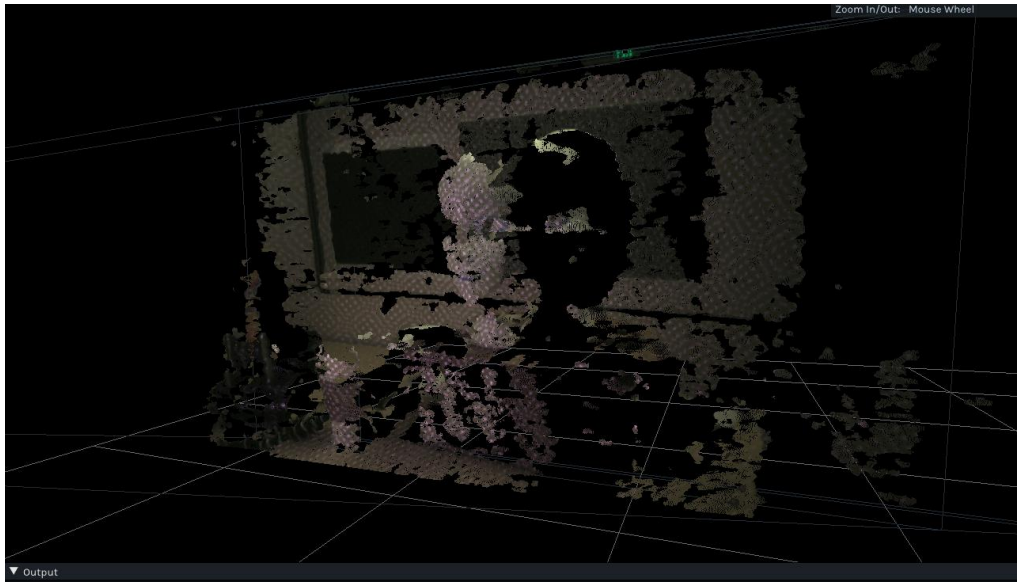
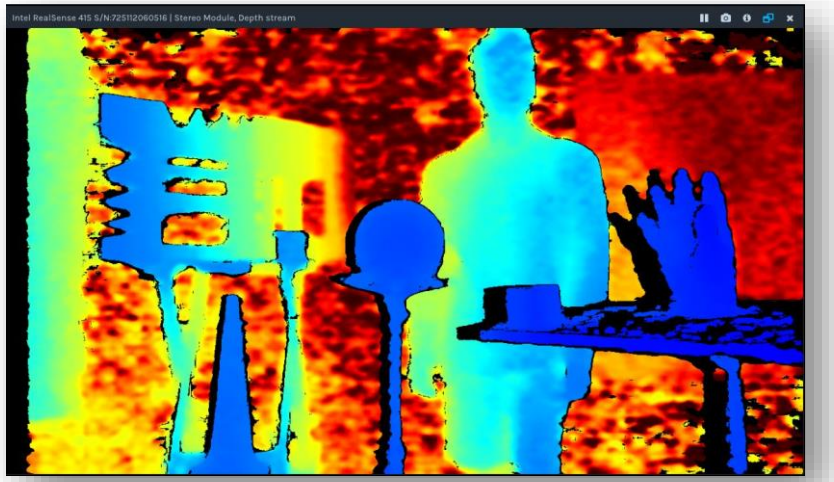


IMAGE QUALITY EVALUATION

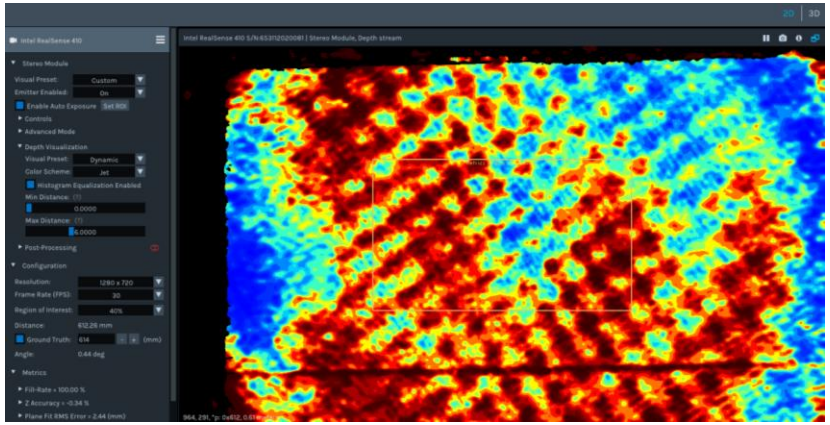
Qualitative

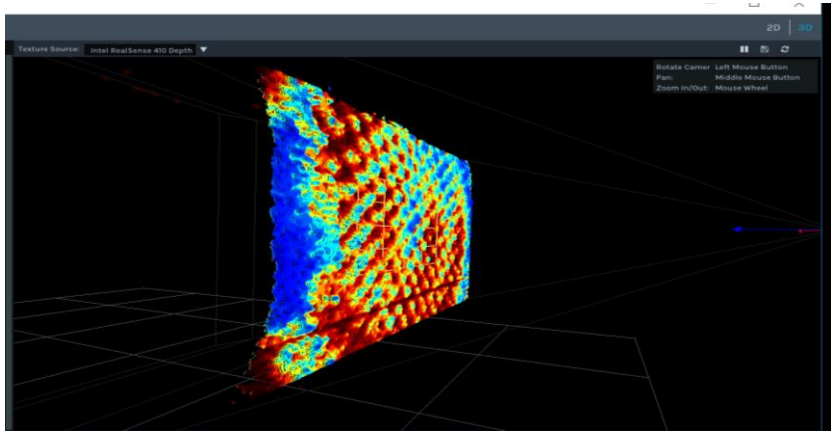
Based on visual inspection of the depth map or point cloud and assess quality based on known properties of the scene



Quantitative

Based on measurements performed on the camera, depth data can be analyzed to produce metrics designed to quantify performance.





