GUIDEBOOK

TIME-OF-FLIGHT FORGES AHEAD

DESIGN TIPS TO BOOST 3D PERFORMANCE AND CUT INTEGRATION TIME & COST

To harness Time-of-Flight (ToF) 3D technology, engineers need to first consider specific elements of their application. Every 3D technology offers benefits and limitations—but by first understanding the environment where the application will run and the target object properties in the scene, one can optimize the benefits of Time of Flight.

WHAT'S INSIDE:

LUCID VISION LABS

OUTDOORS vs CONTROLLED ENVIRONMENTS

Before dealing with camera system specs, the primary consideration is— will the application be used inside, sheltered from outside elements, or will it be used outdoors? Sheltering or enclosing a ToF system gives added control over certain variables and limits random environmental factors. For example, an indoor application allows a degree of control over lighting and temperature, both of which impact ToF performance. In addition, if it is an outdoor application, certain camera properties are required to handle the variable environmental challenges, dictating an IP67 case and a 940nm light emitter wavelength.

AMBIENT LIGHT

For ToF cameras to work, they must measure the phase-shift or pulse delay of emitted light, free of as much ambient light as possible. The emitted light, from either VSCELs or LEDS attached to the camera, is a specific wavelength – most commonly 850nm for indoor applications and 940nm for outdoors. Both wavelengths are used because they are outside the visible spectrum (380 to 740 nm). For instance, while the LUCID Helios compact ToF camera is able to cancel out most ambient light, any extra light may reduce the dynamic range of the sensor. In some cases, pixel saturation occurs if intense ambient light is present. **For outdoor applications**, it is important to choose a ToF camera that uses 940nm emitted light, because that wavelength is where a naturally occurring dip in the sunlight spectrum occurs. In addition, a bandpass or a longpass filter is needed to remove light at other wavelengths.

figure 1: *Sunlight Spectrum*

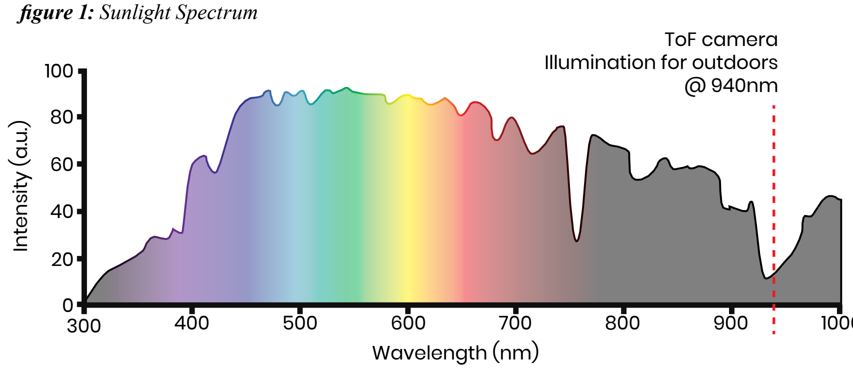
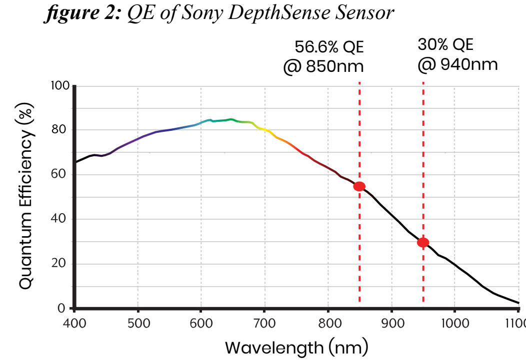


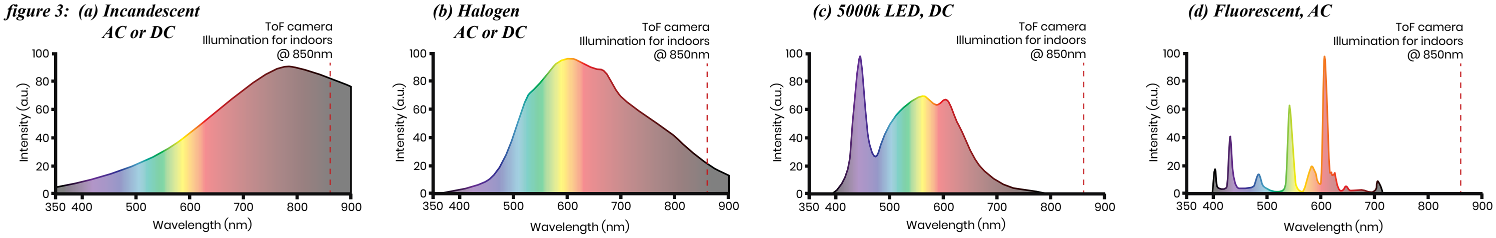
figure 2: *QE of Sony DepthSense Sensor*



The full sunlight spectrum can interfere with the emitted light from ToF cameras. Thus outdoor ToF cameras are set to emit light at 940nm, where a natural dip in the spectrum of sunlight occurs ***(figure 1)***. However, a trade-off happens with lower sensor sensitivity (quantum efficiency) the farther up the spectrum the camera operates ***(figure 2)***. Lower sensitivity results in less usable data for depth calculations. To compensate for lower sensitivity, higher power LEDs or VSCELs are used.

Image 1
A controlled environment maximizes ToF performance. In this image, all sources of external sunlight are eliminated and the interior lighting utilizes high quality DC LED tubing.

Indoor spaces such as industrial, manufacturing, and warehousing facilities usually have few or no windows, thus eliminating most sunlight. Therefore indoor ToF cameras take advantage of the higher sensitivity wavelength of 850nm ***(figure 2: 56.6% QE at 850nm)***. The typical amount of ambient light produced by indoor lighting is easily cancelled out by the camera with minimal loss to dynamic range. However, older traditional types of lighting such as incandescent or halogen can reduce the camera's dynamic range if they are too intense or too close to the camera. Also, AC lighting (i.e. fluorescent, incandescent and cheaper LEDs) may create a "pulsing" effect due to its alternating current ***(Image Set 2, page 4)***. These pulses may reflect off shiny surfaces in the scene. Overall, it is recommended that uniform, DC lighting such as high quality LEDs be used for indoor environments.



Various indoor lighting spectrums are shown above ***(figure 3)***. For best ToF results it is important to minimize outdoor sunlight and indoor lighting interference from older traditional light sources such as incandescent and halogen. High quality LEDs work best with indoor ToF. AC light sources such as fluorescent lighting can sometimes create a pulsing effect due to its alternating current.

COMPENSATE FOR TEMPERATURE DRIFT

The accuracy and precision of ToF cameras are dependent on camera temperature. Temperature changes cause depth calculations to drift. For example, as the camera temperature rises after being turned on or during any large ambient temperature change, objects in the scene "drift" closer or farther away from the camera. Thus proper camera calibration is essential for consistent performance within the stated operating temperature range.

Some ToF camera manufacturers calibrate their cameras to a specific operating temperature after a recommended warm up period, typically 20 to 40 minutes. But what about other temperature changes after warm up? In large indoor spaces, such as warehouses, different temperatures are found in different sections, such as near bay doors or refrigeration systems, as well as at different vertical levels (closer to the ground versus ceiling). The Helios ToF camera is calibrated to deal with temperature changes by compensating for depth drift at multiple temperature readings.

Such calibration greatly reduces drift during temperature transients. However, it is important to understand that calibrated drift compensation can never fully remove all drift. Ultimately a camera calibrated with temperature-drift compensation operating in a "stable" ambient temperature is the wisest scenario for consistent ToF camera performance.

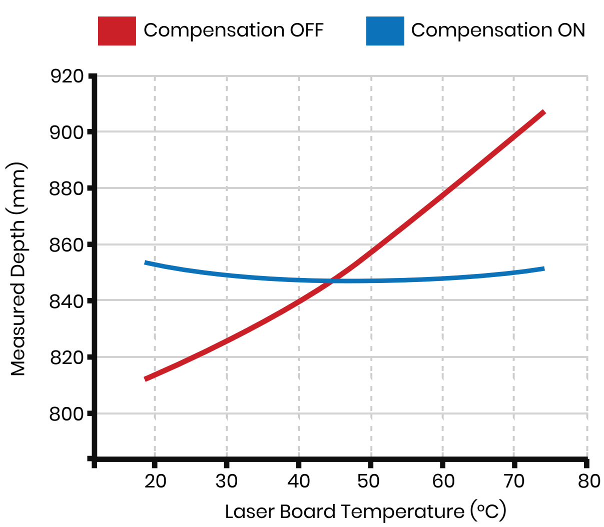


figure 4
Example of drift compensation in relation to temperature change of the camera's laser board. Without compensation, there is a measured depth change of ~90mm versus less than 10mm with compensation turned on.

