

3-D Machine Vision for factory automation, robotic vision and industrial applications -

Generate your own point clouds using 3-D Machine Vision SDK

Ben Lee – presenting (material by Blair Conner)

May 2015

This presentation is reference information and not considered a complete or official training guide

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Agenda

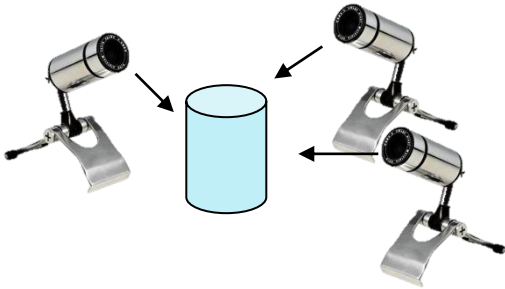
- **Introduction to 3-D machine vision**
 - What are the basics of 3-D machine vision?
- **What is the 3-D machine vision reference design using DLP® technology?**
 - What is included in the software?
 - Where do I download it?
- **Design Considerations for 3-D Machine Vision**
 - How to choose a DLP chipset
 - Scanning and reconstruction considerations
- **Developing with the DLP Structured Light SDK**
 - How to setup the development environment?
 - How to create new modules?

Introduction to 3-D Machine Vision

Many methods for 3-D machine vision

Use Triangulation (Geometry) to Determine the Depth of an Object
By Different Methods:

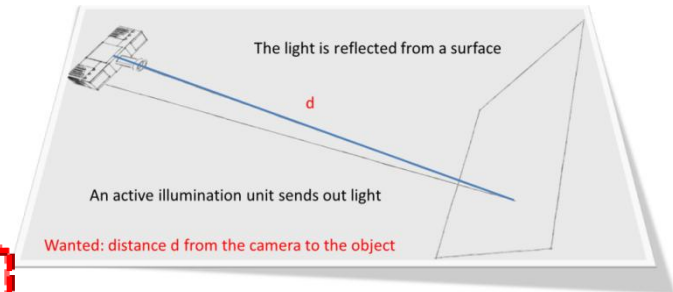
*Stereo Triangulation
or Photogrammetry*



Single Line Laser Scan



Time of Flight



Structured Light

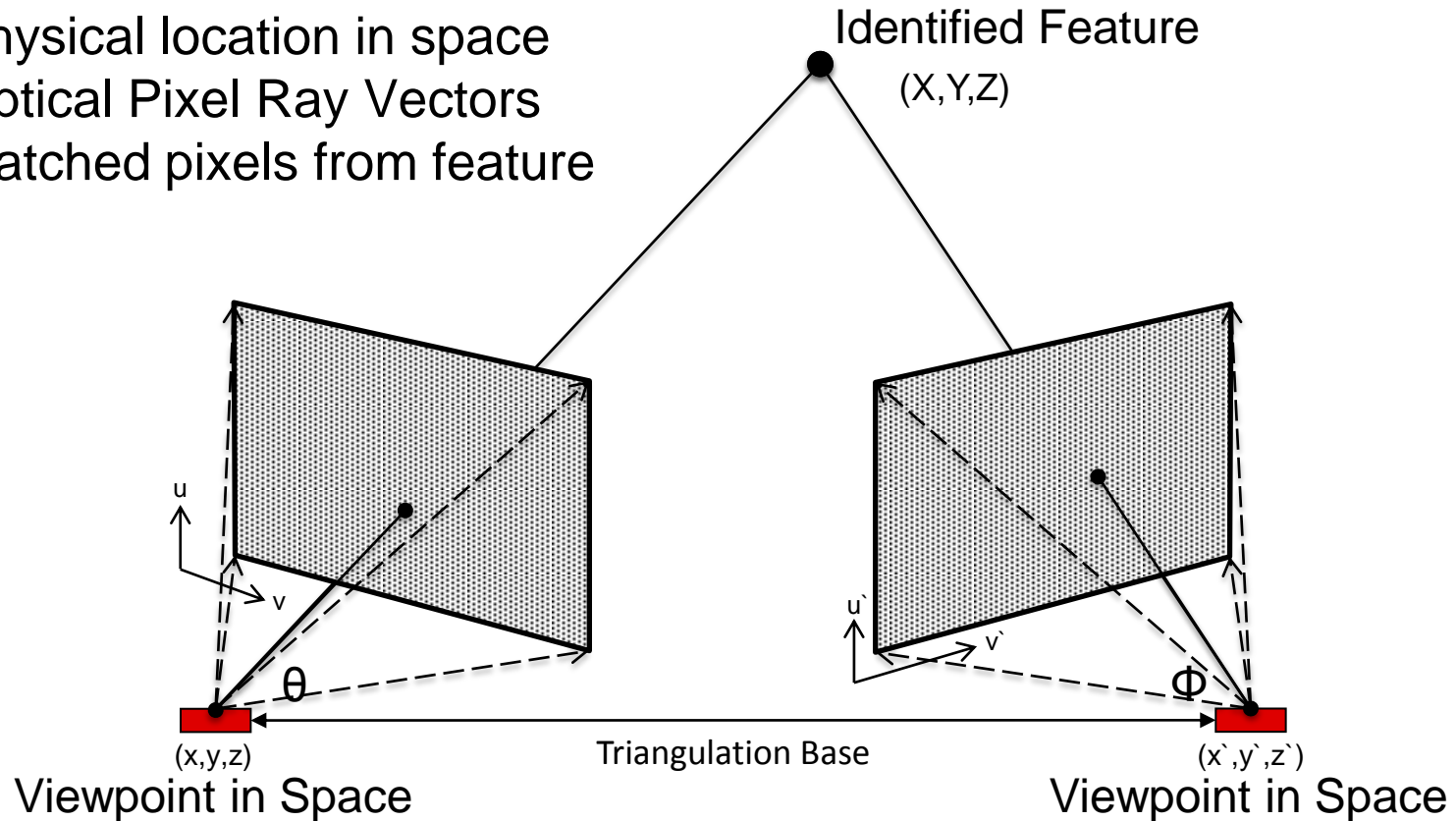


Depth calculated with triangulation

Use Triangulation (Geometry) to Determine the Depth of an Object
By Different Methods:

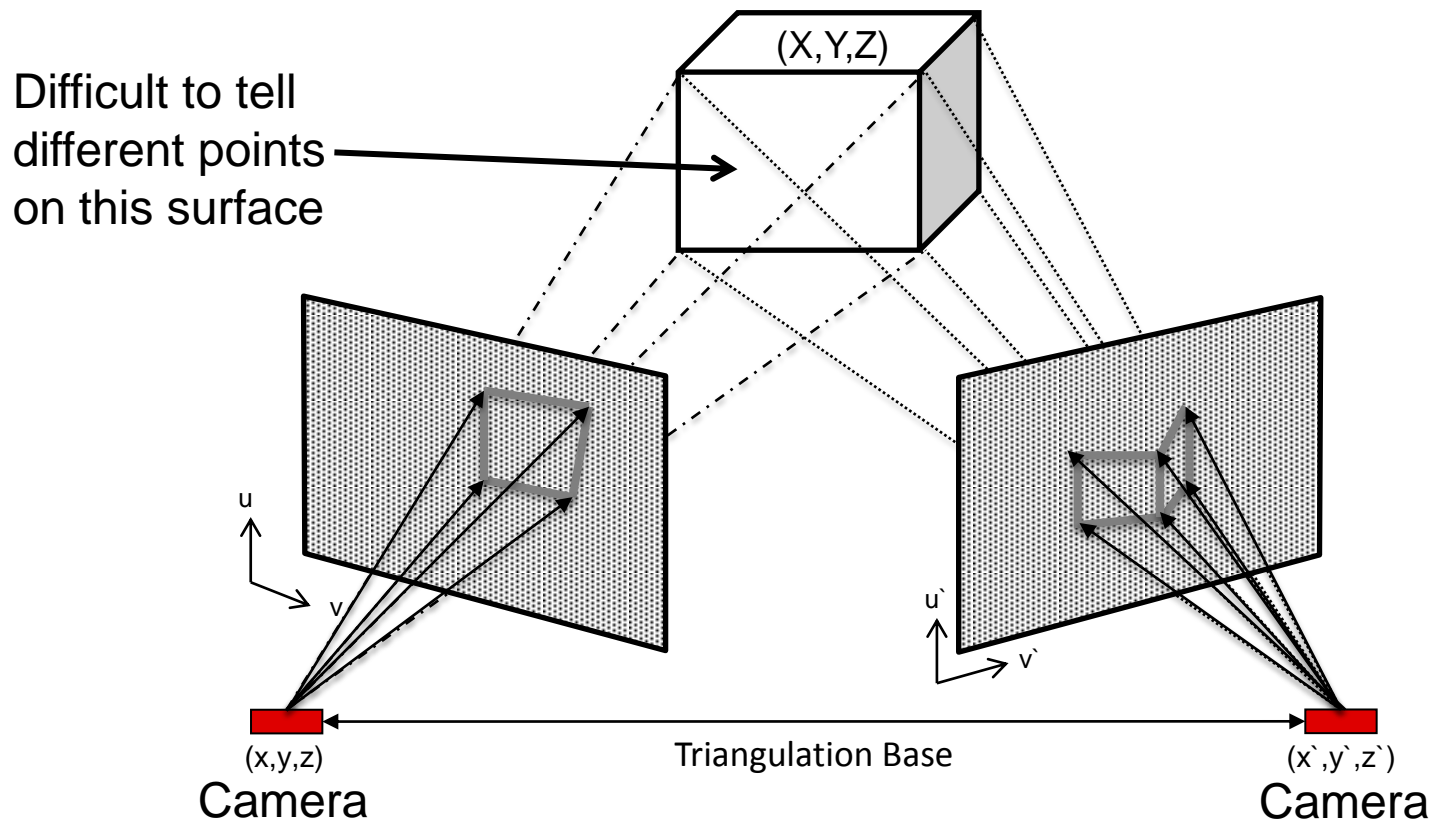
What do we need to know?

- Physical location in space
- Optical Pixel Ray Vectors
- Matched pixels from feature



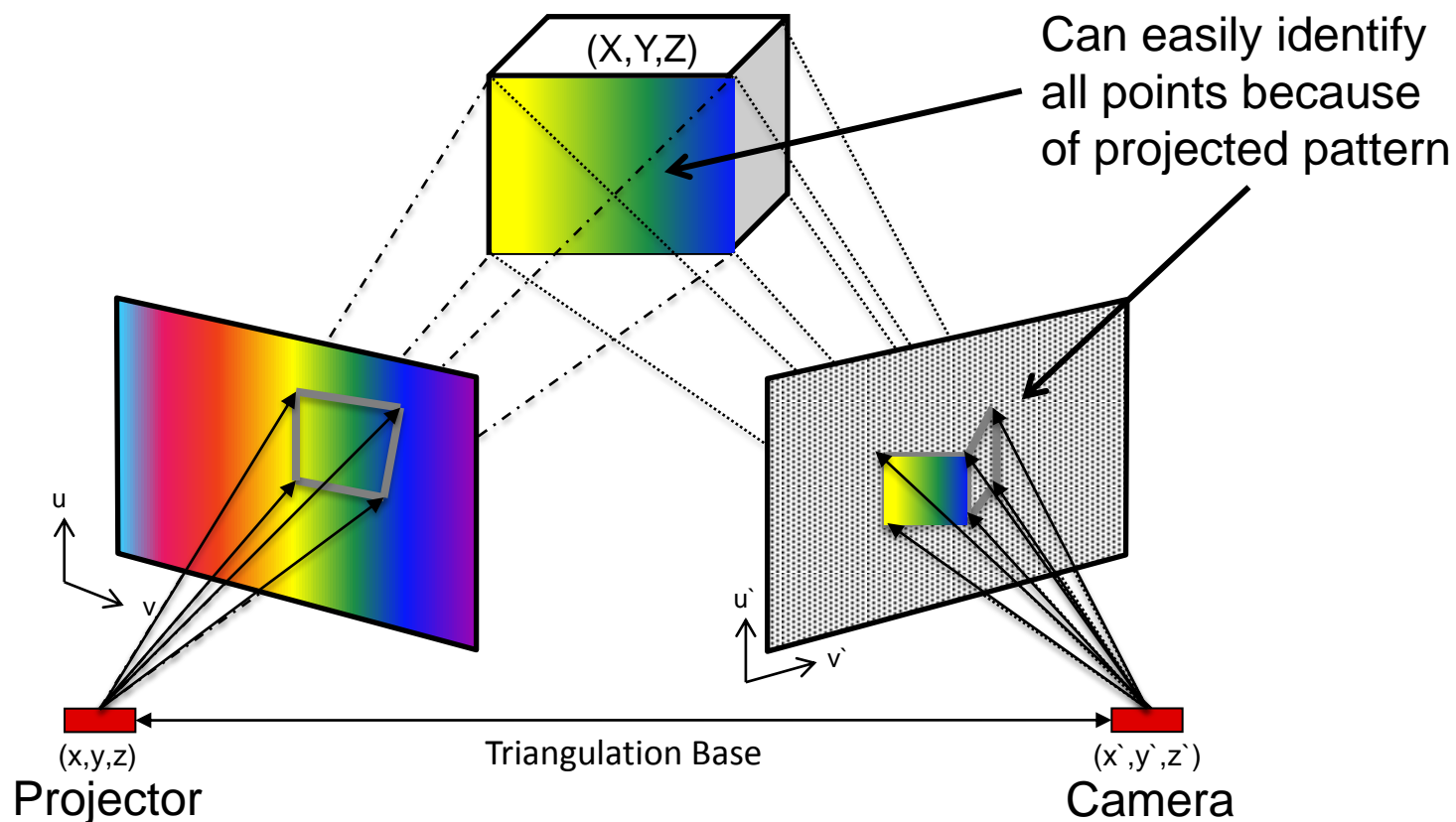
Using Cameras for 3-D Machine Vision

- Two cameras capture different viewpoints of the same object
- What if object does not have many identifiable features?