KEY DEPTH METRICS

A very good snapshot of depth performance can be seen from the histogram of flat target depth values. Ideally, this distribution is narrow, centered near the known (ground truth) distance, and has a complete number of sample points.

- **Fill Ratio:** Percentage of "valid" (w/non-zero depth) pixels over ROI.

*Typical good value: >99%, <98% poor

- **Z-Accuracy:** Offset of mean/median depth from ground truth.

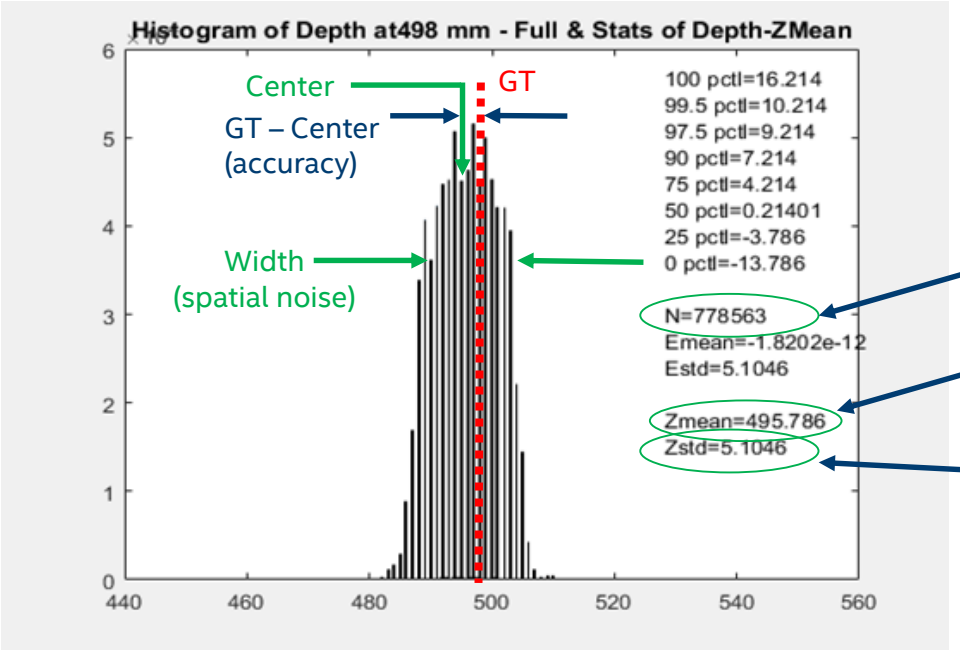
Typical good value: <1%, >2% poor

- **RMS Error (Spatial Noise):** Variation in depth over ROI.

Typical good values: <0.4% (~0.2 pixels), >1% poor

- **Temporal Noise:** Variation in depth per pixel over time (frame-to-frame).

Typical good values <0.2%, >0.5% poor



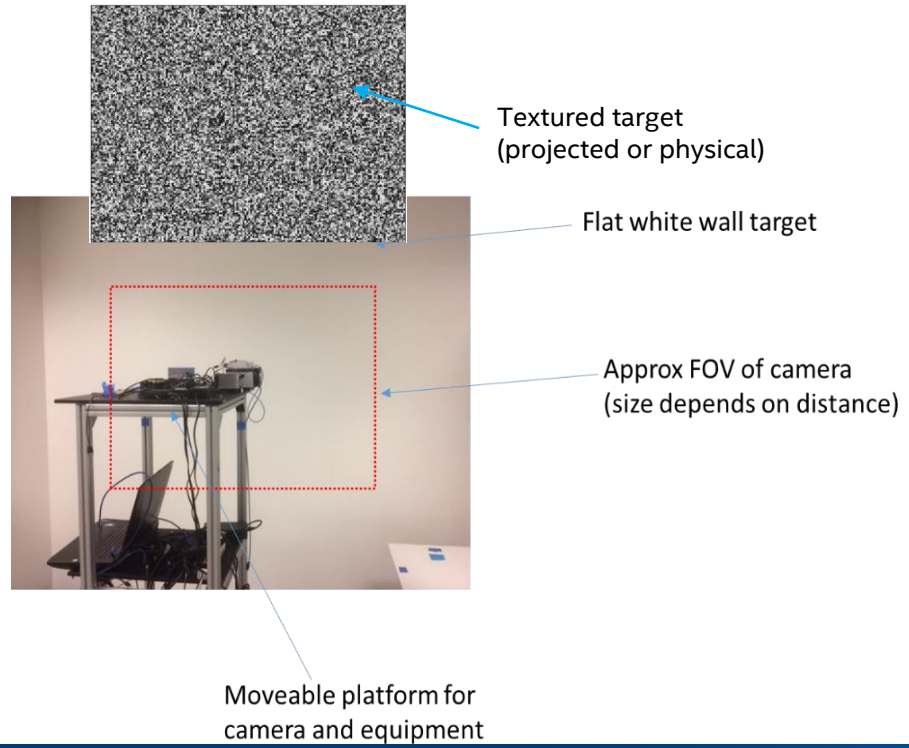
Sample of raw depth data from a DS5 camera during a flat target test

*For D415 @ Z ~ 1m, HD resolution, center 40% ROI, Active
Consult datasheet for latest specifications