CASE DESIGN - WEATHER PROOFING

For challenging applications where dust and water are present, it is best to choose an IP65/IP67 rated ToF camera. IP (Ingress Protection) rated cameras guarantee a level of protection from particles and moisture as defined in the IEC standard 60529. Choosing a camera already IP65/67 rated – as opposed to building an additional enclosure around a non-rated camera – eliminates additional transparent surfaces introduced by the enclosure in front of the ToF sensor and light emitters, which can hinder performance.

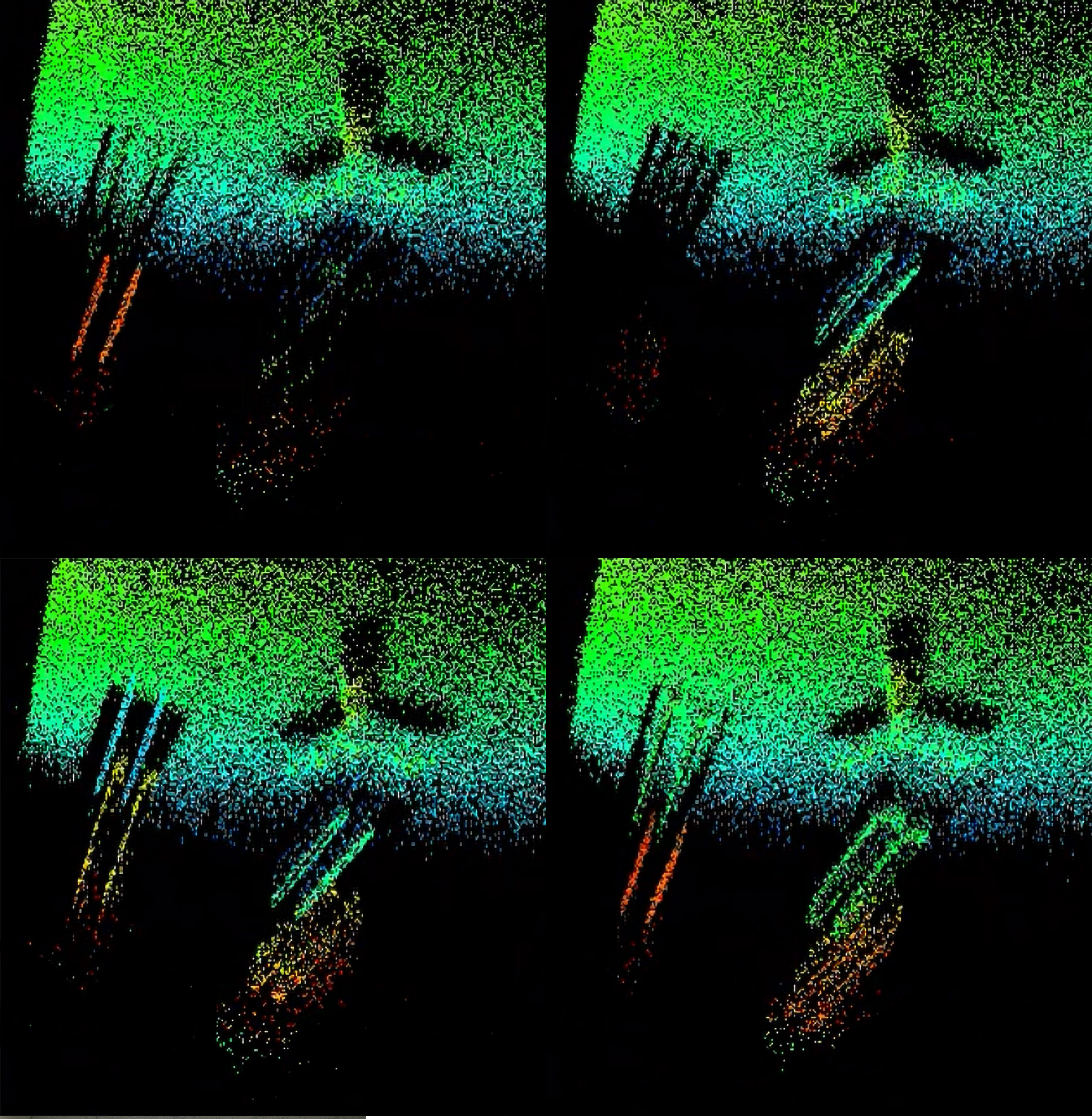
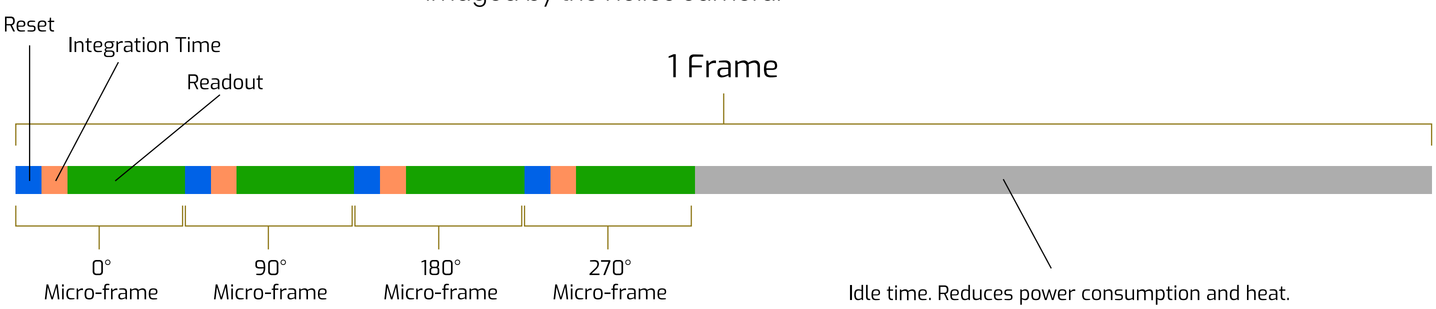


Image Set 2

An example of AC fluorescent lighting producing a pulsating effect in the point cloud. This is due to the lighting 100/120 Hz flicker along with slight discrepancies in the two detection junctions (taps) in the Sony DepthSense sensor.

TARGET & CAMERA MOTION

After physical environment concerns, any relative motion of the camera and imaging target must be addressed. Is the target or the camera in motion while imaging? Unlike conventional cameras, ToF units need multiple micro-frames to make depth calculations. In the case of the Helios, four micro-frames make up a single depth frame, with these individual micro-frames phase-stepped by 90º (0º, 90º, 180º, 270º) from one another. For the Helios camera to run at 30 frames per second (fps), it needs to take 120 micro-frames. If the target or camera were to move too fast during those four micro-frames, the resulting depth frame (and point cloud data) would be distorted. For example, in a conveyor-belt-based inspection, the speed of the targets moving across the camera's field of view must provide adequate time to be properly imaged by the Helios camera.