3-D Machine Vision with Structured Light

- One camera captures projected patterns
- The projected patterns inherently create identifiable features



What subsystems are needed?

Subsystems	Purpose
Calibration	<ul style="list-style-type: none">• Determine physical locations and directions• Determine optical parameters of camera and projector<ul style="list-style-type: none">○ Focal length○ Focal point○ Radial distortion coefficients
Camera	<ul style="list-style-type: none">• Capture high-speed patterns for analysis
DLP Platform	<ul style="list-style-type: none">• Project high-speed patterns
Structured Light	<ul style="list-style-type: none">• Generate structured light patterns• Decode captured images and generate disparity map which details which projector pixels are viewed by camera
Geometry	<ul style="list-style-type: none">• Uses calibration data and feature identification to reconstruct (X,Y,Z) point

Process Flow: Calibration

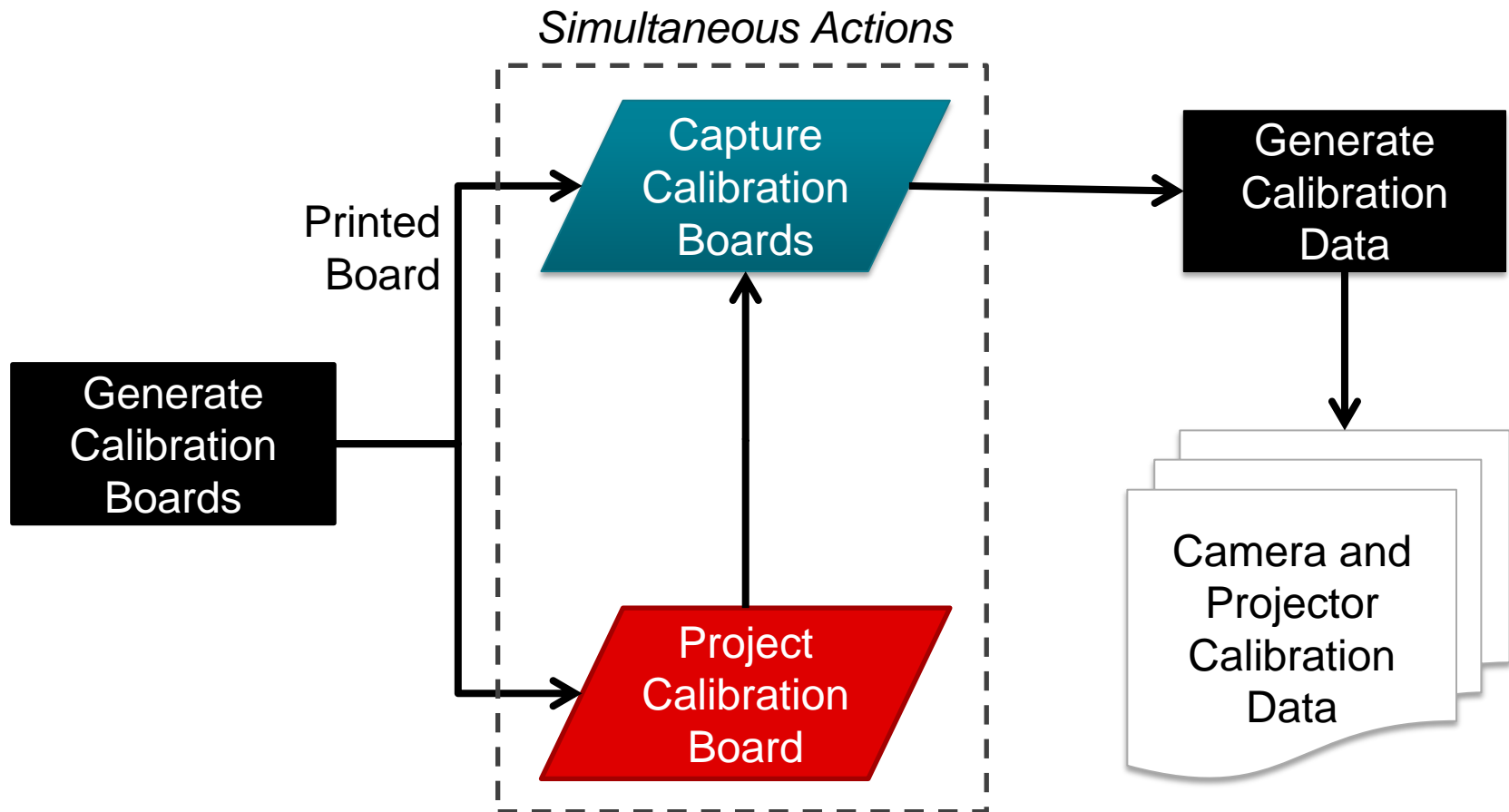
Calibration

Camera

DLP®
Platform

Structured
Light

Geometry



Process Flow: Scanning

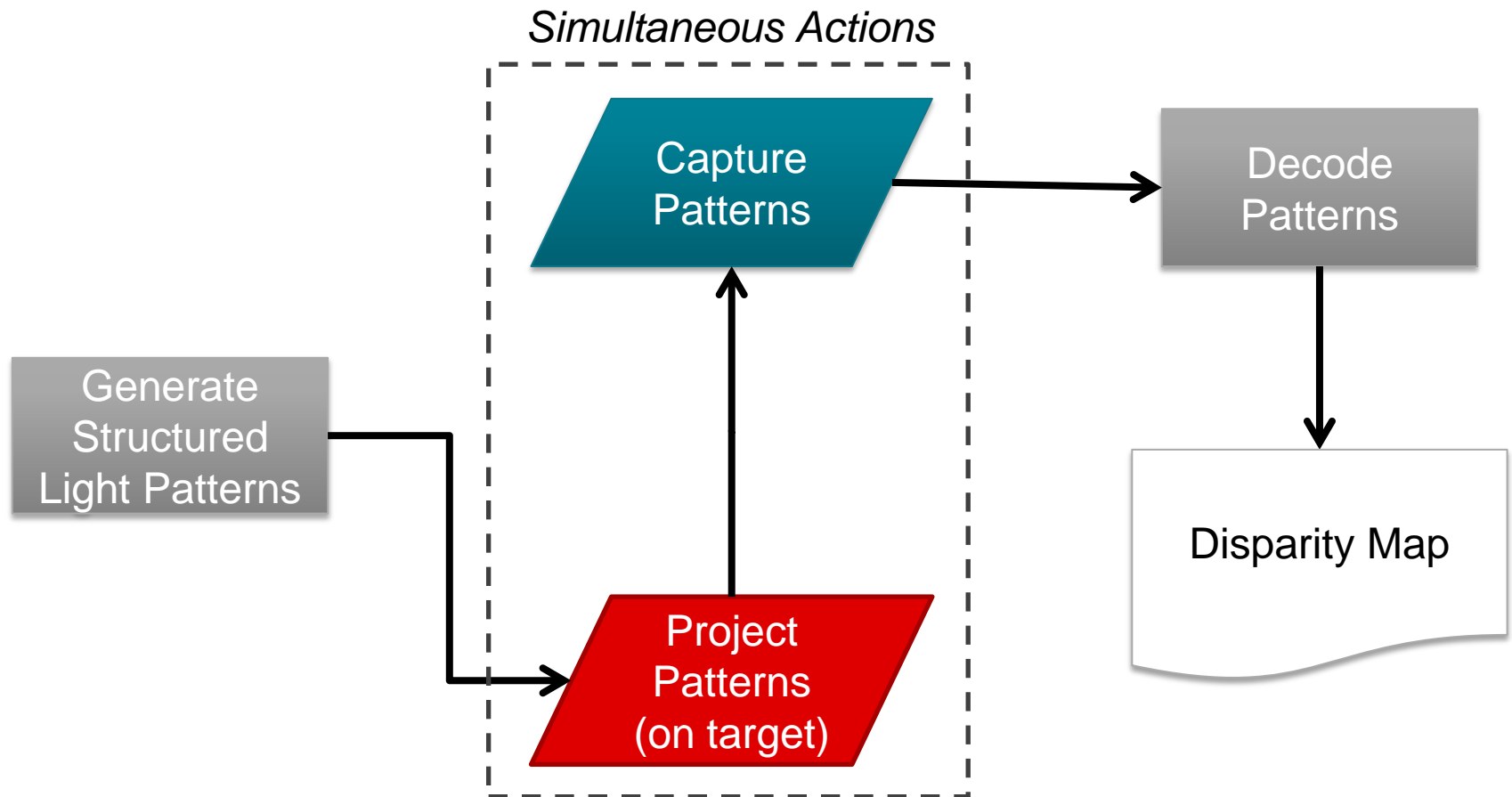
Calibration

Camera

DLP®
Platform

Structured
Light

Geometry



Process Flow: Reconstruction

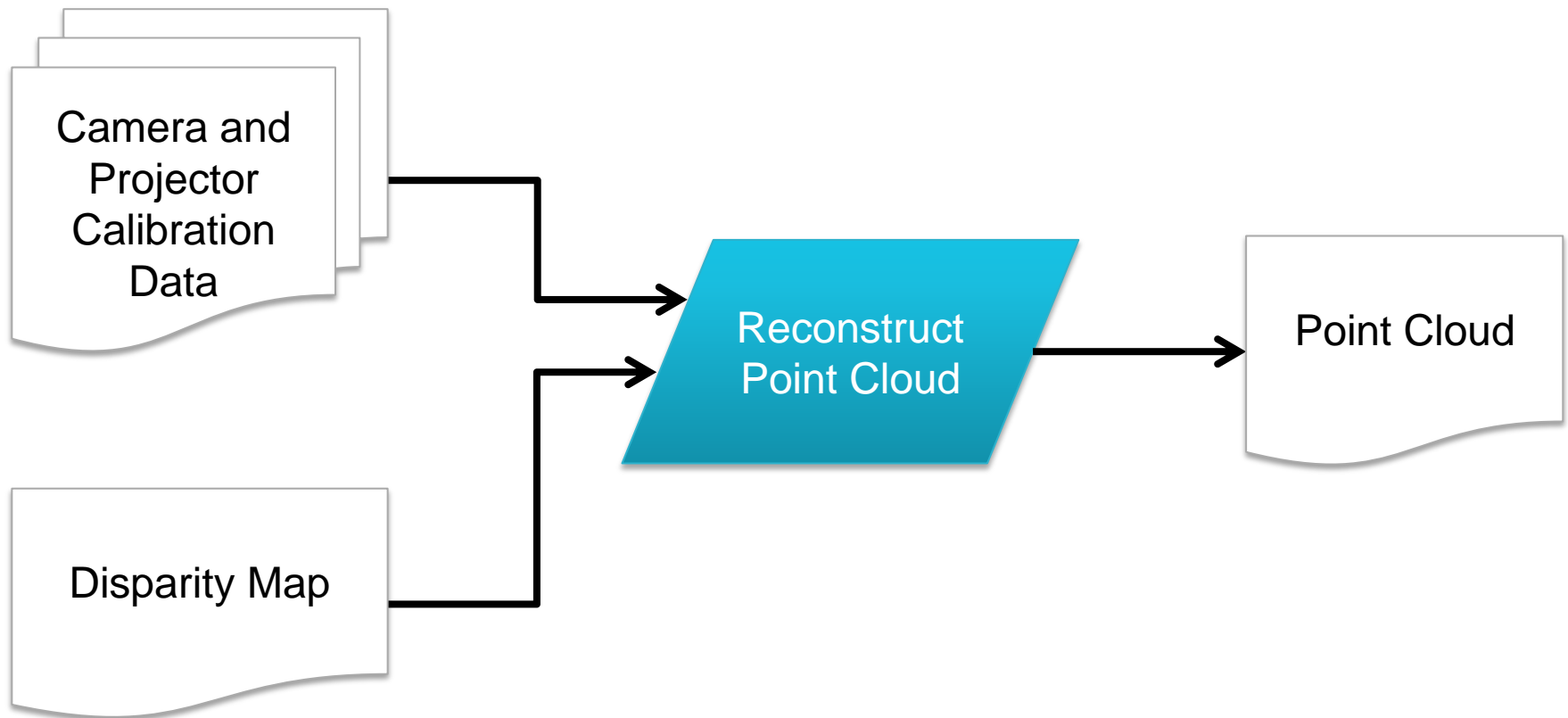
Calibration

Camera

DLP®
Platform

Structured
Light

Geometry



What is the DLP® 3-D machine vision reference design?

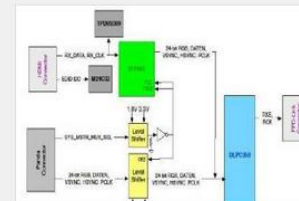
Jump Start Development with **TI Designs**

What are TI Designs?