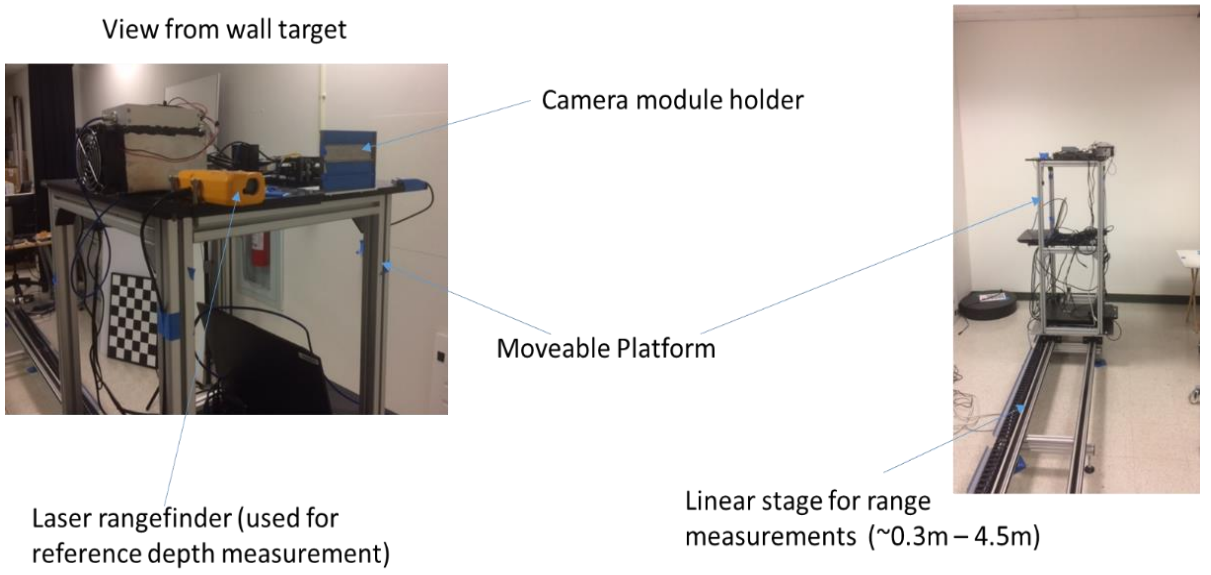
Metric values may be expressed in absolute units, e.g., mm or as % of depth.

IMAGE QUALITY MEASUREMENT – BASIC Z-PERFORMANCE

- Quantitative depth quality is evaluated primarily based on “flat target” testing (either textureless or textured). This provides a simple, well-defined, and standardized environment to capture images and compute metrics.
- In all measurement methods, image data is captured and then analyzed, either off-line or in real-time, to compute the performance metrics.
- Measurements are performed as a function of distance from the target and may be run for different resolutions, frame rate, depth settings, ambient conditions, etc.