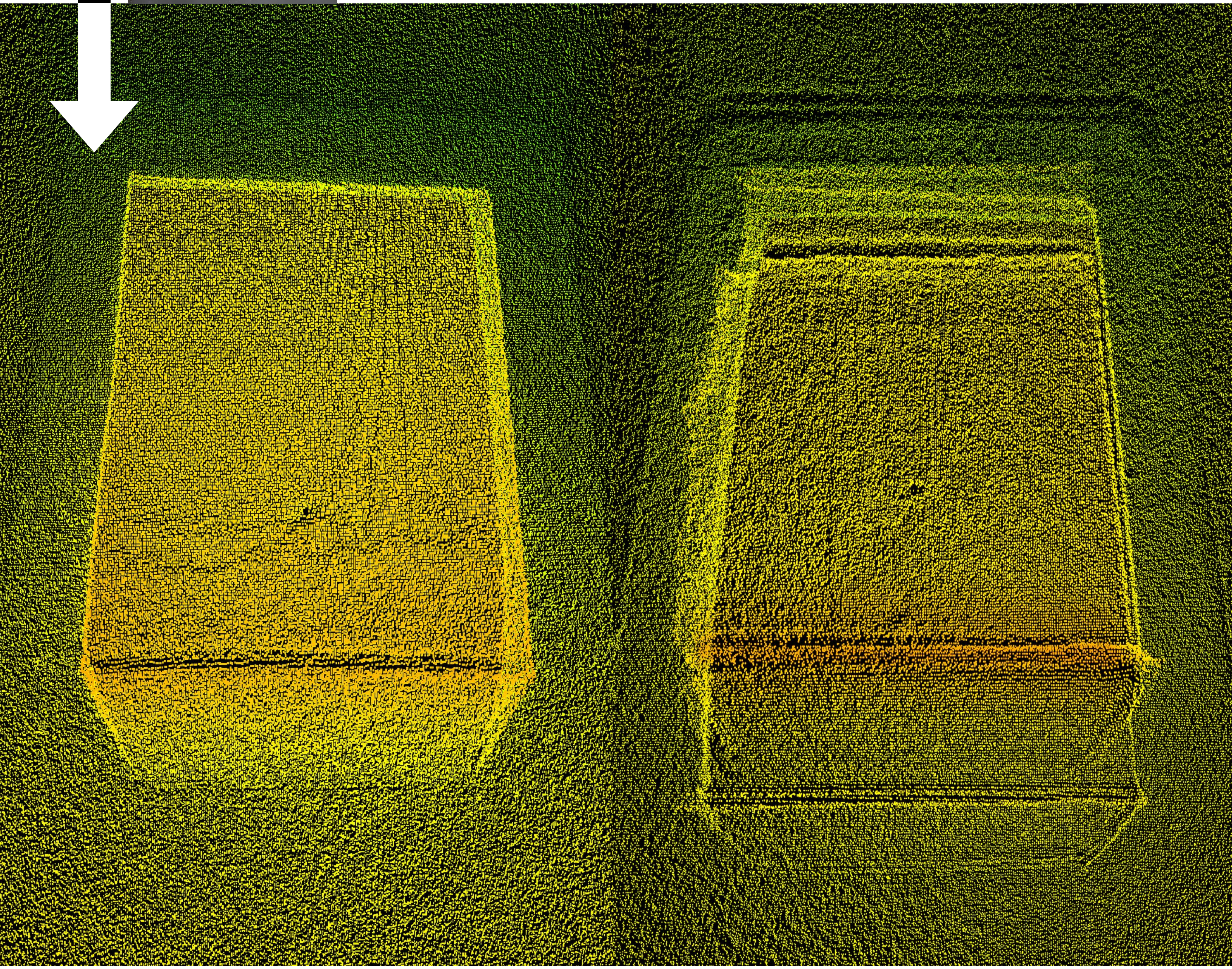


FRAME RATE

Accurate point clouds and depth information are critical for proper visual tracking. Such information is used, for example, for: coordinating movement of robotic arms in object handling; volume control as with package overfill protection; or foreign object detection. Users should test to determine the maximum speed of the object for the given camera frame rate. The Helios camera is equipped with two modes: "Far Mode" which runs at 15 fps with a maximum range of 6m; and "Near Mode" running at 30 fps with a maximum range of 1.5m. (Note that the Helios Flex camera module runs at twice the frame rate speeds (60 fps / 30 fps) compared to the Helios camera.) Although higher frame rates are possible with other ToF cameras, they are usually accompanied by a reduction in resolution.

MODE	WORKING RANGE	HELIOS FRAME RATE	HELIOS *FLEX* FRAME RATE
Near Mode	1.5m or less	30 FPS	60 FPS
Far Mode	6m or less	15 FPS	30 FPS

Image Set 3
Comparison of a box moving at an appropriate speed (left) versus one moving too fast (right). Targets moving too fast can create point cloud offset overlays that mesh within themselves.



SPECULAR AND DIFFUSE TARGETS

ToF works best on targets with surfaces that have neither high specular reflection nor absorbent non-reflective surfaces. Both extremes lead to point cloud distortions. For example, black piping has both low reflectivity (black color) and high specular surfaces, creating both voids and spikes in the point cloud ***(Image Set 4, Example c.)*** Targets that are black or very dark will absorb light and thus return the least amount of light creating voids or holes in the point cloud. Targets with high specular reflections can saturate pixels creating spikes in the point cloud that are closer in distance than their true position. Targets with these properties may not be suitable for ToF.

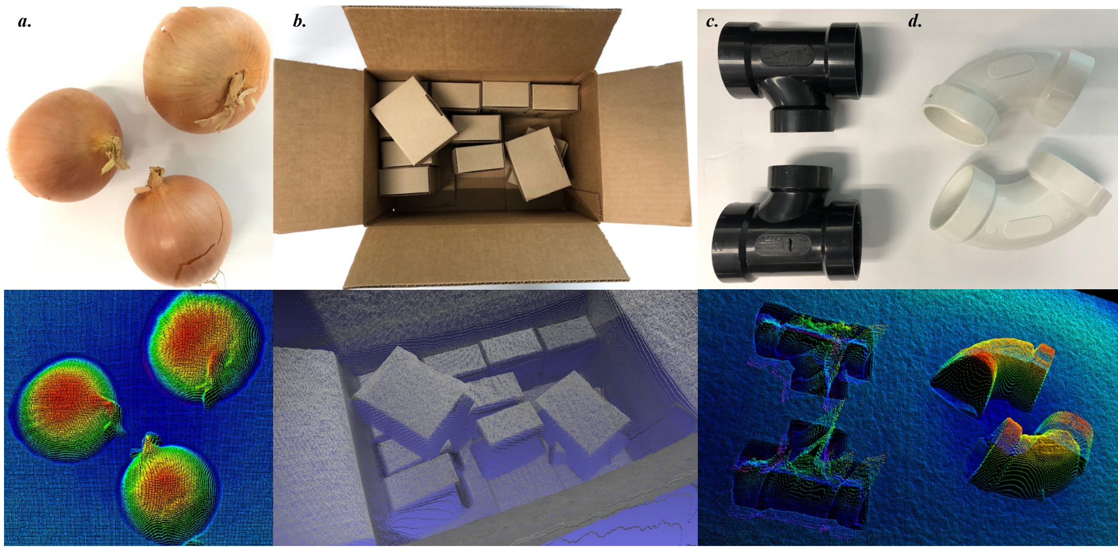


Image Set 4
Various point cloud examples of different objects.
a. Onions
b. Cardboard boxes
c. Black PVC pipes
d. White PVC pipes

Targets with diffuse surfaces and high reflectivity work best for ToF ***(Image Set 4, Example a, b, d)***. These targets send enough light back to the ToF sensor without specular reflections. Some objects however, exhibit properties that are less than ideal but are still discernible within the scene. In these situations it is possible to increase target details via changes in exposure time and gain, image accumulation, and filtering.

EXPOSURE TIME AND GAIN

Determining the best exposure time maximizes usable depth data for both high and low reflectivity targets. **The Helios camera enables two discrete exposure time settings — 1,000µs and 250µs, as well as high and normal gain settings.** The 1,000us setting is the default exposure time and also the maximum exposure time allowed. Longer exposure time and high gain should be used for scenes further from the camera, or when imaging objects with low reflectivity. Shorter exposure time and normal gain is used for scenes closer to the camera, or objects that appear over saturated.

EXPOSURE TIME	GAIN	BEST FOR
1,000µs	High	Dark objects, farther distances
250µs	Normal	Highly reflective objects, closer distances

IMAGE ACCUMULATION

The Helios processing pipeline is capable of accumulating multiple frames for improved depth calculations. This is helpful for targets that produce noisy data. With image accumulation, depth frames are averaged over a set number of frames, improving imaging results. It should be noted that the higher the number of frames accumulated, the slower the depth data generation, as more images must be captured to calculate the data.