- Comprehensive designs include schematics or block diagrams, BOMs, design files and test reports
- Created by experts with deep system and product knowledge
- Spans TI's portfolio of analog, embedded processor and connectivity products
- Supports a broad range of applications including industrial, automotive, consumer, medical and more

Schematic/Block Diagram

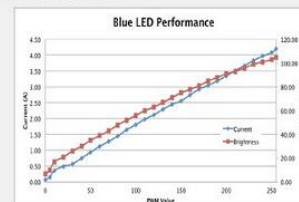
Quickly understand overall system functionality.



[Download Schematic](#)

Test Data

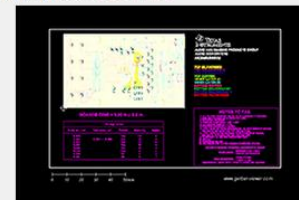
Get results faster with test and simulation data that's been verified.



[Download Test Data](#)

Design Files

Download ready-to-use system files to speed your design process. [Get Viewer](#).



[Download Design Files](#)

Jump Start Development with **TI**Designs

Where to find DLP TI Designs?

The screenshot shows the Texas Instruments website with several elements highlighted by red boxes to guide the user to the TI Designs section:

- Address Bar:** The URL www.ti.com is highlighted.
- Navigation Menu:** The **Applications & Designs** tab is highlighted.
- Category List:** Under the Applications & Designs section, the **TI Designs >** link is highlighted.

The TI Designs section provides the following information:

- Find reference designs** leveraging the best in TI technology – from embedded processors to analog signal chain and power management.
- All TI Designs include** a schematic, test data and design files.

Other categories listed include:

- Automotive >**
 - Advanced Driver Assistance Systems (ADAS)
 - Body Electronics & Lighting
 - Hybrid/Electric & Power Train Systems
 - Infotainment & Cluster
 - Passive Safety
- Communications Equipment >**
 - Enterprise Switching
 - Residential
 - Telecom Infrastructure
 - Wireless Infrastructure
- Enterprise Systems >**
 - Front Projection
 - High-performance Computing
 - Servers
- Industrial >**
 - Appliances
 - Building Automation
 - Display & Digital Signage
 - Electronic Point of Sale (EPOS)
 - Factory Automation & Control
 - Lighting
 - Medical, Healthcare & Fitness
 - Motor Drive & Control
 - Smart Grid & Energy
 - Space, Avionics & Defense
 - Test & Measurement
 - Other Industrial
- Personal Electronics >**
 - Mobile Phones
 - PC/Notebooks
 - Printers & Other Peripherals
 - Storage
 - Tablets
 - TV/Set-top Box/Audio

Footer information includes links for Careers, Contact us, Corporate Citizenship, Investor Relations, Mobile apps, Mobile site, myTI account, TI worldwide, and Website feedback. A URL www.ti.com/general/docs/refdesignsearch.tsp is also provided.

Jump Start Development with **TI**Designs

Where to find DLP TI Designs?

The screenshot shows the TI Designs Reference Design Library website. The browser address bar displays www.ti.com/general/docs/refdesignsearch.jsp. The page features the TI Designs logo and a navigation menu with 'TI Home >'. The main content area is divided into three columns:

- Reference Design Library**: A section titled 'Jump start system design and speed time to market' with a list of benefits: comprehensive designs, expert knowledge, portfolio span, and broad application range. It also includes a notice about authorized use.
- Search TI Designs**: A search interface with three filters: 'Search by Keyword' (text input), 'Search by Applications' (dropdown menu), and 'Search by Products' (dropdown menu). The 'Search by Products' menu is open, showing a list of categories. The 'DLP & MEMS' category is highlighted with a red rectangle. Below the menu, there is a description of the TI Precision Designs library and a link to 'Search All 1,000+ Designs'.
- Featured TI Design**: A section titled 'SimpleLink™ Wi-Fi® CC3000 Boosterpack Reference Design'. It includes an image of the boosterpack and a description of its features. A 'View Design' button is present.

At the bottom right, there is a 'Videos' section with a video player and a 'What's new with TI Designs?' section with a TI Designs logo.

Jump Start Development with **TI**Designs

Where to find DLP TI Designs?

The screenshot shows a web browser window with the URL www.ti.com/general/docs/refdesignsearchresults.tsp?familyIds=1742. The page displays search results for DLP TI Designs. On the left, there is a sidebar with a search filter for 'Sensor Products' and a list of categories: 'Sensor Products', 'Switches & Multiplexers', and 'Wireless Connectivity'. Below this is a button labeled 'Additional resources'. The main content area features a search result for 'Accurate Point Cloud Generation for 3D Machine Vision Applications using DLP® Technology'. This result includes a description, key features, purchase options, available resources, and a list of TI devices. To the right of the main result is a section titled 'Products Matched' showing 'Advanced Light Control' with an image of a circuit board. At the bottom, there is a partial view of another search result for 'High Resolution, Portable Light Steering Reference Design using DLP Technology'.

TI Designs Reference Design

www.ti.com/general/docs/refdesignsearchresults.tsp?familyIds=1742

Sensor Products
Switches & Multiplexers
Wireless Connectivity

Additional resources

Accurate Point Cloud Generation for 3D Machine Vision Applications using DLP® Technology

Description

The 3D Machine Vision reference design employs Texas Instruments DLP Software Development Kit (SDK) allowing developers to easily construct 3D point clouds by integrating TI's digital micromirror device (DMD) technology with cameras, sensors, motors or other peripherals. The highly (...)

Key Features

- Integrated API and driver support for DLP chipsets to enable fast and programmable patterns
- Integrated camera support for synchronized captures
- Projector and camera calibration routine
- Structured light algorithms for disparity map, depth map and point cloud generation
- API Documentation
- Full access to (...)

Purchase Options

[Order Now](#)

Available resources

- [Schematic/Block Diagram](#)
- [Bill of Materials](#)
- [Software](#)
- [Technical Reference](#)
- [User's Guide](#)
- [Assembly Drawings](#)

TI Devices

- DLP4500
- DLPC350
- MAX3232
- SN74AHC1G09
- SN74AVC1T45
- [More](#)

Products Matched

Advanced Light Control

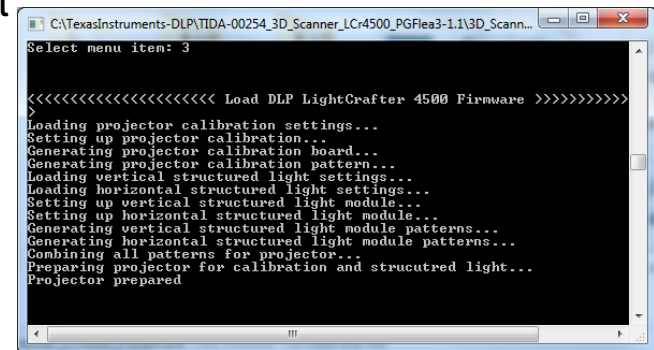
High Resolution, Portable Light Steering Reference Design using DLP Technology

Description

Purchase Options

Accurate Point Cloud Generation for 3-D Machine Vision Applications using DLP® Technology

- Provides a 3-D scanner software solution to shorten development time with DLP technology
- No software or optical development required for evaluating DLP technology for generating 3-D point clouds!
 - Generates and decodes structured light patterns
 - Calibrates camera and projector
- Available design files
 - Schematic (<http://www.ti.com/lit/pdf/tidr157>)
 - Bill of Materials (<http://www.ti.com/lit/pdf/tidr958>)
 - Command-line 3-D Scanner with DLP Structured Light SDK (<http://www.ti.com/lit/zip/tidc535>)
 - Camera Trigger Cable Assembly Guide (<http://www.ti.com/lit/df/tidu457a/tidu457a.pdf>)
- Available from TI Designs
 - <http://www.ti.com/tool/TIDA-00254>



Where to find software, BOM, and trigger cable assembly guide?

1. Go to the TIDA-00254 tool page (<http://www.ti.com/tool/TIDA-00254>)
2. Software installer listed under Download Design Files button
3. Schematic and BOM listed under their respective buttons

The screenshot shows the TIDA-00254 tool page in a web browser. The page is titled "Accurate Point Cloud Gen" and has the URL "www.ti.com/tool/TIDA-00254". It features four main sections: "Schematic/Block Diagram", "Test Data", "Design Files", and "Bill of Materials (BOM)".

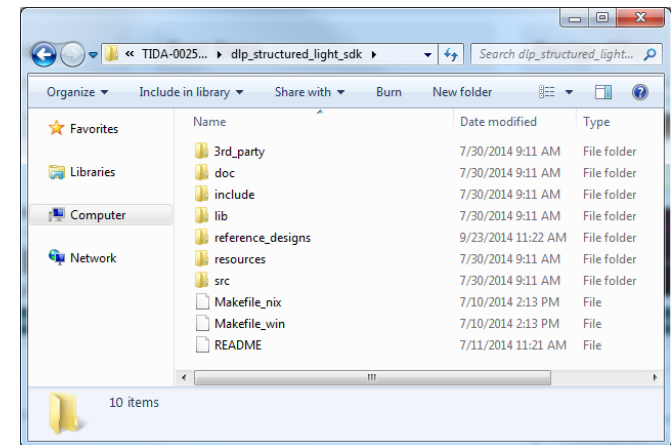
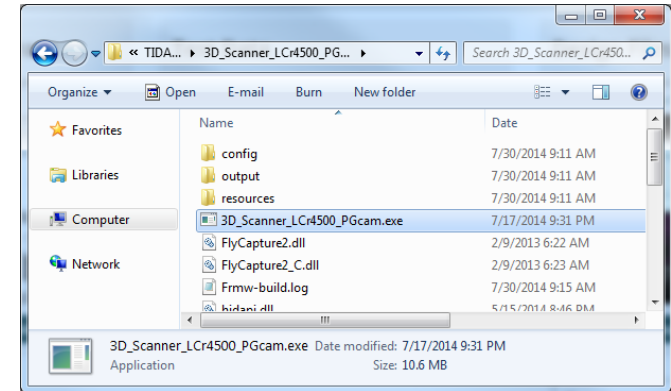
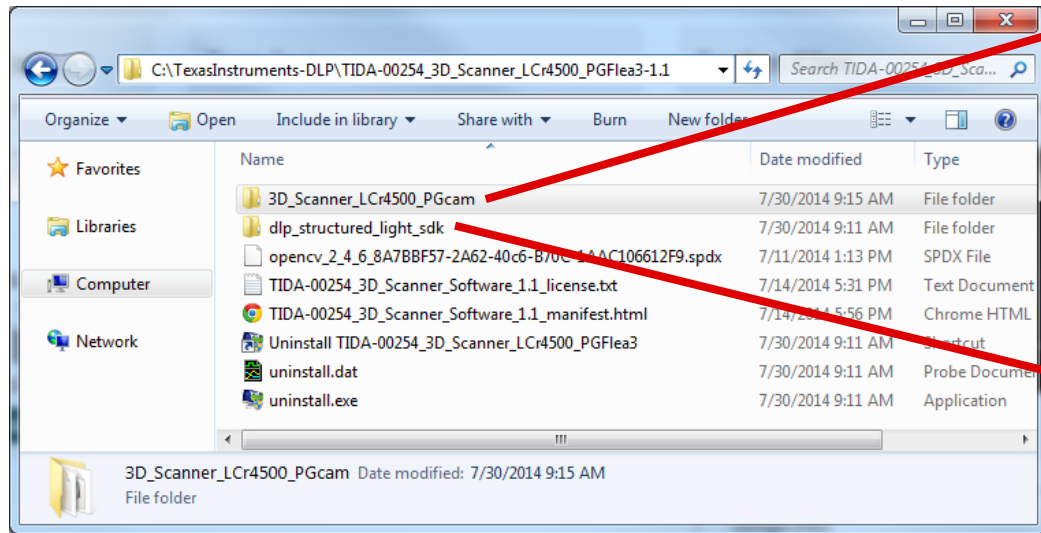
- Schematic/Block Diagram:** Described as "Quickly understand overall system functionality." It includes a block diagram showing a Windows 7 PC connected to a USB 3.0 Port, which is connected to a CAMERA (Point-Drive Plus USB 3.0/30M). The CAMERA is connected to a CAMERA SENS (Computer Model 3.0/30M). Below the diagram is a "Download Schematic" button.
- Test Data:** Described as "Get results faster with test and simulation data that's been verified." It includes a 3D point cloud visualization of a camera trigger cable. Below the image is a "Download Test Data" button.
- Design Files:** Described as "Download ready-to-use system files to speed your design process. Get Viewer." It includes a thumbnail image of a design file. Below the image is a "Download Design Files" button.
- Bill of Materials (BOM):** Described as "Find the complete list of components in this reference design." It includes a "Download BOM" button.

At the bottom of the page, there is an "Order Now" button. A small window titled "Design Files" is open, showing a list of files:

File Name	Download Date
TIDA-00254 Camera Trigger Cable Assembly (Rev. A)	26 Sep 2014
Software Files	
TIDA-00254 Windows Installer	25 Jul 2014

Where is the 3-D Scanner Application and DLP Structured Light SDK source code?

1. Go to the TIDA-00254 tool page (<http://www.ti.com/tool/TIDA-00254>)
2. Software installer listed under Download Design Files button (<http://www.ti.com/lit/zip/tidc535>)



Design Considerations for 3-D Machine Vision

How to choose a DLP® Chipset?