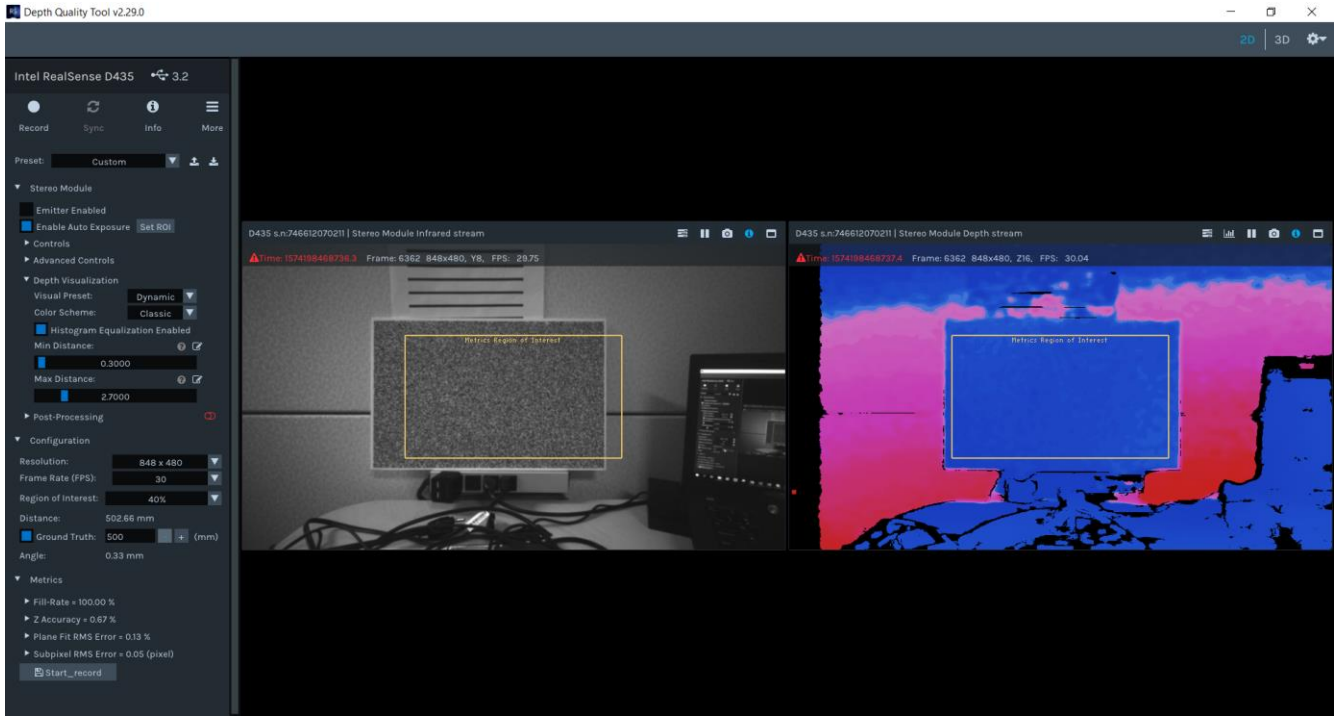


A typical camera characterization apparatus



DEPTH QUALITY MEASUREMENT TOOLS

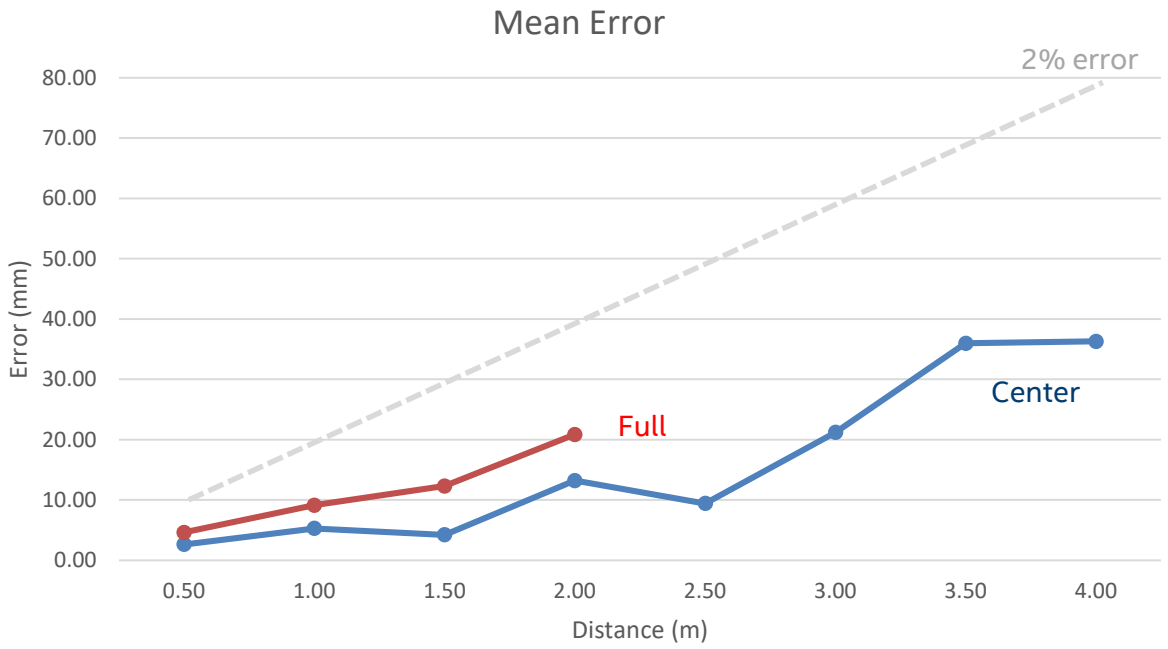
- **Offline**: Typically used for official validation. Depth data captured and analyzed later.
- **Real-time**: Test application that captures, analyzes data, and computes metrics in real-time (per frame or based on sequence). Metrics are usually a subset of full validation that contain only the key metrics needed for basic depth camera health check.
- For D400 cameras, **Depth Quality Tool** is the recommended tool for basic real-time measurements

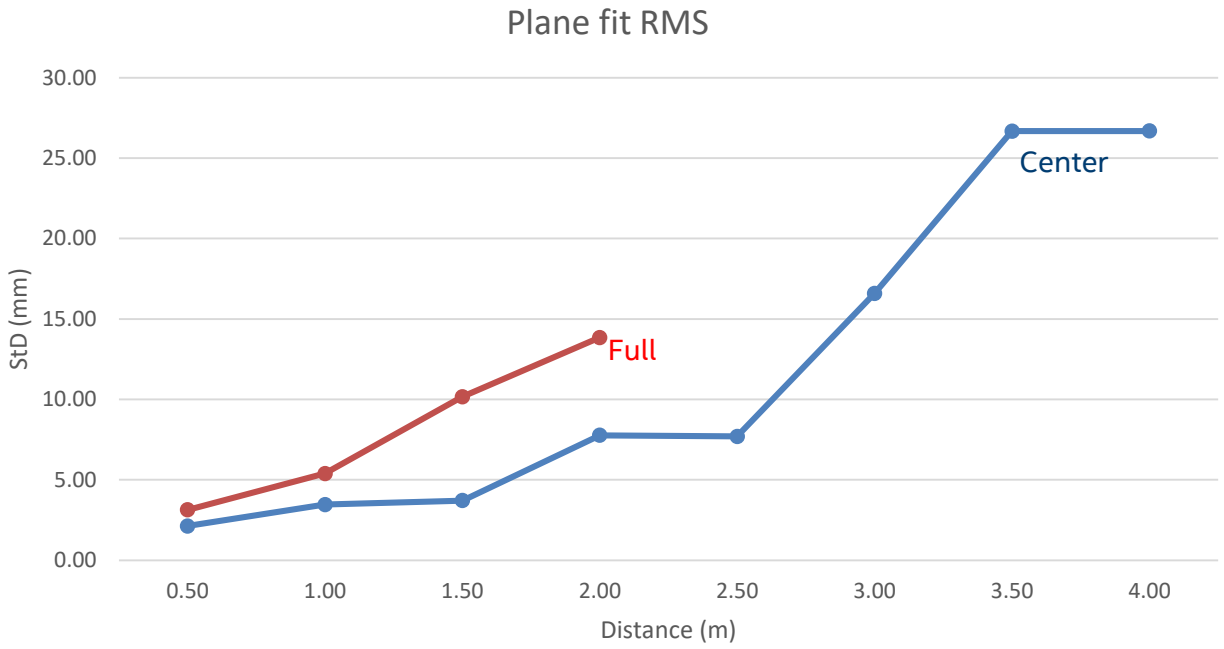


SAMPLE DEPTH QUALITY DATA – ASR SHORT RANGE

1280x720, 30 FPS, P=210mW, AE

Target: Flat white wall, ~100-200 Lux fluorescent lighting



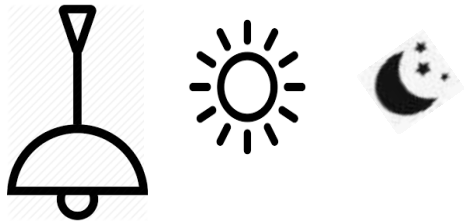


mean Error (mm)								
SN	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00
Center 40%	2.62	5.28	4.21	13.19	9.41	21.20	35.95	36.28
Full FOV	4.60	9.12	12.29	20.85				