15 FPS (2 IMAGES) **4 FPS (8 IMAGES)** **1 FPS (32 IMAGES)**

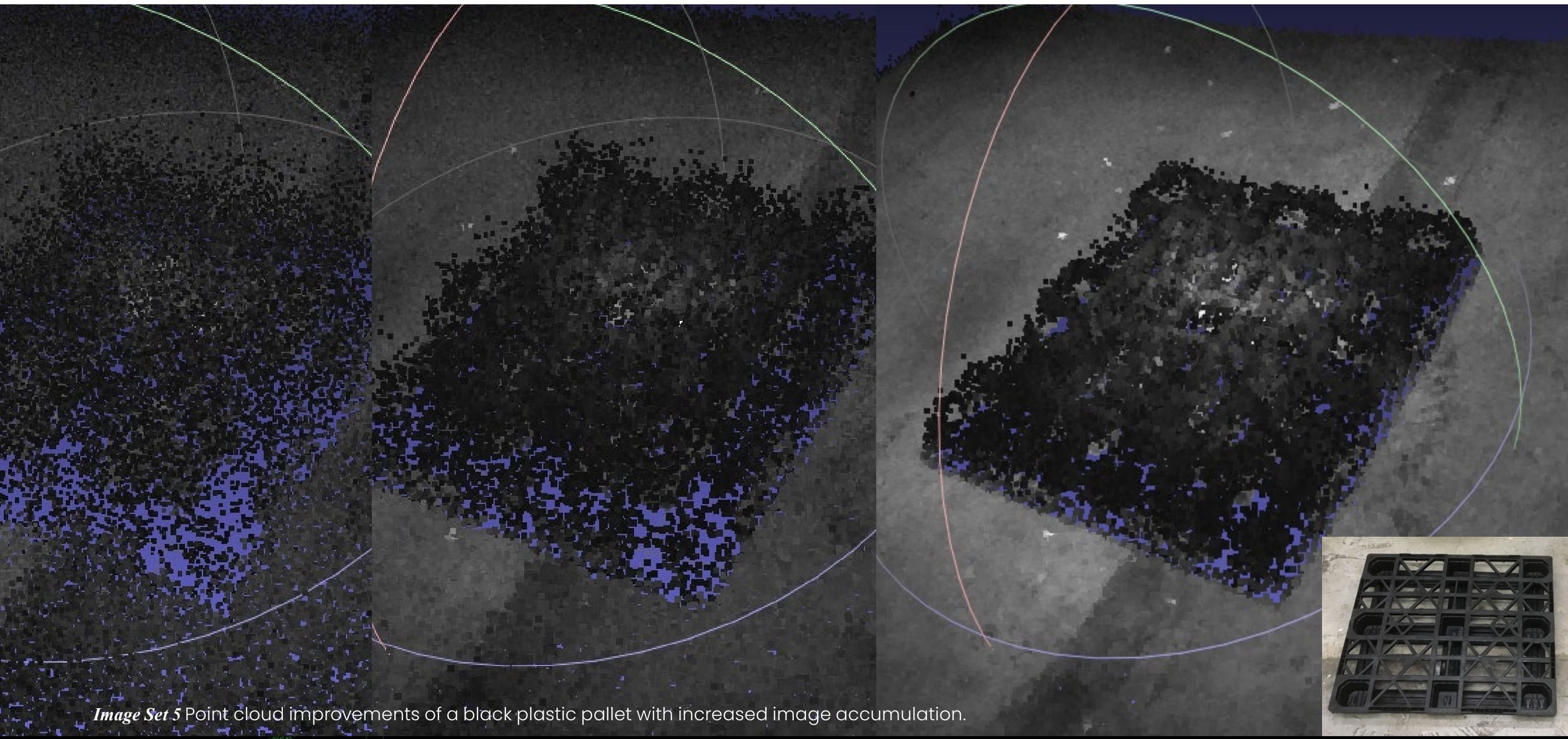


Image Set 5 Point cloud improvements of a black plastic pallet with increased image accumulation.

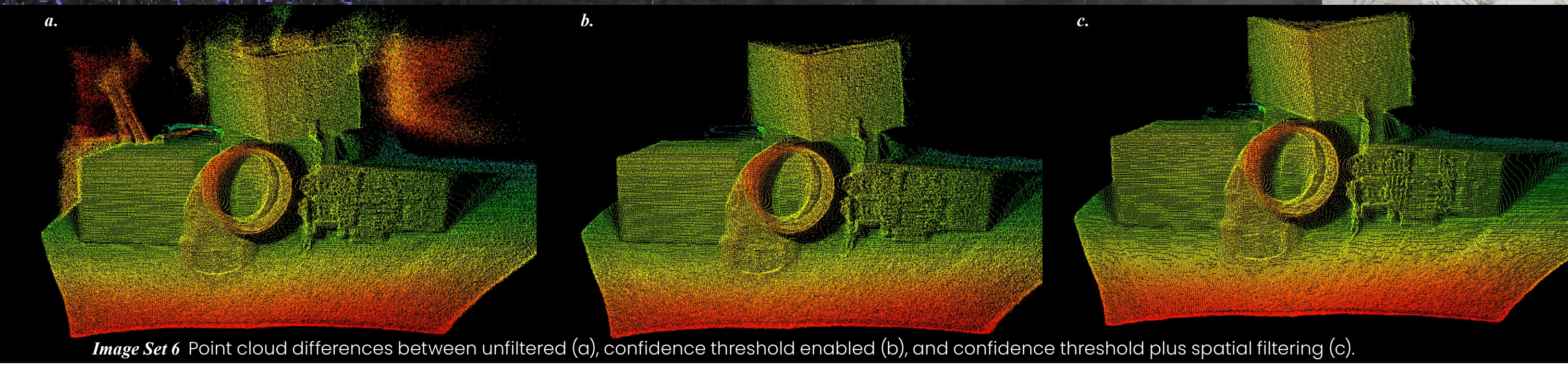


Image Set 6 Point cloud differences between unfiltered (a), confidence threshold enabled (b), and confidence threshold plus spatial filtering (c).

CONFIDENCE THRESHOLD

Depth data confidence is based on a level of intensity for each point. If a returning signal is too weak, there is low confidence in the resulting depth data. Thresholding removes depth data with low intensity/confidence, improving scene clarity.

SPATIAL FILTERING

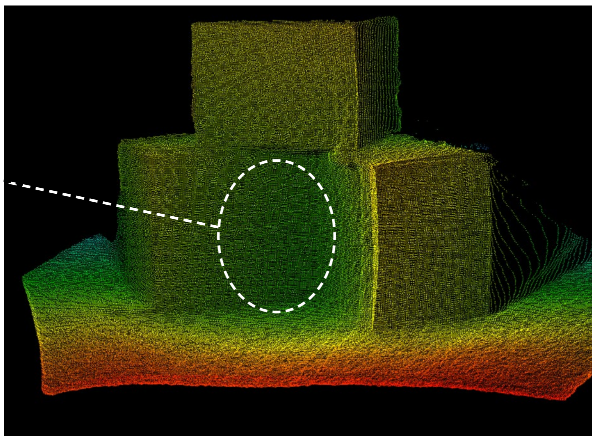
Spatial filtering reduces noise by adjusting and averaging depth data differences between neighboring pixels — smoothing out surfaces. Additionally, the Helios camera also uses edge-preservation in its spatial filtering, reducing noise in surfaces while maintaining object-edge sharpness.