- What am I trying to scan?
 - Darkly colored objects → Need more light
 - Lightly colored/shiny objects → Need less light
 - Moving objects → Need fast scan times
 - Static objects → Scan time less important
 - Biometrics → May need non-visible wavelengths
 - Clear objects → Need non-visible wavelengths
- How portable should scanner be?
 - Smaller chipsets need smaller optics and are more portable
- Are fast scan times needed?
 - Camera is typically the limiting factor if binary patterns are used
 - Non-binary patterns such as three phase methods can cause the projector speed to limit overall system
- What is the desired accuracy of the point cloud?
 - Determined by camera and projector resolutions, baseline distance, focal lengths, and structured light method

How to determine point cloud resolution?

Spatial X and Y

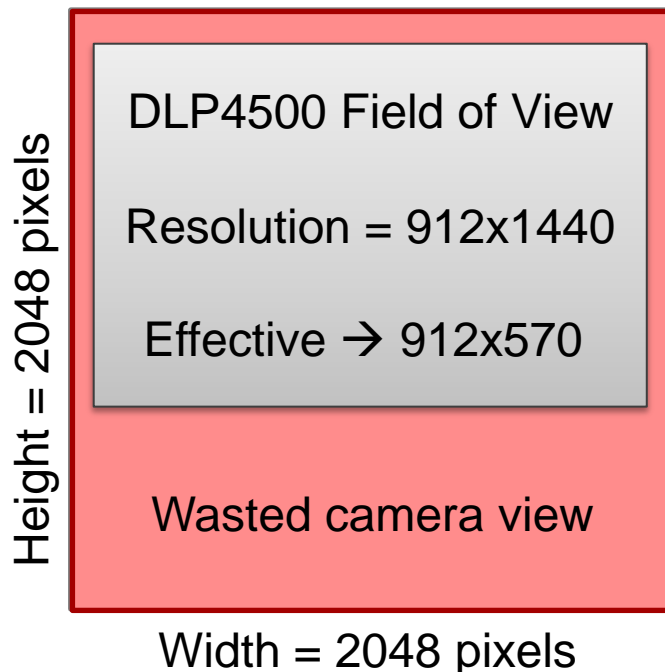
- Inversely proportional to field of view
 - Scanning larger areas worsens spatial resolution
 - Scanning smaller areas improves spatial resolution
- Proportional to camera and projector resolution
 - Increasing camera or projector resolution improves spatial resolution
 - Also increases number of points in cloud

Z-Depth

- Inversely proportional to focal length and baseline
 - Longer focal lengths improve accuracy
 - Increasing the baseline distance improves accuracy
- Proportional to the object distance and disparity resolution
 - Accuracy decreases as distance increases
 - Increasing camera and projector resolutions improves accuracy

System Resolutions & Field of Views

- Nyquist theorem requires at least 2x sampling
 - Camera width resolution must be double projector width resolution
 - Camera height resolution must be double projector height resolution
 - Camera pixel count should be at least 4 times larger than projector's!
- Field of view and “effective resolution” must be considered



Field of view mismatch means smaller effective resolution...

$$2048 \text{ pxls} * 60\% = 1228 \text{ effective pxls}$$

Check pixel sampling...

$$\frac{1228 \text{ effective pxls}}{1140 \text{ projector pxls}} = 1.07 < 2$$

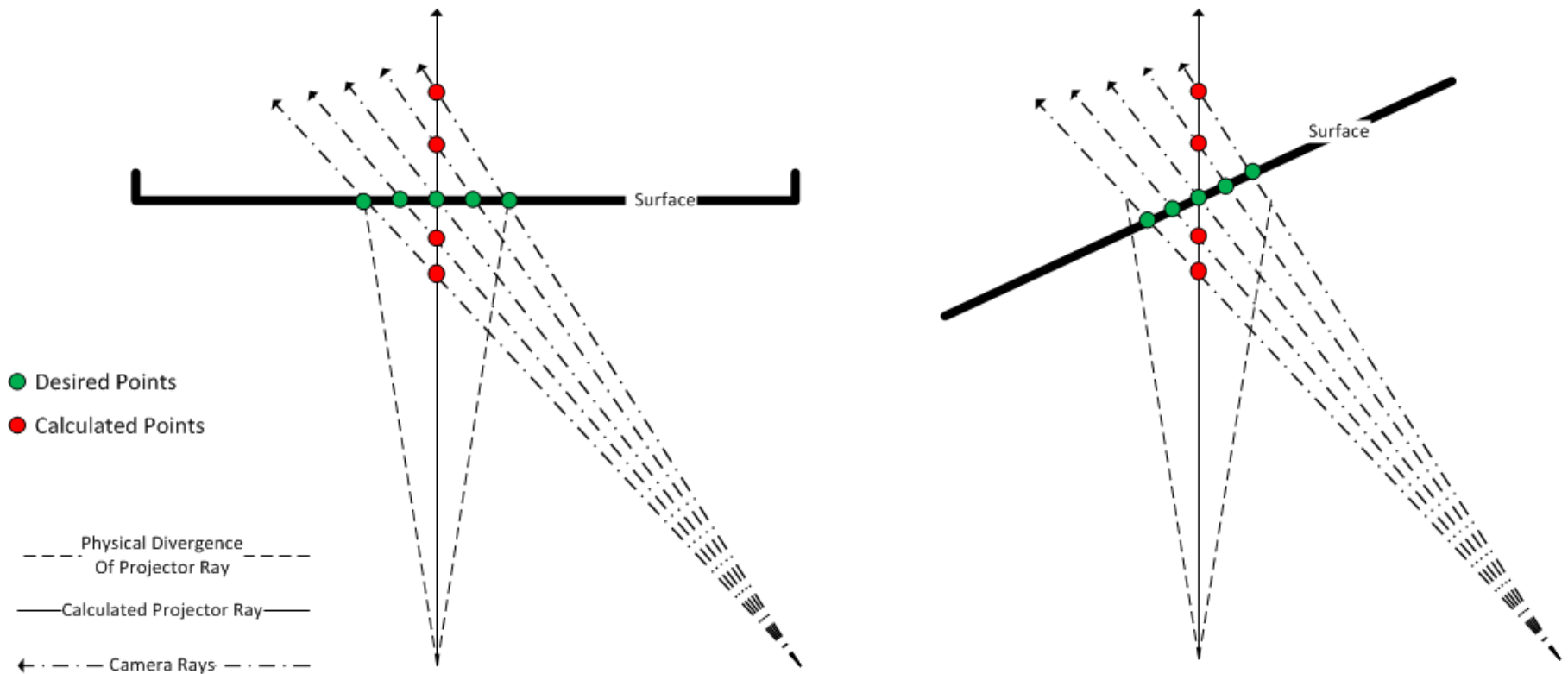
Cannot resolve all projector rows!!

$$\frac{1228 \text{ effective pxls}}{570 \text{ projector pxls}} = 2.15 > 2$$

Can resolve projector row pairs

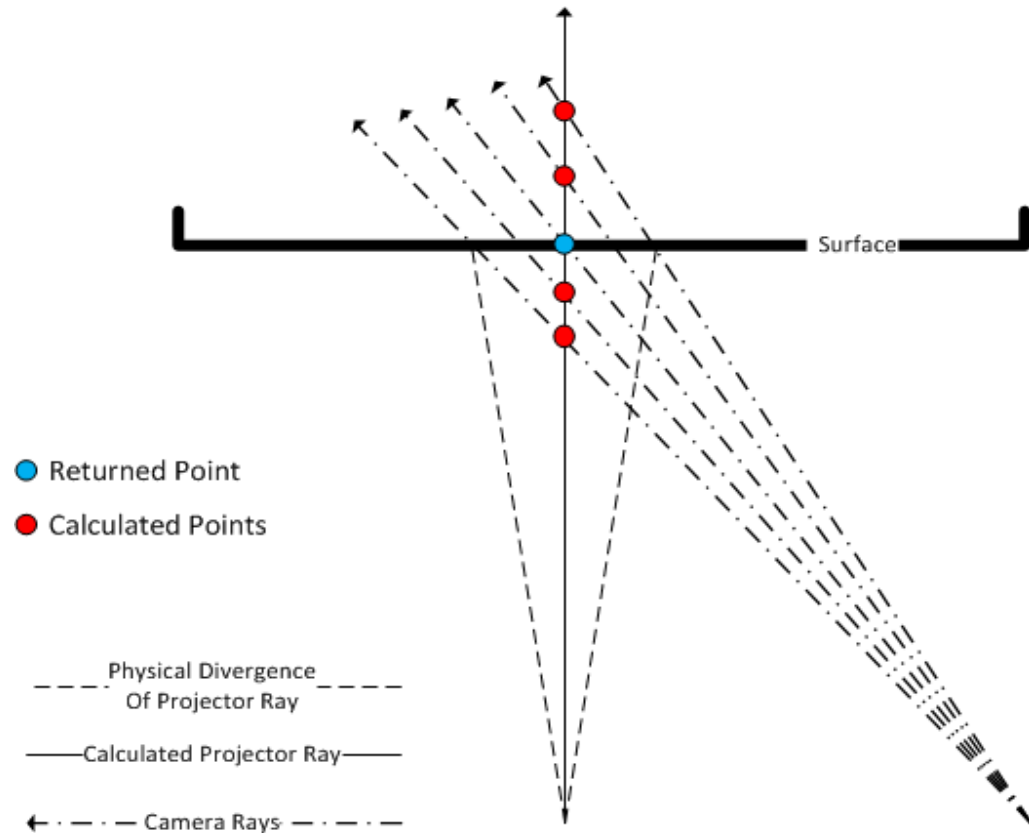
Effects of pixel over-sampling

- Decreased point cloud accuracy from divergent beams
 - Projector rays are straight lines rather than divergent beams
 - Over-sampling the projector rays leads to incorrect point reconstructions



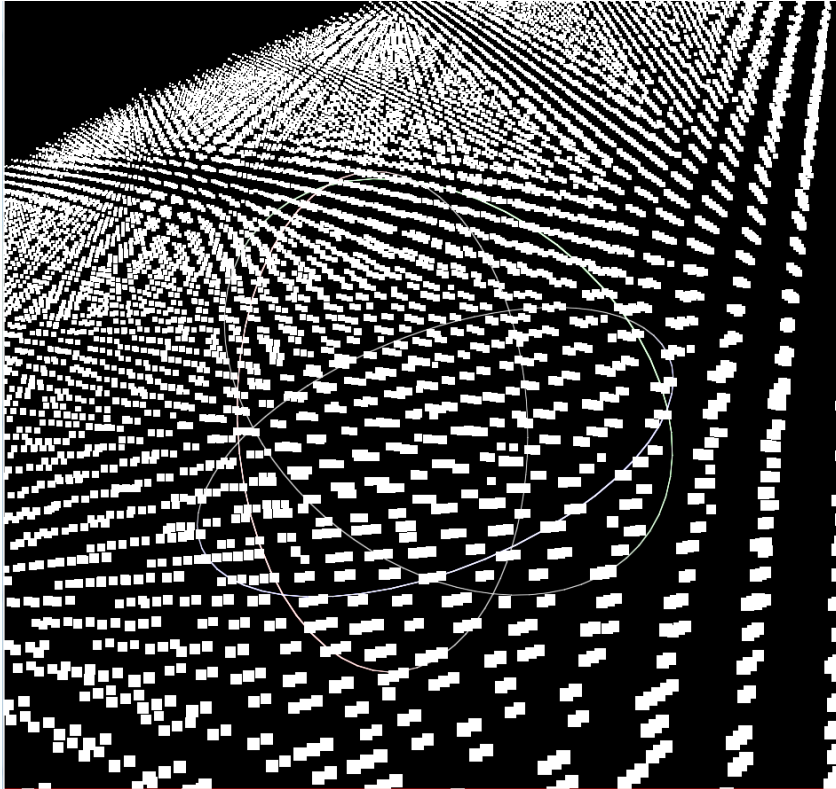
Overcoming pixel over-sampling

- When both vertical and horizontal patterns are used every camera ray is associated to a specific projector ray
- During reconstruction, group points according to their projector ray and filter!
- This method limits the number of points to the number of projector pixels
- This method will not work for scans with a single orientation of patterns