std (mm)								
SN	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00
Center 40%	2.13	3.46	3.71	7.77	7.69	16.59	26.68	26.69
Full FOV	3.13	5.39	10.16	13.85				

FACTORS AFFECTING DEPTH QUALITY

Product use cases largely drive environment in which depth quality is assessed from among factors below



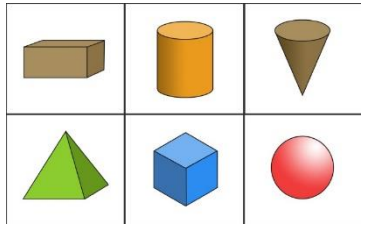
Lighting - should be tested in different lighting conditions in which the product is used. Different technologies will behave differently in specific lighting conditions.

Different Materials, Flat uniform surfaces (Ex. White board/wall), Textured Patterns

- Ex: Autonomous vacuum cleaners would test different floor materials such as light and dark tile, wood, carpet, and linoleum; body scanning would test materials that might be worn by the user and different colors/patterns of that material.

Range or Distance

- Ex 1: A room scanning device designed to remain in the center of a large space and rotate while capturing walls, ceiling, and objects in detail will require accurate depth at long distance.
- Ex 2: A robot or drone in motion can use depth at longer distances for path planning without requiring accurate depth at those distances.



Shape

- Quantitative testing currently done with flat targets due to Ground Truth availability.
- Qualitative testing looking at the point cloud for edge fidelity, flat or round surfaces, and proper angles on different geometric shapes.

ADDITIONAL 3D IMAGE QUALITY CHARACTERISTICS OF INTEREST

Types of quantitative testing/characterization not currently done (@ Intel)

- **2D (x,y) spatial resolution:**

Resolution chart with variable width slots or features.

- **Minimum detectable object size:**

Targets with variable size objects (spheres, cylinders) - 3D resolution.

- **Edge Fidelity:**

Sharpness of edges (depth discontinuities).

- **Full 3D Object/Scene Reproduction:**

Error in reproducing a specific scene or object (e.g., mannequin). RMSE from ground truth.

EFFECT OF CALIBRATION ON DEPTH QUALITY

- Approximately 27 parameters that are determined during a full calibration procedure:
  - Intrinsic – individual camera factors (PP, FL, distortion)
  - Extrinsic – relative left-right camera position & orientation

- Post-factory re-calibration can usually be done by adjusting 1-2 intrinsic and/or extrinsic parameters:
  - Px/Py – shift of lens-sensor position to adjust disparity or alignment of images (~0.2 – 1 pixel).
  - Rx/Ry/Rz – rotation of camera for same purpose (<0.2 deg).

Most degradation of depth quality can be corrected quickly with proper adjustment of one or more of these parameters.

Temperature variations, mechanical shock/vibration or stress can lead to degradation that requires re-calibration.

BACKUP

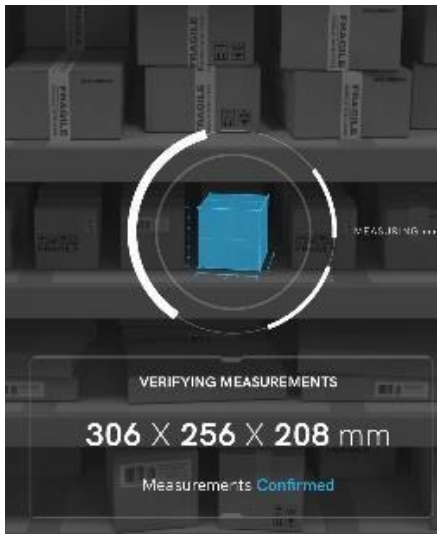
OTHER PERFORMANCE METRICS

“Fill Factor” – Combines fill ratio, Z accuracy, and RMSE in to a single figure of merit.
Example: % of all pixels that are within 3% of ground truth distance.