SCENE COMPLEXITY SIMPLIFIED

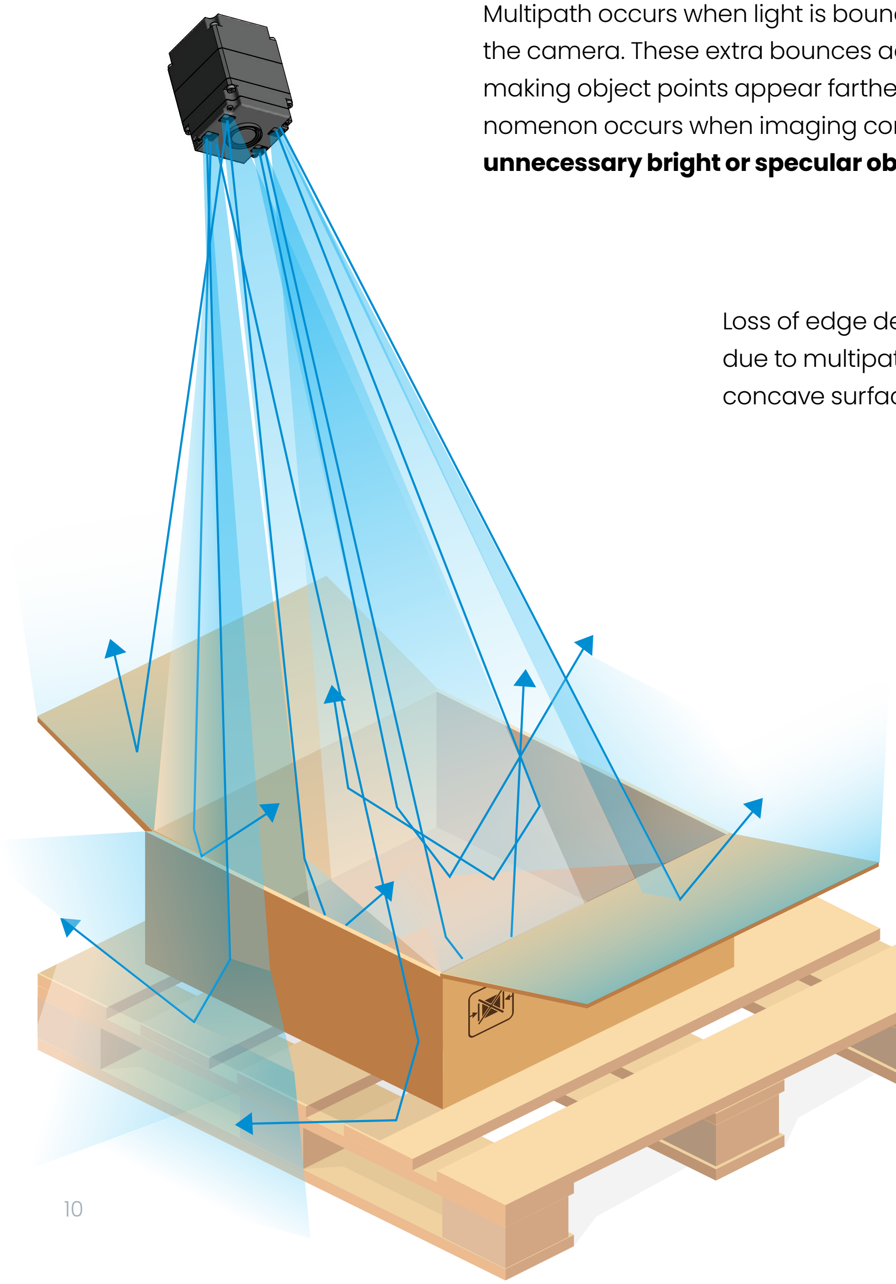
All surfaces reflect light to some degree, which is necessary for ToF to function. But when light gets reflected multiple times before being received by the camera's ToF sensor, the delay and displaced location of the reflected light negatively impacts depth calculations. For instance, if the surface of the target is very complex, with multiple concave and convex corners in a variety of angles, or if the target is placed in an environment with various angled surfaces, the optical paths of the ToF emitted light combine and interfere with one another.

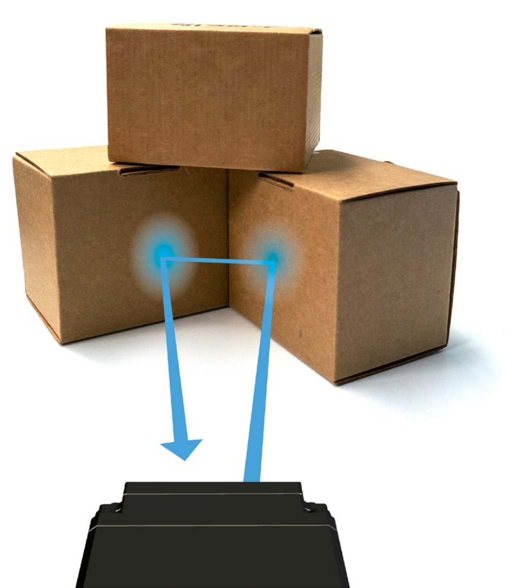
MULTIPATH

Multipath occurs when light is bounced off several surfaces before it is reflected back to the camera. These extra bounces add additional distance to the round-trip light path, making object points appear farther away and rounding off concave corners. This phenomenon occurs when imaging concave objects such as corners of a box. **Removing unnecessary bright or specular objects from a scene can reduce multipath errors.**



Loss of edge detail due to multipath on concave surface.





MULTIPATH - SURFACE BACKGROUND REFLECTIVITY

Multipath also occurs because of reflectivity of the surface "floor" on which the target is placed. For certain target shapes, this multipath warps the object. For example, cylindrical or spherical shapes can appear more triangular because the light reflects off the surface floor, then towards the curved target, and finally back to the camera. The extra reflection adds time to the returning light, resulting in a depth point that is farther than reality. **To reduce target distortion, choose a darker background and remove highly reflective surfaces behind your targets.**

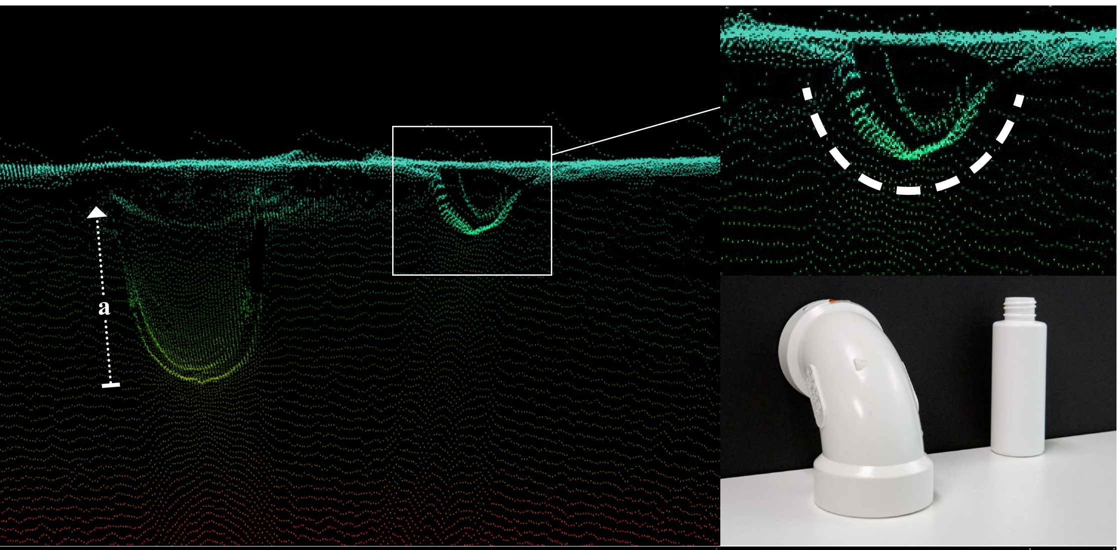


Image Set 7
Example of depth data using a dark background. Black background absorbs light resulting in less multipath distortions. Target objects appear cleaner and more accurate.