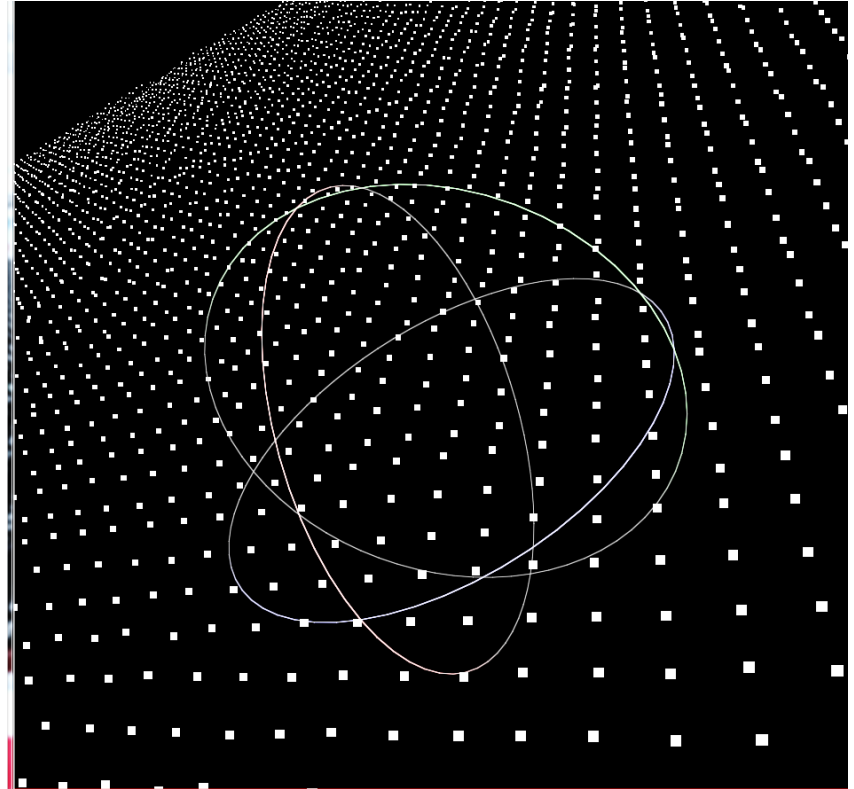


Example of filtering points by projector ray

No Filtering



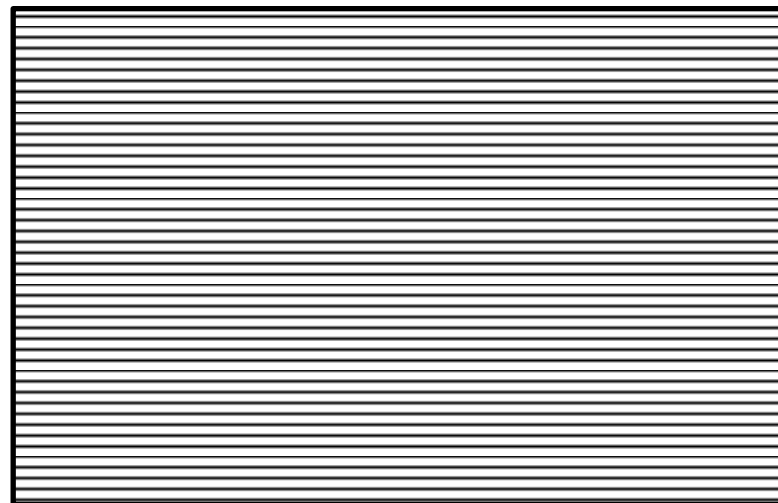
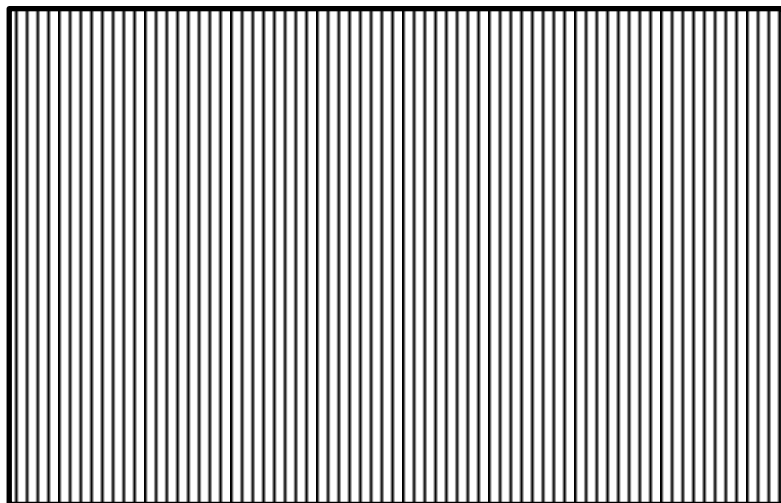
Points Filtered Per
Projector Ray



Note the lower density and higher accuracy of the point cloud

What about using one pattern orientation?

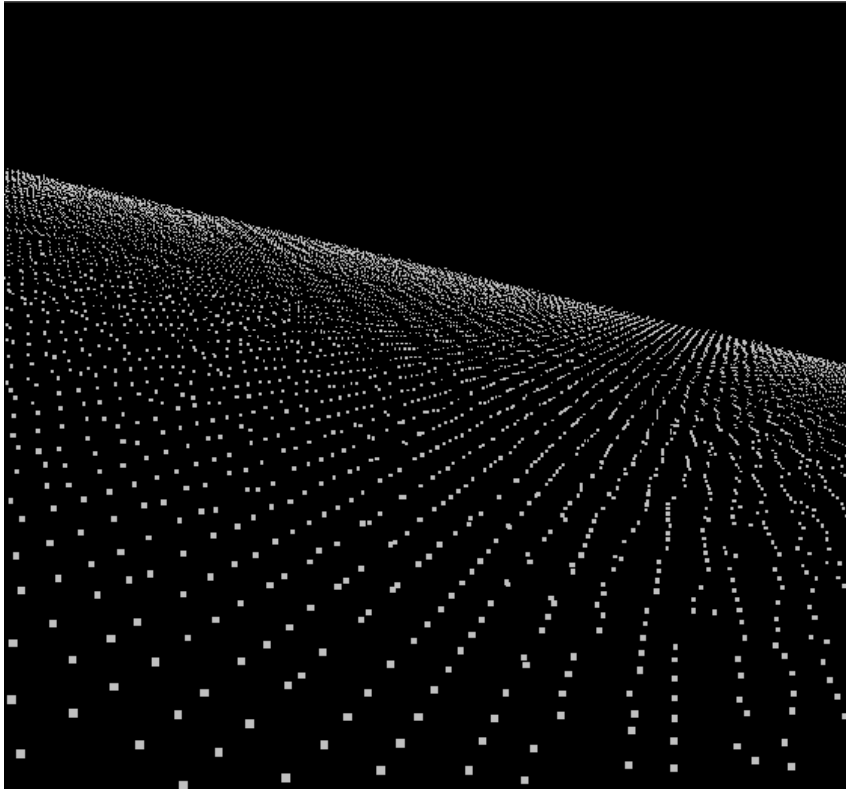
- If only vertical or horizontal patterns are used, filtering by projector ray is not possible since only planes are identified



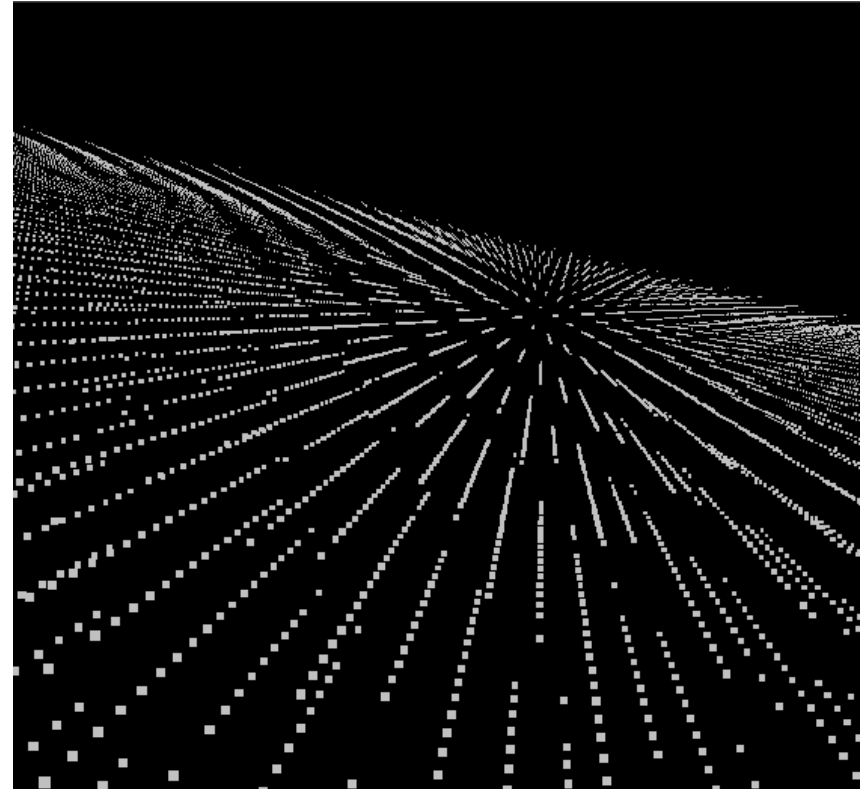
- Single pattern orientation scans offer several advantages
 - Faster scan times
 - Point cloud density a function of projector planes (rows or columns) and camera resolution rather than only projector pixels

Example of Pattern Orientation Clouds

Filtering w/ Both Orientations



Only Vertical Orientation



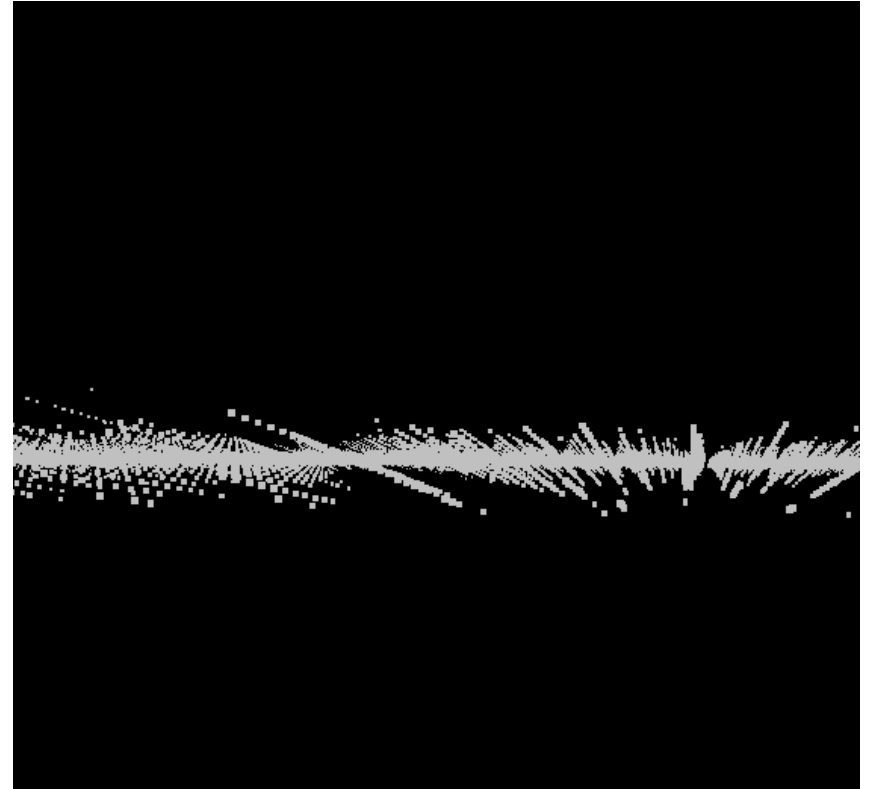
Note the higher point cloud density

Example of Pattern Orientation Clouds

Filtering w/ Both Orientations



Only Vertical Orientation

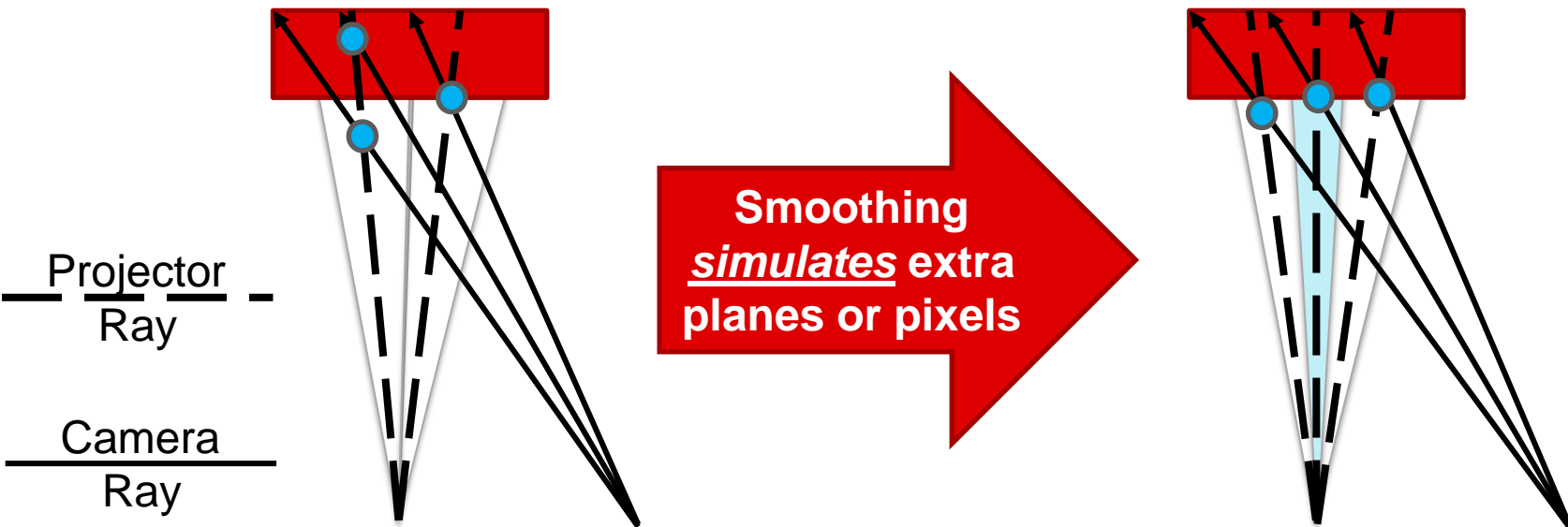


Note the higher point cloud density but lower depth accuracy

Smoothing the Disparity Map

- How to solve over sampling when using single orientation patterns?
 - After constructing the disparity map with projector planes, apply a smoothing filter on the disparity map
- Consider three camera pixels which see two projector planes

$\{ 1, 1, 2 \}$ ← Disparity Map Values → $\{ 1, 1\frac{1}{2}, 2 \}$



- Note: This can smooth edges that should be sharp!