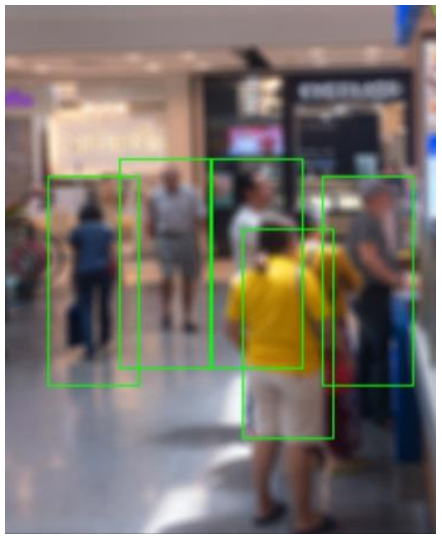
3D CAMERA APPLICATIONS

Robotics

Scanning



Measurement



Tracking

Facial Authentication

STEREO CAMERAS
D415 D435
D435i D465

Q1 2020 Launch

TRACKING CAMERA
T265

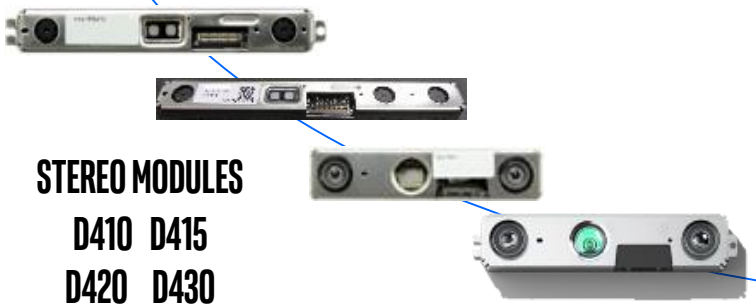
LiDAR CAMERA
L515
Q1 2020 Launch

intel REALSENSE™ TECHNOLOGY

CODED LIGHT CAMERA
SR305

CODED LIGHT MODULE
SR300

D4 VISION PROCESSOR AND
BOARD



STEREO MODULES
D410 D415
D420 D430

DEPTH QUALITY DEPENDENCE ON TECHNOLOGY

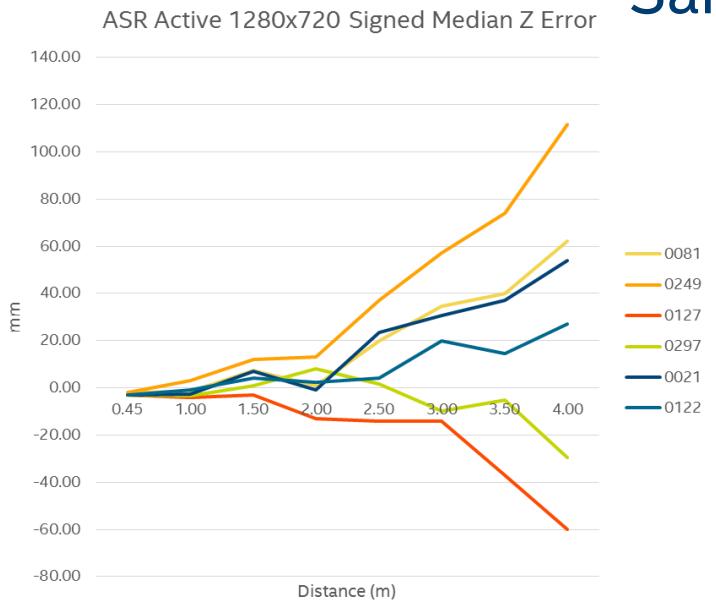
- Depth quality evaluation methods and metrics in general do **NOT** depend on underlying technology, however the image quality itself may have technology-specific characteristic.

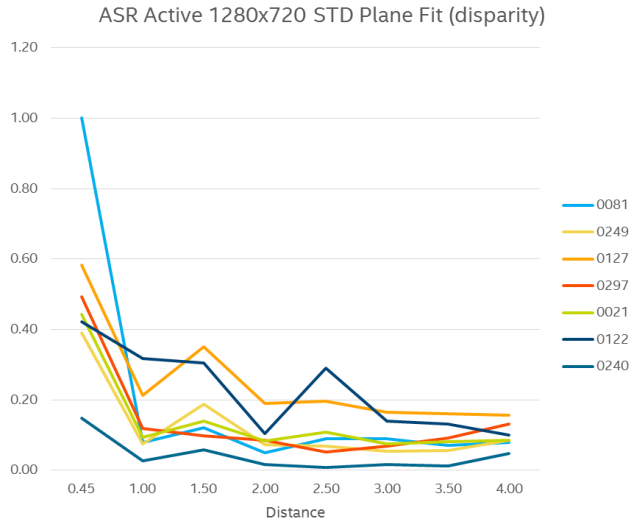
- Active depth Technologies such as Structured Light and TOF rely on projected light and therefore work well in scenes with ***little texture*** and ***low lighting***, such as uniform walls in a factory or office environment. Therefore, these are the conditions recommended for evaluation.

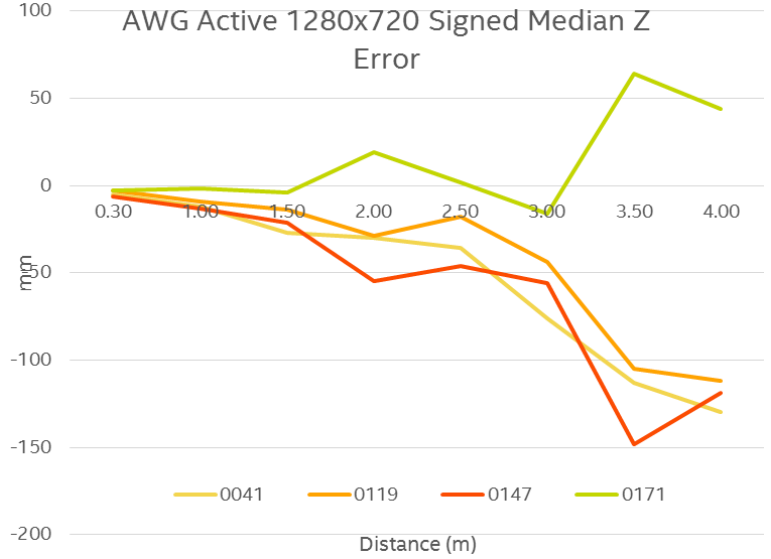
- Stereo depth (such as D400 family) which does not rely solely on projected light and can benefit from natural texture and ambient lighting, may be evaluated in a variety of scenes and conditions.