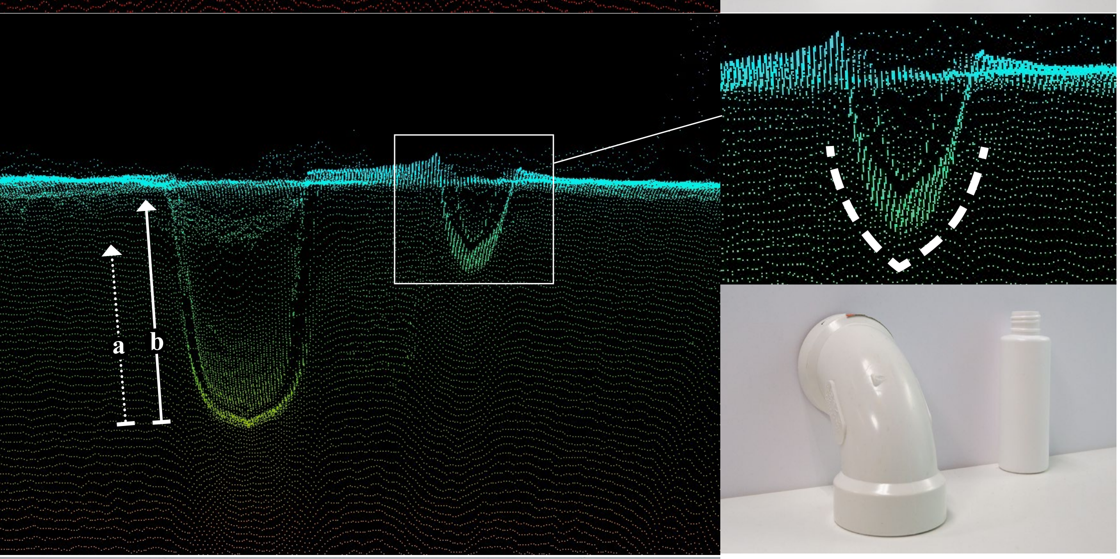
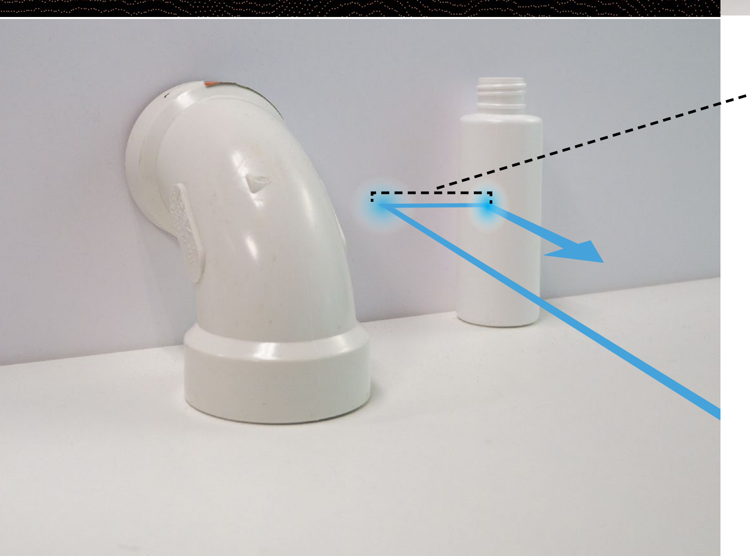


Image Set 8
Example of depth data using a white background. White background adds more reflections to the light path resulting in distorted curves of the target objects.



This type of multipath "pushes" the curved surface farther away, creating a more triangular look. In the case of the larger plastic white pipe, the added multipath reflections "stretch out" the resulting point cloud (**a** vs **b**).

WORKING DISTANCE CONSIDERATIONS

All 3D camera technologies have working distance limitations—ToF is no exception. However, ToF cameras have the benefit of being factory calibrated for specific distances right out-of-the-box. Most ToF cameras have a maximum working distance of 6-8m along with specific distance modes with different imaging properties. Such modes help improve accuracy and precision at the expense of frame rate by taking advantage of different emitted light frequencies.

MODULATION FREQUENCY

For ToF cameras, depth is calculated using either pulsed light or continuous wave (CW) light. The Helios camera calculates depth based on modulated CW emitted light. This modulated light is emitted at a specific frequency depending on the distance mode. For example, the Helios camera has twin working distance options: **Near Mode** and **Far Mode**. The farther the target, the lower the frequency of modulation needed. However, the slower the modulation, the lower the precision of the depth data. To improve performance at longer distances, the Helios camera employs two modulation frequencies in far mode which results in better depth data at the expense of a slower frame rate.

MODE	WORKING RANGE	FRAME RATE	MODULATION FREQUENCY
Near Mode	1.5m or less	30 FPS	100 MHz
Far Mode	6m or less	15 FPS	75 MHz & 100 MHz

AMBIGUITY (WRAP AROUND)

If an object is outside the range of the camera working distance mode (1.5m for Near Mode or 6m for Far Mode), the distance of the object becomes ambiguous. For example, when in Near Mode, an object at a distance of 1.8m will appear at 0.3m, in other words it “wraps around” the back of the scene, popping up in the front.

Depending on the application set up, objects behind targets and beyond the maximum working distance could appear in front, interfering with depth measurements. To reduce such object ambiguity, first correctly chose the working distance mode and either remove the undesired objects physically or restrict the range of the scene through software. The Helios camera allows users to tailor the range of the scene by adjusting the starting and ending distances. For instance, if an ambiguous object at 1.8m appears at 0.3m one can reduce the start of the scene to 0.4m—effectively removing any depth data between 0.0m to 0.4m.

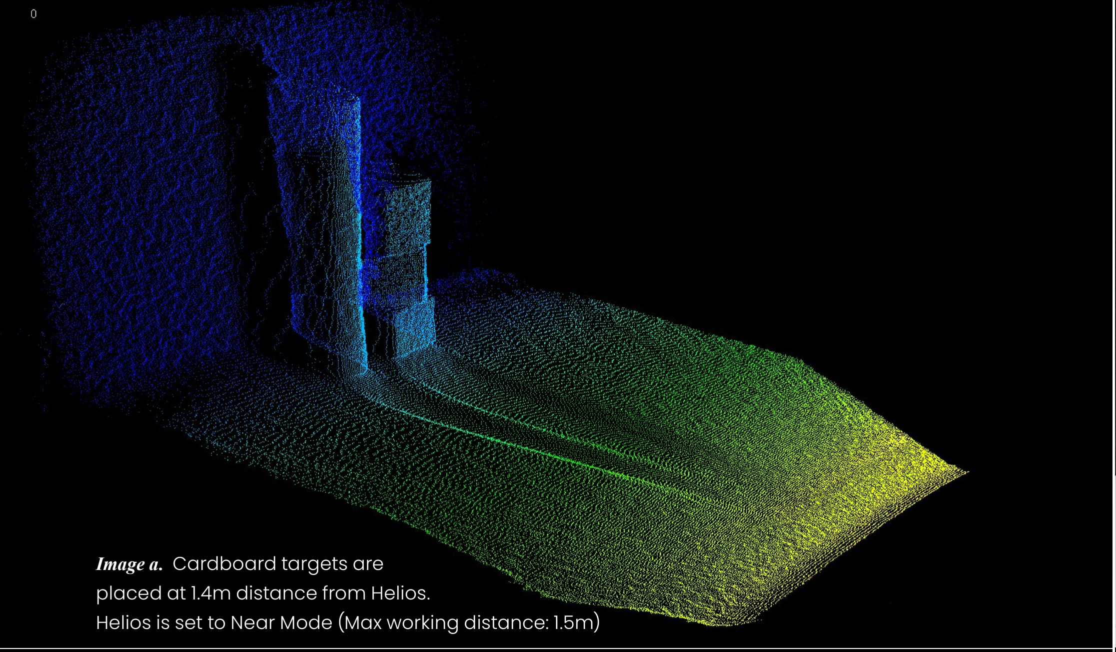
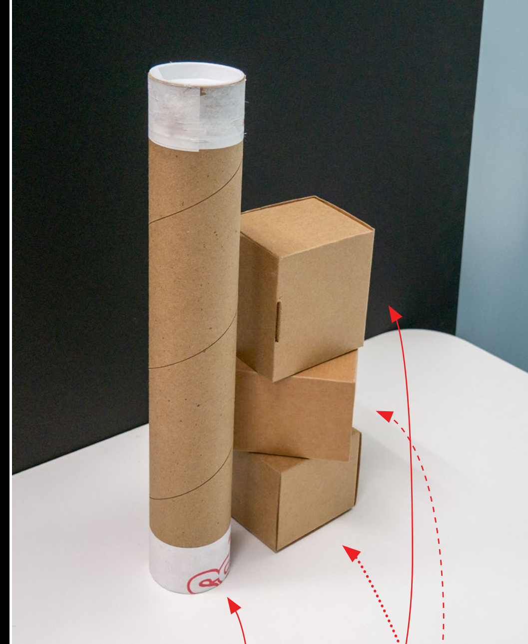


Image a. Cardboard targets are placed at 1.4m distance from Helios. Helios is set to Near Mode (Max working distance: 1.5m)