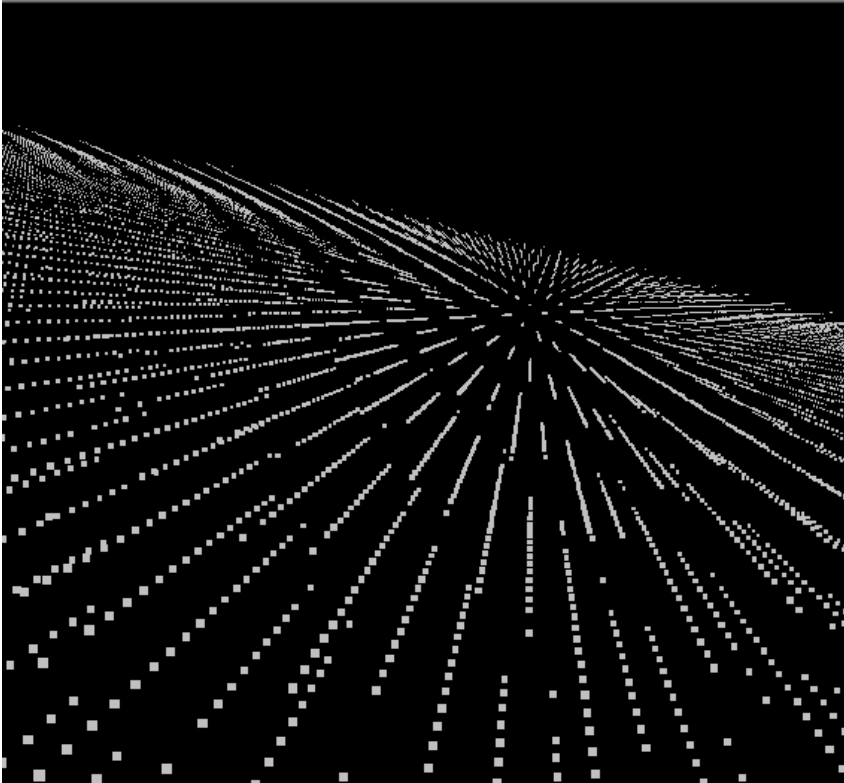
Smoothing a Disparity Map Example



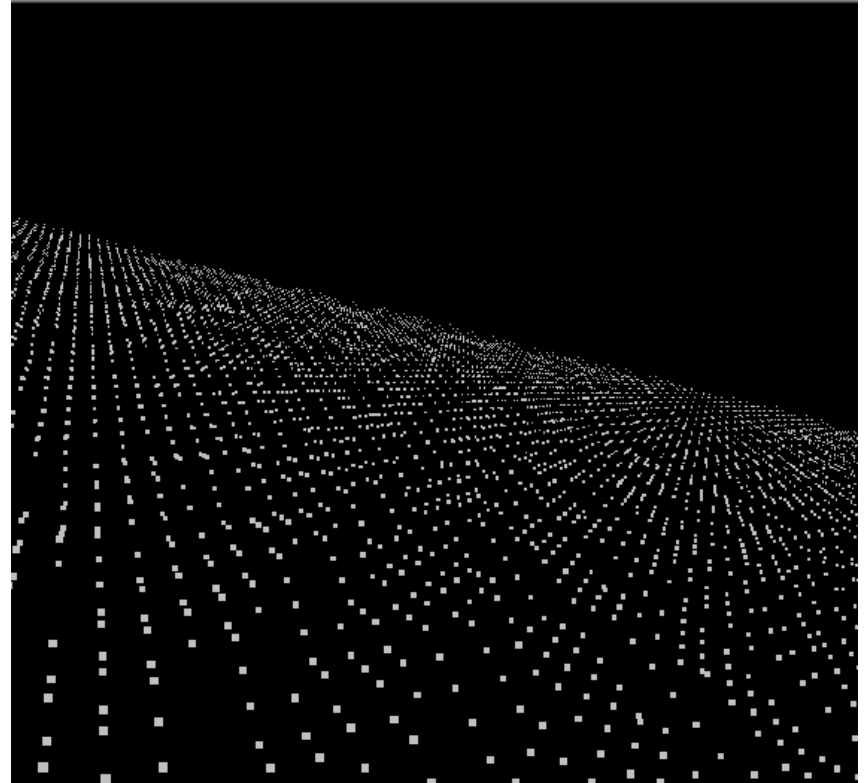
Note: This is an **extreme** example!

Example of Disparity Smoothing

No Smoothing



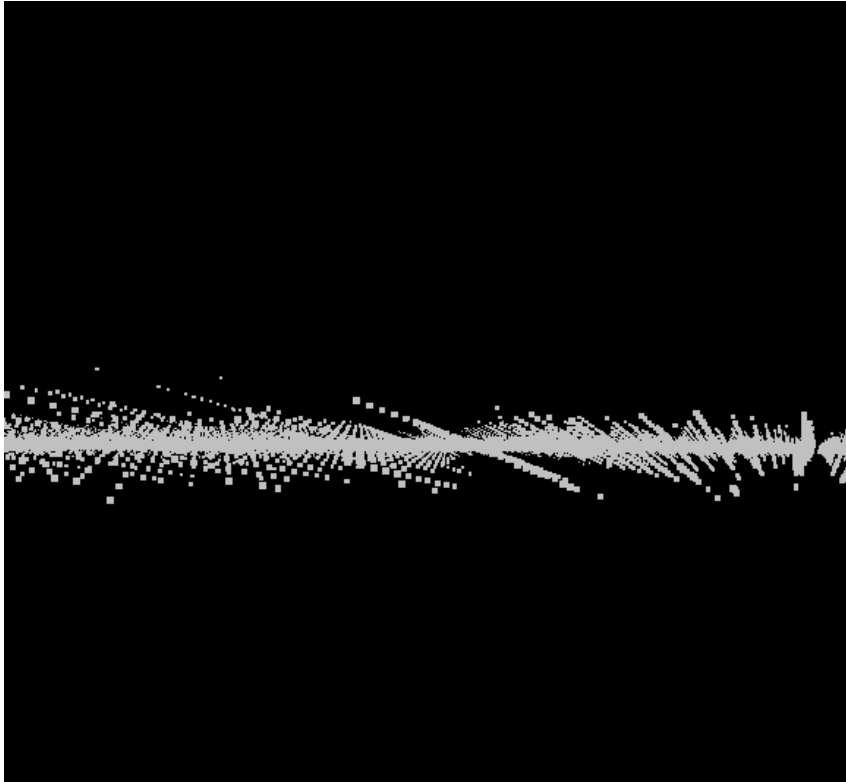
Smoothing Applied



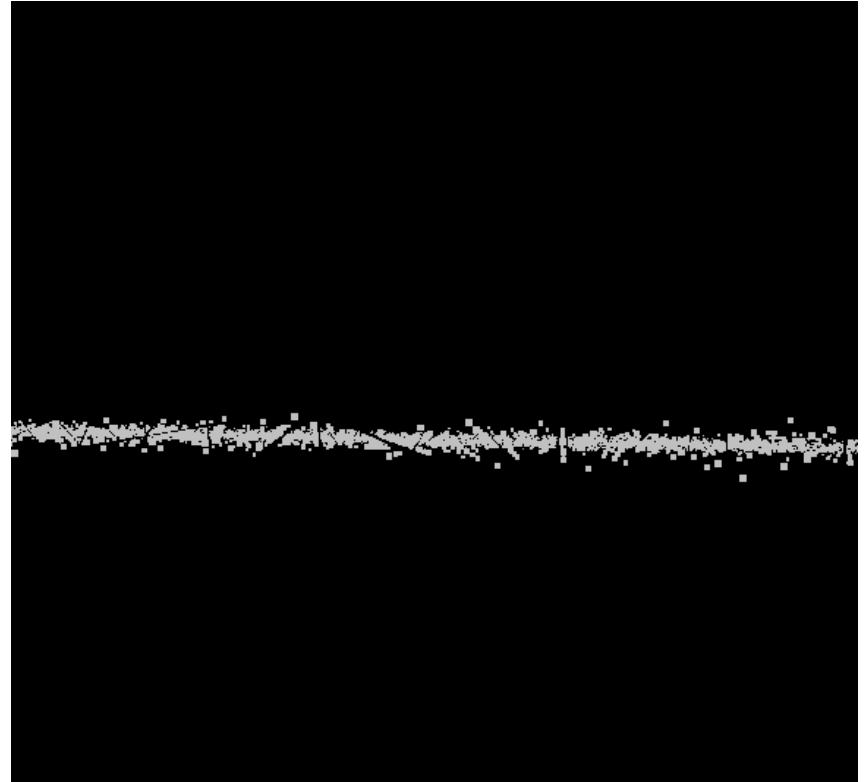
Helps but does not completely remove cloud “thickness”

Example of Disparity Smoothing

No Smoothing



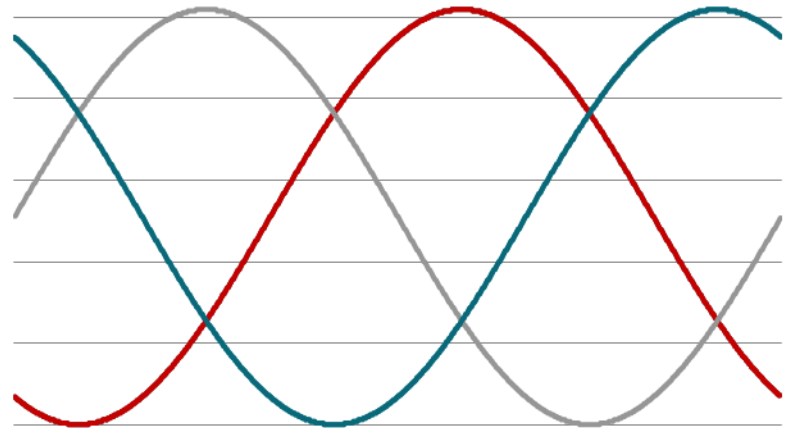
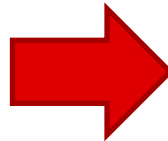
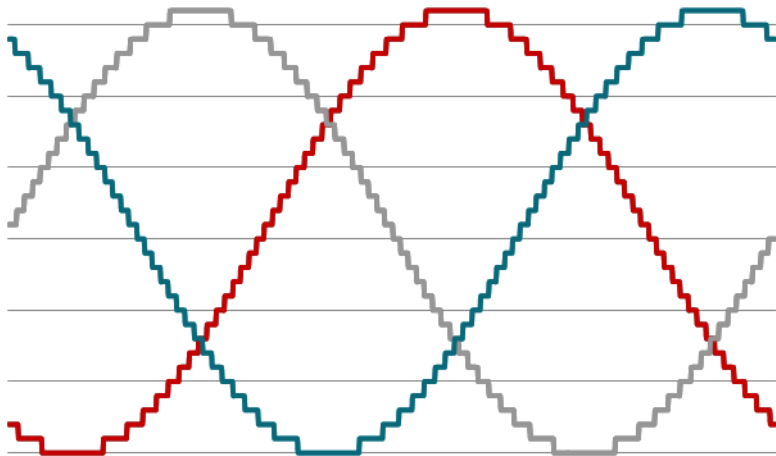
Smoothing Applied



Helps but does not completely remove cloud “thickness”

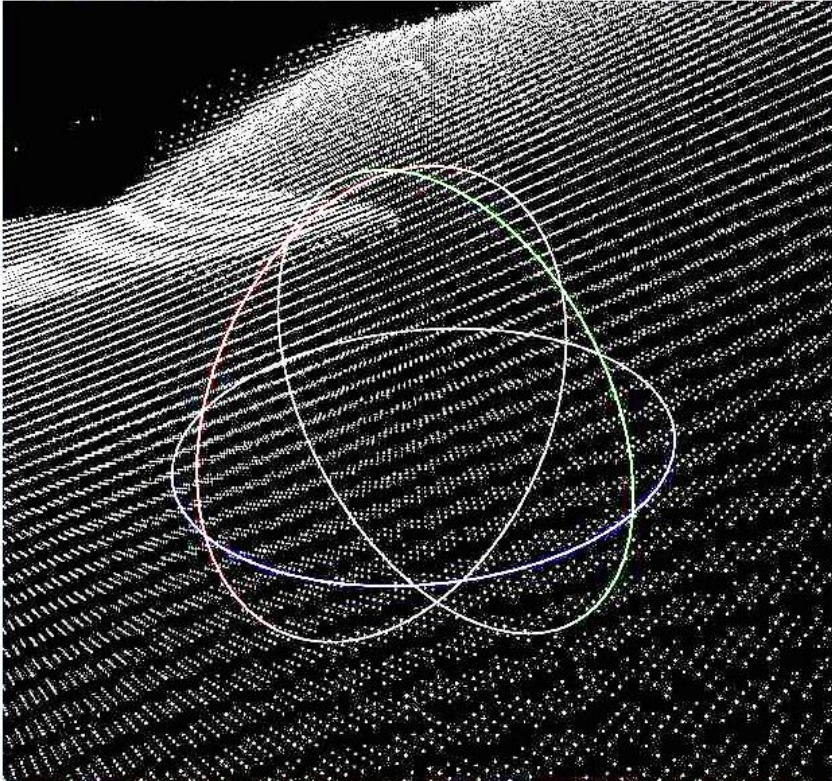
Alternative to Disparity Map Smoothing?