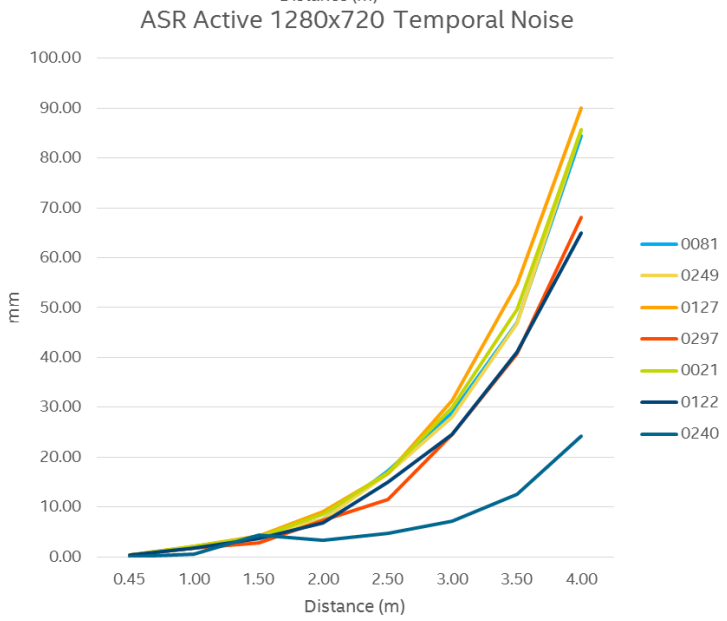
	Lighting			**Target Scene**				**Distance**	
	Low Light	Sunlight	Indoor normal light	Uniform, high reflectivity surface (Ex. Flat White wall)	Texture	Geometric shapes/edges	Materials (Low Reflectivity, Diffuse, Dark)	Near	Far
Stereo									
Active Stereo									
TOF									
Structured Light									

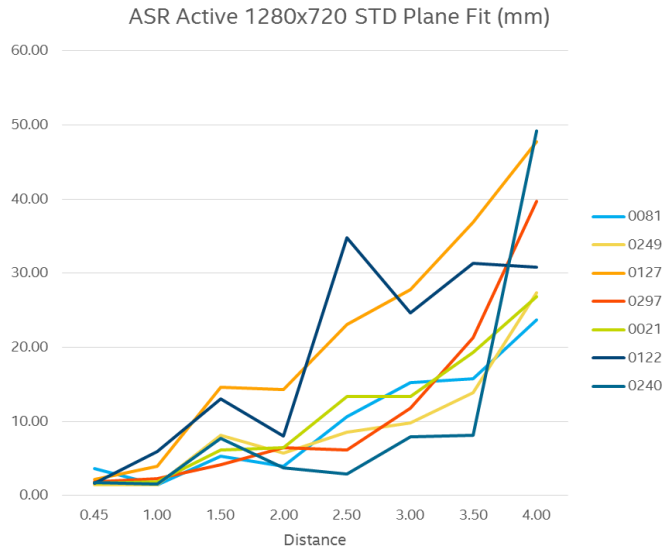
Sample Depth Data – More examples

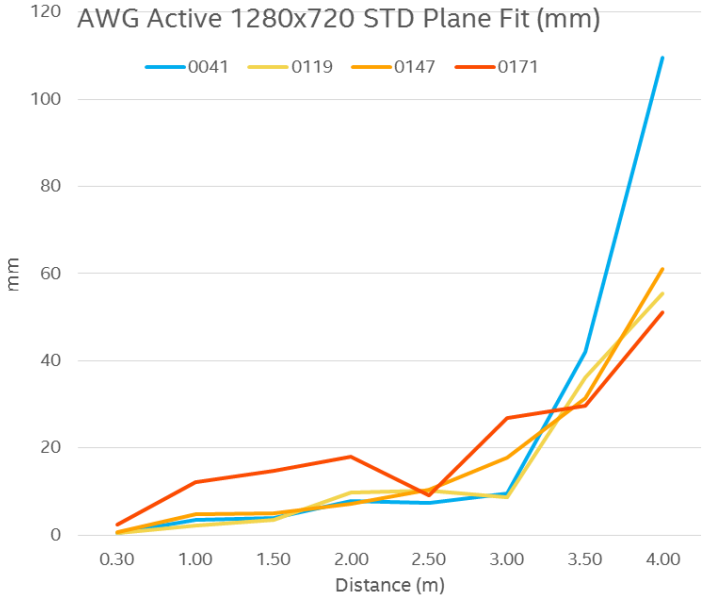












INTEL® REALSENSE™ D400 SERIES DEPTH QUALITY

- RealSense™ 400 series provides excellent depth quality under all lighting conditions, and longer range
- Great configurability - Viewer and Depth Quality tools in SDK provide different Presets (High Density, High Accuracy, Close Range, Hand etc.) OR users can tune their own for their applications

2D RGB Image

HIGH DENSITY PRESET

D415

DEPTH MAP(1280x720)