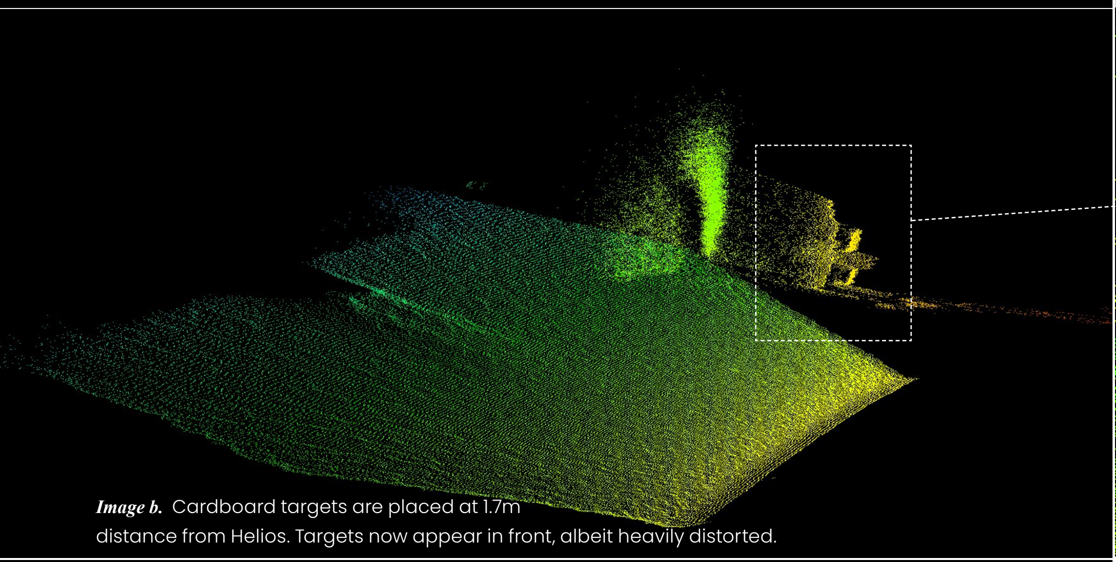
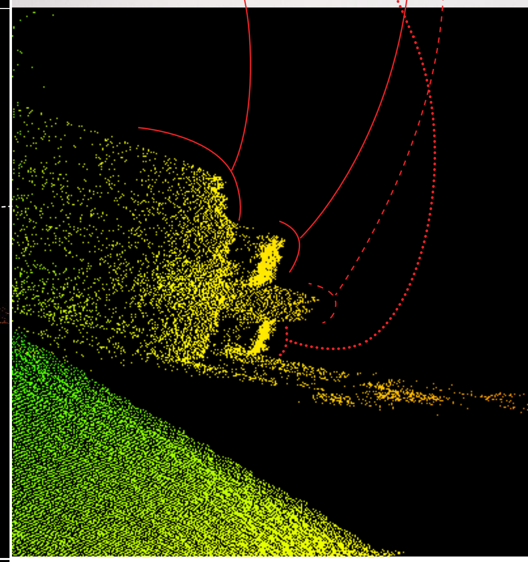


Image b. Cardboard targets are placed at 1.7m distance from Helios. Targets now appear in front, albeit heavily distorted.



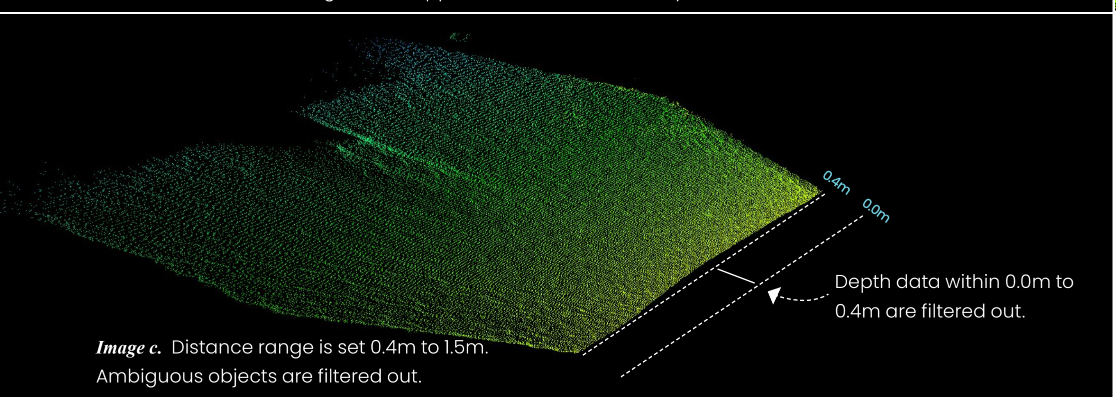


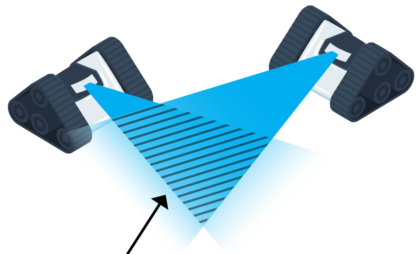
Image c. Distance range is set 0.4m to 1.5m. Ambiguous objects are filtered out.

Image Set 9
Example of object ambiguity. Cardboard objects at a distance of 1.4m from the Helios ***(Image a)*** are moved to a distance of 1.7m. This causes the cardboard objects to appear at the front of the scene ***(Image b)***. To remove these ambiguous objects you can adjust the range that the Helios displays. In ***Image c***, the range is adjusted to only show 0.4m to 1.5m.

FREQUENCY CROSS-TALK

Far large scenes, it is possible to add ToF cameras next to each other to capture a wider area. When doing so it is necessary to account for the field of view and modulation frequency of each camera. If the modulated emitted light is the same frequency for all cameras and it crosses into each adjacent field of view, interference can produce a fluctuating or distorted point cloud ***(Image set 9)***. This type of cross- talk interference is also an issue with ToF mobile robotics or any other applications where ToF paths might cross or intersect.

To remove frequency cross-talk, users can change the modulation frequency for each camera or trigger the cameras at alternating times. **The Helios allows for five different modulation frequencies, also called channels,** permitting upwards of five Helios cameras to work together without cross-talk. Alternatively, multiple cameras can be connected together and triggered at different times via software or a hardware trigger. The Helios supports Precision Time Protocol (PTP IEEE 1588) for synchronizing camera clocks for precise triggering.



Frequency cross-talk can affect robotics using ToF.