- Consider if the projector is in focus or not
 - Binary patterns are less robust against de-focus and “fuzzy” pixels are determined invalid during decoding
 - Smoothing disparity map helps, but softens edges due to manipulating the pixels of the captured image
- Phase shift patterns often times use sinusoidal patterns
 - Fuzzy pixels, over-sampling, and diamond pixels help smooth sine waves!
 - Edges are retained because camera *captures* the already averaged projection

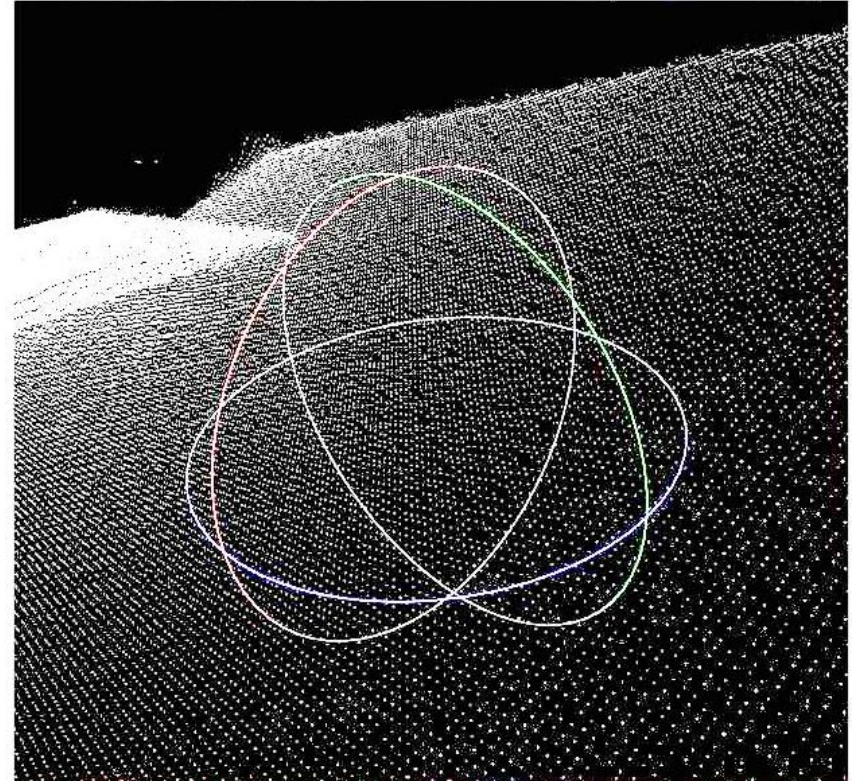


Example of Three Phase with Sub-Pixels

No Sub-Pixels



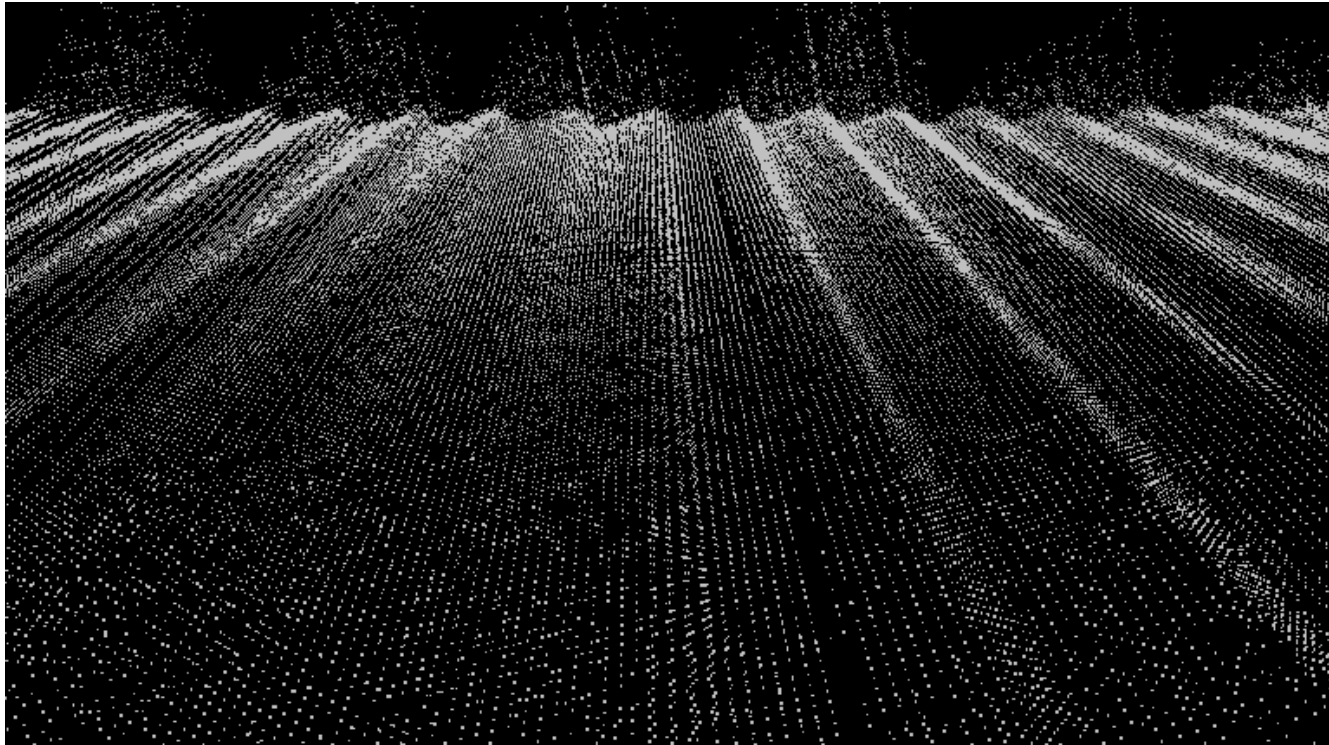
Sub-Pixels Calculated



No loss in point cloud density or edge definition!

Phase Shift Scans and Ambient Light

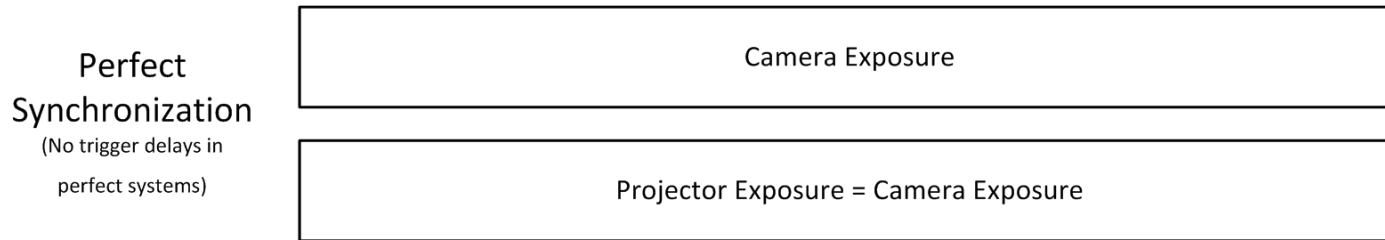
- Many indoor light sources pulse a 60 Hz!
- Notice the effect of fluorescent lighting on this 120 Hz speed scan



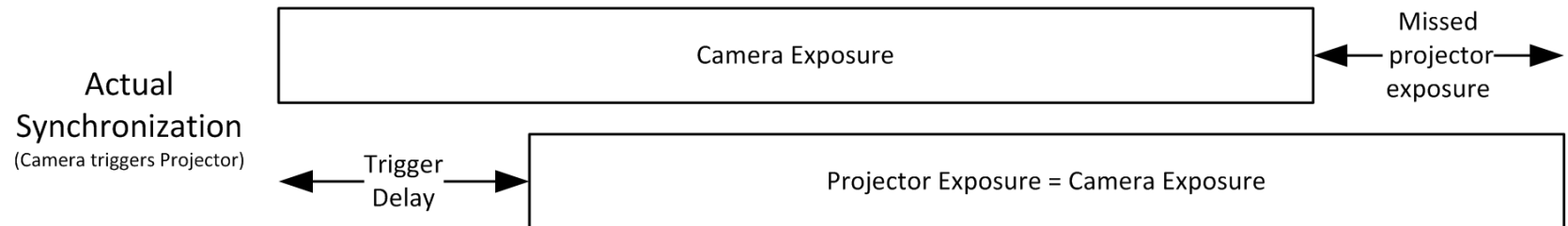
- Camera and pattern exposures must be very long to average the ambient light pulses or scan must be taken in darkness

Synchronizing the Camera with Projector

- Ideally everything matches up perfectly



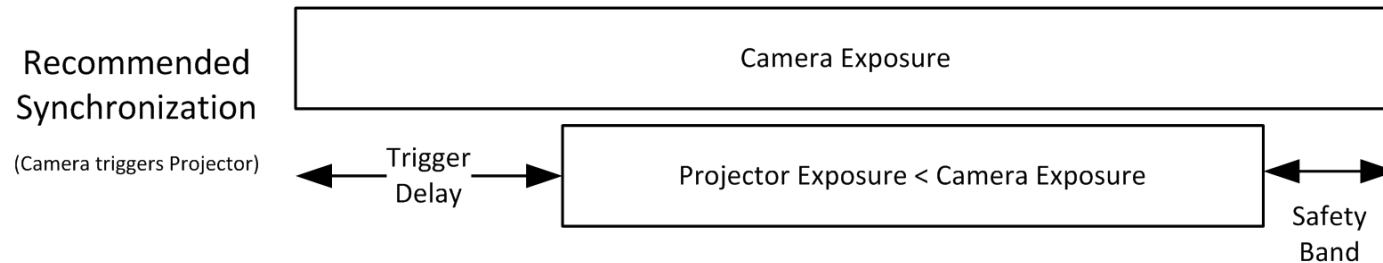
- There is always a delay in the triggers



- Camera exposure may capture part of the next or previous projected pattern
- Delay could cause the camera exposure to miss part of the pattern
 - This could cause issues in the linearity of non-binary patterns

Synchronizing the Camera with Projector

- Recommended synchronization setup



- Camera triggers projector
 - Most cameras with triggers run faster in a free run mode rather than a triggered mode
 - If the projector triggered the camera, the trigger delay would cause the camera exposure to miss part of the exposed pattern
- Projector exposure shorter than the camera exposure
 - Ensures the camera exposure captures the entire projected pattern and thus greyscale linearity remains intact

Developing with the DLP® Structured Light SDK

Developing the DLP® Structured Light SDK

- Setting up the development environment
 - Install the DLP Structured Light SDK
 - Install and compile OpenCV
- Scalable solutions with object oriented programming (OOP) in C++
 - Case Study: Consider that the 3-D Scanner Demo software is practically identical for the DLP LightCrafter™ 4500 EVM and DLP LightCrafter 6500 EVM (and now the DLP LightCrafter 3000 EVM)
 - What are the primary abstract modules?
 - How to use abstracted modules?
- Creating new modules
 - Where should source code go?
 - How to creating a new camera module?


Setting up the development environment

- DLP® Structured Light SDK
 - Currently included with 3-D Machine Vision Reference Design
 - As new DLP evaluation modules are added (DLP LightCrafter, LightCrafter 6500 EVM, etc.) the DLP Structured Light SDK source code will move to its own tool page
 - This is to prevent duplication of code on ti.com
- OpenCV
 - Download the source code from www.opencv.org
 - Brief instructions
 - Install CMake
 - Use CMake to create Makefile
 - Compile with make
 - Detailed compilation instructions are available in the Machine Vision Reference Design User's Guide

Scalable Solutions with OOP

- Consider the DLP LightCrafter™ 4500 and LightCrafter 6500 EVMs
 - Both chipsets have different API, resolutions, speeds, etc.
 - Did I need to rewrite each application with all of the chipset specific API ?
 - NO! Only a single line of code needed to change