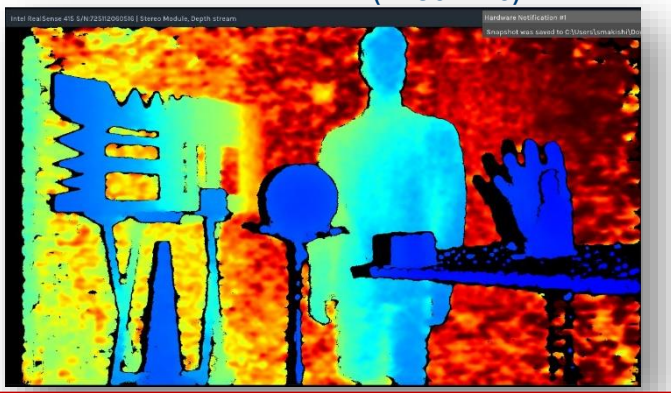
POINTCLOUD WITH COLOR TEXTURE

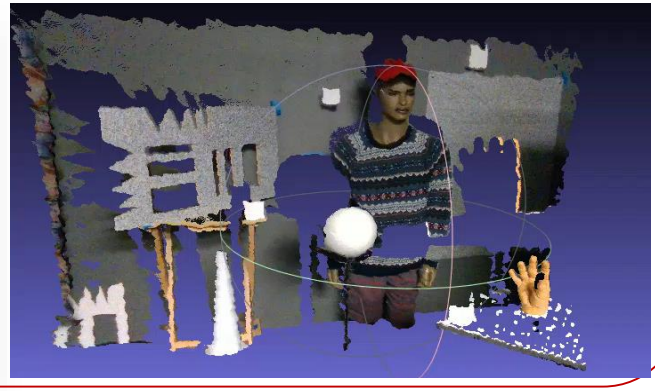
Ex. Usages:

BGS

3D Enhanced Photography

Collision Avoidance

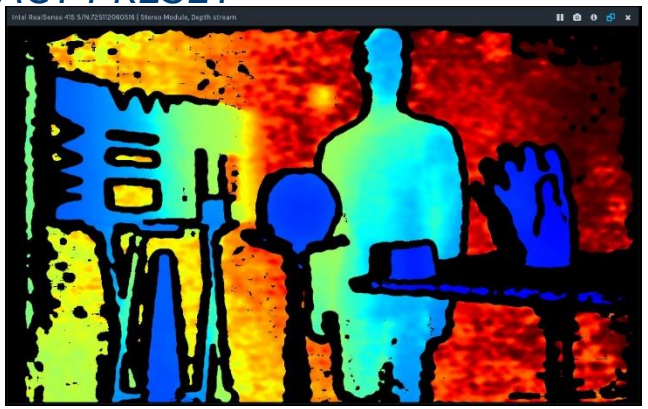




HIGH ACCURACY PRESET

Ex. Usages:

3D Object Scan



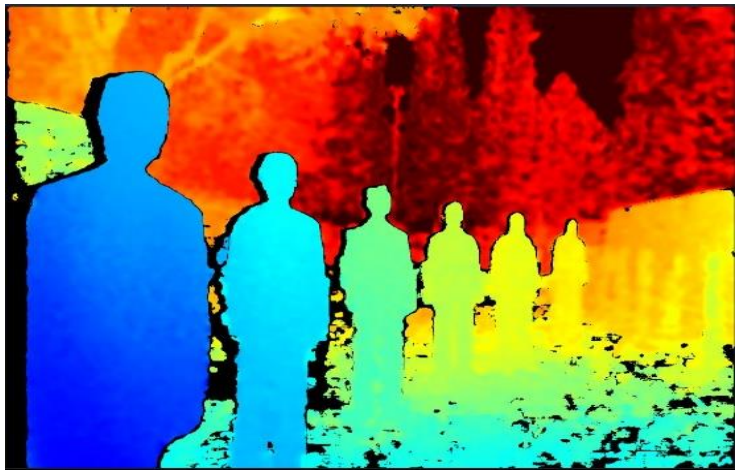
3D test scene configured to include a variety of object types, textures and distances, captured through RealSense™ Viewer 2.8.1.

INTEL® REALSENSE™ D415/D435 OUTDOORS

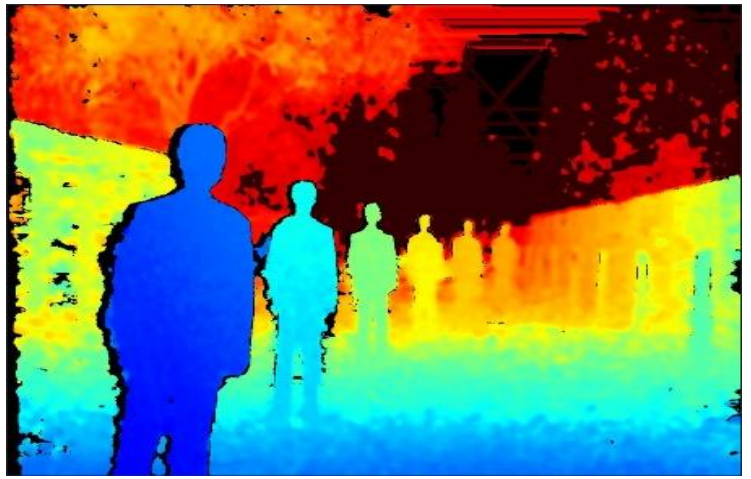
- Stereo takes advantage of visible light for best Outdoor performance and Range
- Projector can be off with enough visible light and texture => low power!

2D RGB

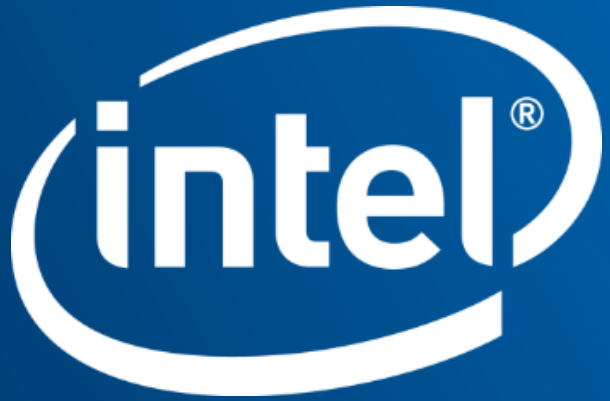
DEPTH MAP **415**



435 (Note the Wider FOV**)**



3D test scene outdoors captured through RealSense™ Viewer 2.8.1 – 10m?.


intel