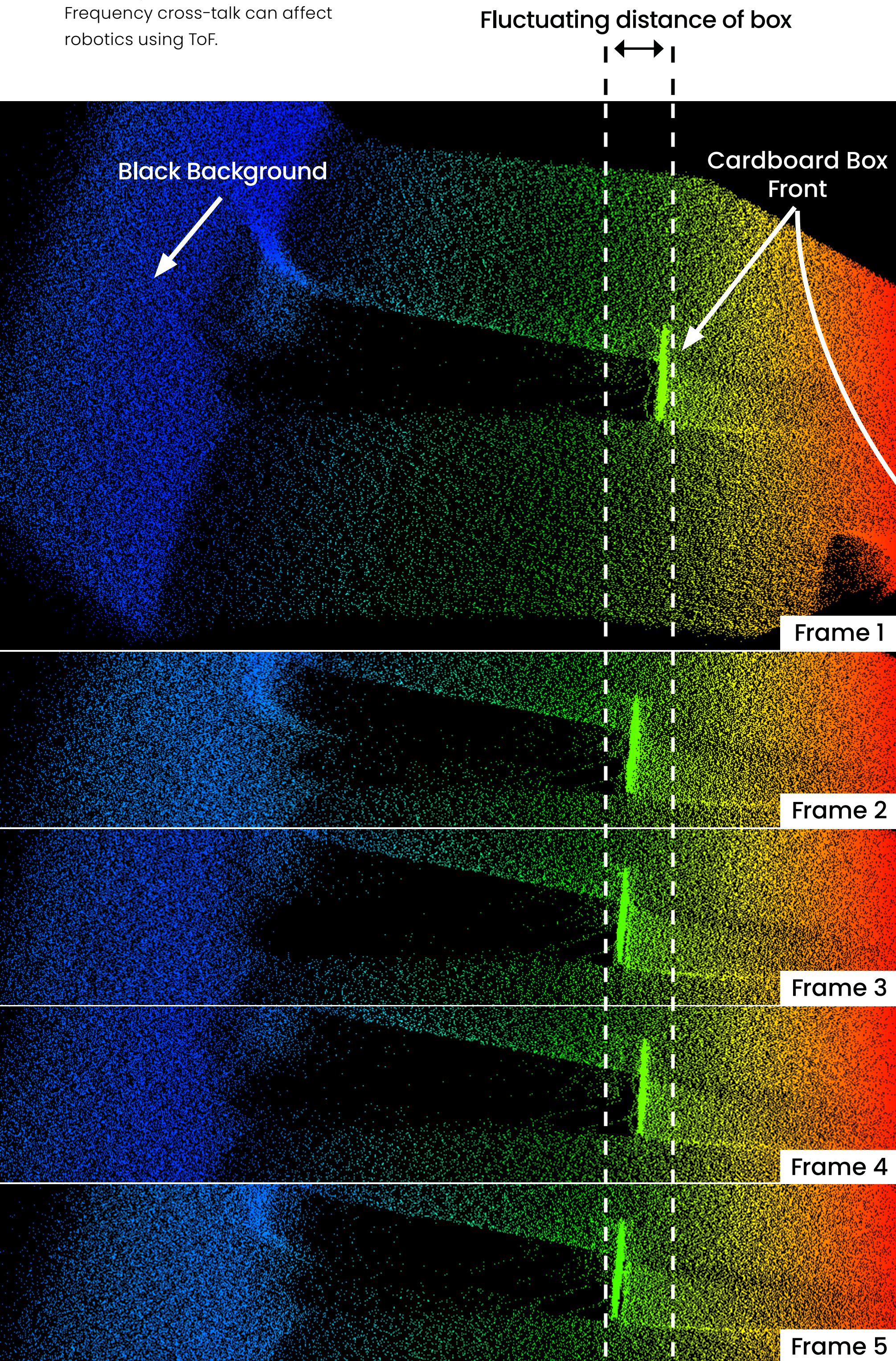
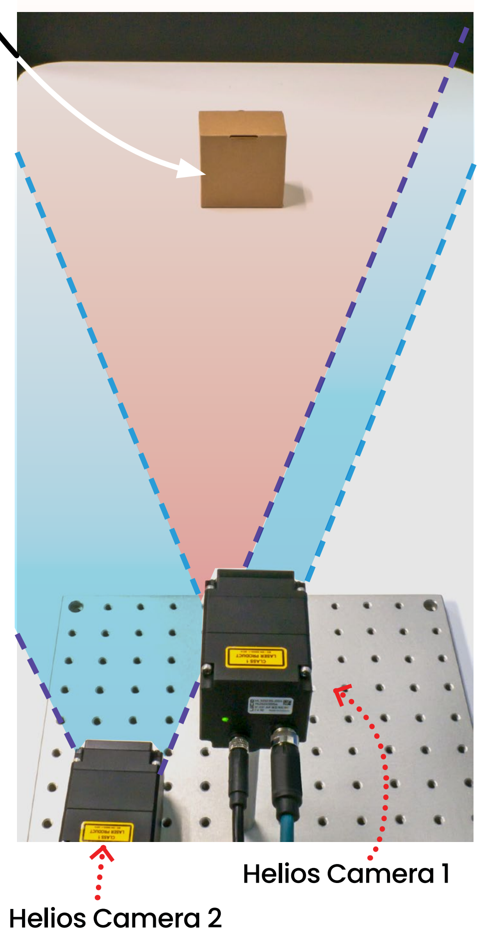


Image Set 9
(Left) A series of point cloud images from Helios Camera 1 shows the result of frequency cross-talk between two Helios cameras next to each other with the same modulation frequency (below). The result is a cardboard box with fluctuating point cloud depth data for every frame.



PUT IT ALL TOGETHER

For demanding, rapid real-time object detection, time-of-flight 3D technology improvements provided by LUCID's Helios ToF camera with Sony's DepthSense IMX556PLR sensor, not only boost speed, precision and accuracy, but also simplify integration time and cost. By careful consideration of the ToF working environment, specific target object characteristics, and scene backgrounds, modern 3D camera systems—via their characteristics, features and options, and onboard software processing—are readily tailored to an application. Integration is eased by an inherently compact camera because illumination is near the lens and there are no moving mechanical parts. Astute configuration hints and examples noted in the guide permit integrating a ToF camera in a timely manner, minimizing difficulties and optimizing 3D-depth performance and results.

Helios ToF Camera for Windows and Linux PCs

Helios *Flex* ToF Camera for NVIDIA® Jetson™ TX2

To learn more about the Helios 3D ToF camera visit thinklucid.com/helios

Looking for more information about Time of Flight?
For an introduction to Sony's DepthSense Time of Flight sensor and other 3D technologies please download our free white paper: Time of Flight Gets Precise: Enhanced 3D Measurement With Sony® DepthSense® Technology

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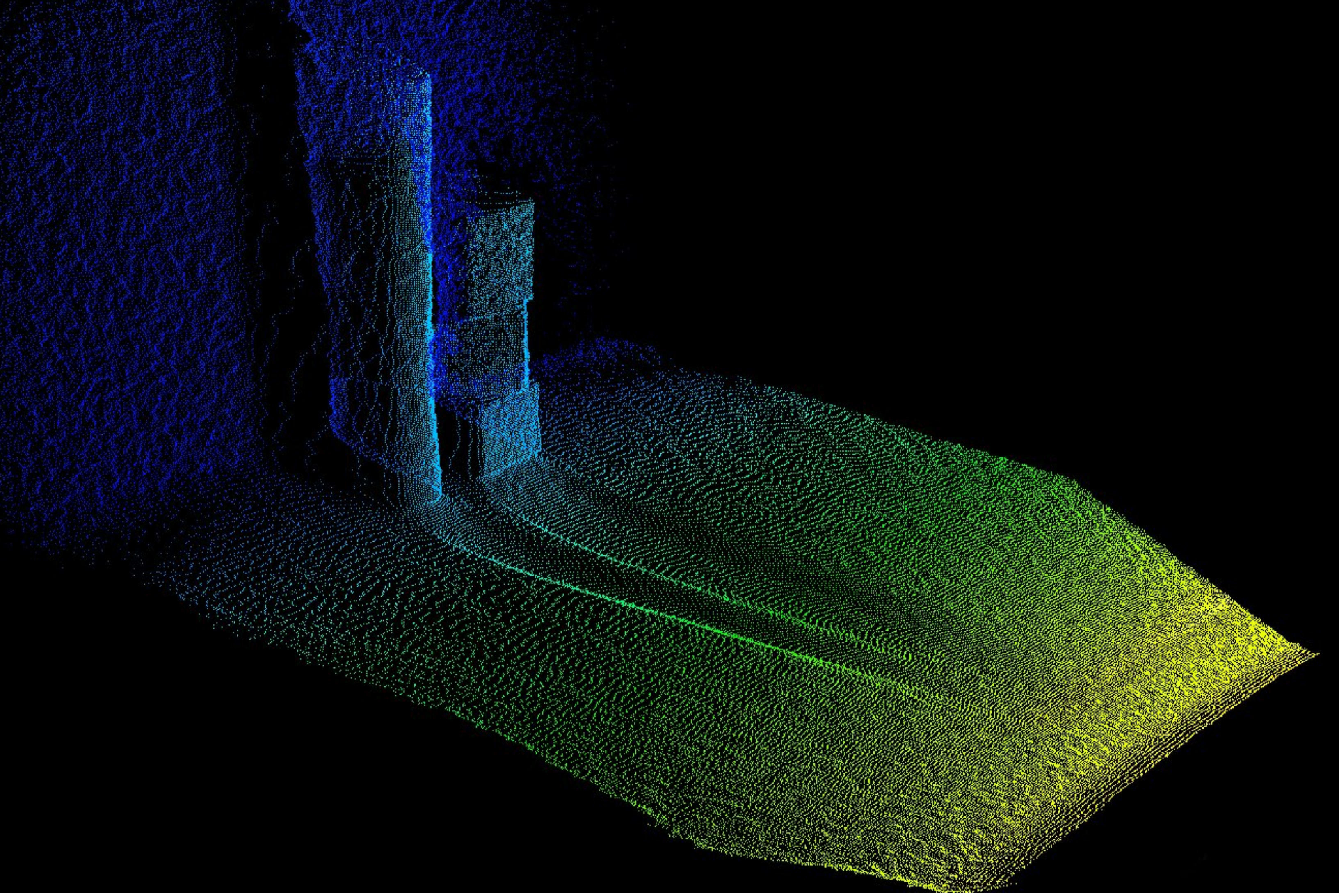

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