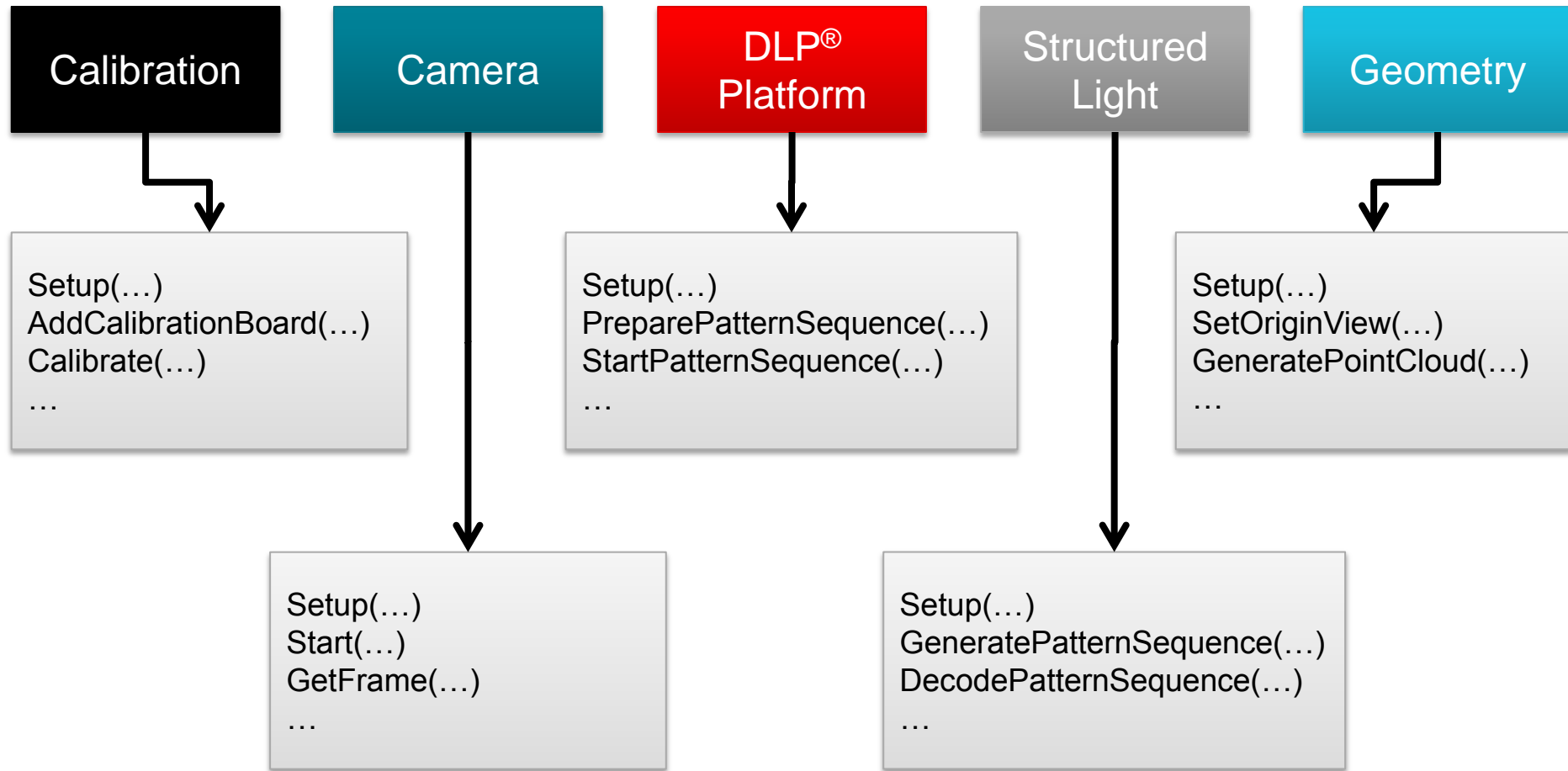
```
1412 // System Variables
1413 dlp::PG_FlyCap2_C camera;
1414 dlp::LCr4500 projector;
```



```
1412 // System Variables
1413 dlp::PG_FlyCap2_C camera;
1414 dlp::LCr6500 projector;
```

- **The DLP LightCrafter 3000 & 6500 EVM SDK to be added soon!**
- How is this possible?
 - DLP Structured Light SDK contains modules which define interfaces
 - C++ allows you to reference sub-classes as their parent class

What are the primary abstract modules?



- Each module (base-class) defines an interface which all sub-modules (sub-classes) must follow

How to use abstracted modules?

- Function Declaration uses the abstracted base-class modules

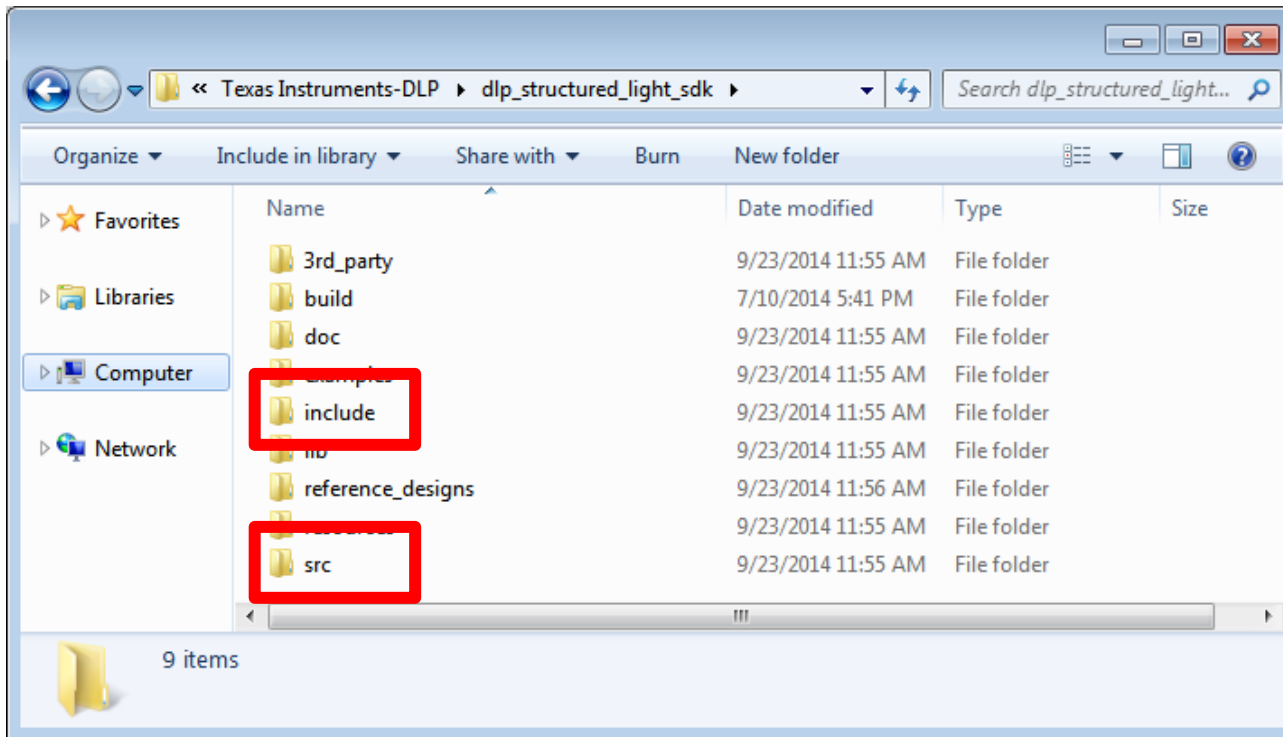
```
void ScanObject(dlp::Camera      *camera,  
               const std::string &camera_calib_data_file,  
               dlp::DLP_Platform *projector,  
               const std::string &projector_calib_data_file,  
               dlp::StructuredLight *structured_light_vertical,  
               dlp::StructuredLight *structured_light_horizontal,  
               const bool        &use_vertical,  
               const bool        &use_horizontal,  
               const std::string &geometry_settings_file){
```

- Specific sub-modules can be passed as the parent type though

```
// System Variables  
dlp::PG_FlyCap2_C camera;  
dlp::LCr6500      projector;  
  
ScanObject(&camera,  
          calibration_data_file_camera,  
          &projector,  
          calibration_data_file_projector,  
          &structured_light_vertical,  
          &structured_light_horizontal,  
          true,  
          true,  
          geometry_settings_file);
```

Where should source code go?

- Use the current sub-modules for reference
 - Header files should be located in the /include directory
 - Source files should be located in the /src directory



- Add new source files to QT PRO file or CMakeLists.txt

How to creating a new camera module?

- Reference the module base-class header files to identify what functions need to be written for a sub-class
 - All virtual functions must be written by the sub-class!

```
class Camera: public dlp::Module{  
    public:  
  
    // Define by subclass  
    virtual ReturnCode Connect(int camera_id) = 0;  
    virtual ReturnCode Disconnect() = 0;  
  
    virtual ReturnCode Start() = 0;  
    virtual ReturnCode Stop() = 0;  
  
    virtual ReturnCode GetFrame(Image* ret_frame) = 0;  
}
```

NOTE: This is only an example!! Please reference camera.hpp for the complete camera module declaration

```
class PG_FlyCap2_C : public Camera  
{  
    public:  
  
    // Define pure virtual functions  
    ReturnCode Connect(int camera_id);  
    ReturnCode Disconnect();  
  
    ReturnCode Start();  
    ReturnCode Stop();  
  
    ReturnCode GetFrame(Image* ret_frame);  
}
```

Notice that the sub-class contains the exact same methods

Conclusion

- Industrial 3-D Machine Vision systems are complicated as a whole, but the different processes can be broken down into manageable sub-systems
- The TI design featuring the DLP® LightCrafter™ 4500 EVM enables faster evaluation periods for assessing DLP technology with 3-D machine vision (about 30 minutes!)
- Choosing the best DMD and other system factors is completely dependent on the application
- The DLP Structured Light SDK provides a scalable and easy to use framework for developing various applications using DLP technology

A large, glowing white question mark is centered on the right side of the image. It is set against a dark, textured, and aged paper background with visible cracks and creases. The light from the question mark creates a warm, yellowish glow that fades into the surrounding dark texture.






Questions

Live Demonstration!

Steps to use to 3-D Machine Vision design

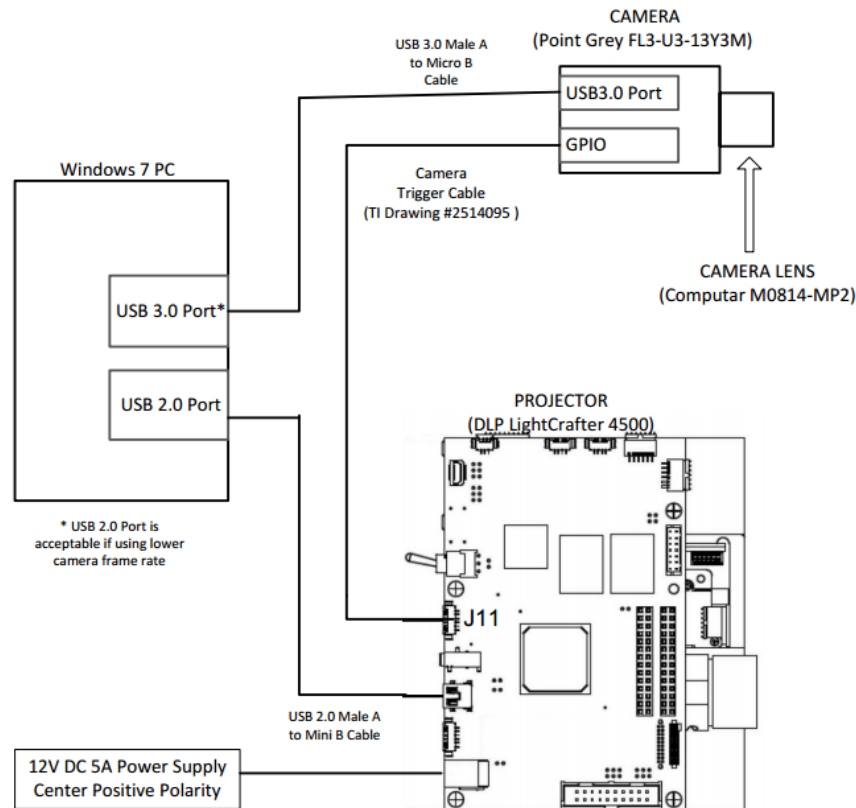
1. Install software → Done!
2. Connect the hardware
3. Make calibration board → Done!
4. Prepare the software and projector
5. Calibrate Camera
6. Calibrate System
7. Perform Scan
8. Develop your own applications!

Installing software

Software	Purpose	Required for application	Required for development
Point Grey FlyCapture2 SDK http://www.ptgrey.com/	<ul style="list-style-type: none"> • Camera drivers • Camera interface code libraries 		
DLP Machine Vision Reference Design Download http://www.ti.com/lit/zip/tidc535	<ul style="list-style-type: none"> • Precompiled application • DLP Structured Light SDK 		
Meshlab http://meshlab.sourceforge.net/	<ul style="list-style-type: none"> • Point Cloud Viewer • Surface Reconstruction • Analysis 	(optional)	
OpenCV (source code) http://opencv.org/	<ul style="list-style-type: none"> • Image data management and processing code libraries 		

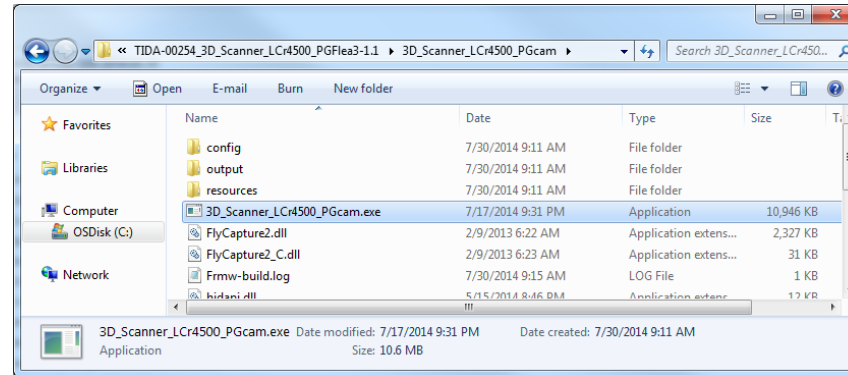
Connecting the Hardware

- Connect Camera to USB3.0 port if available
- Connect DLP® LightCrafter™ 4500 EVM to any USB port
- Connect Camera trigger cable to DLP LightCrafter 4500 EVM input trigger

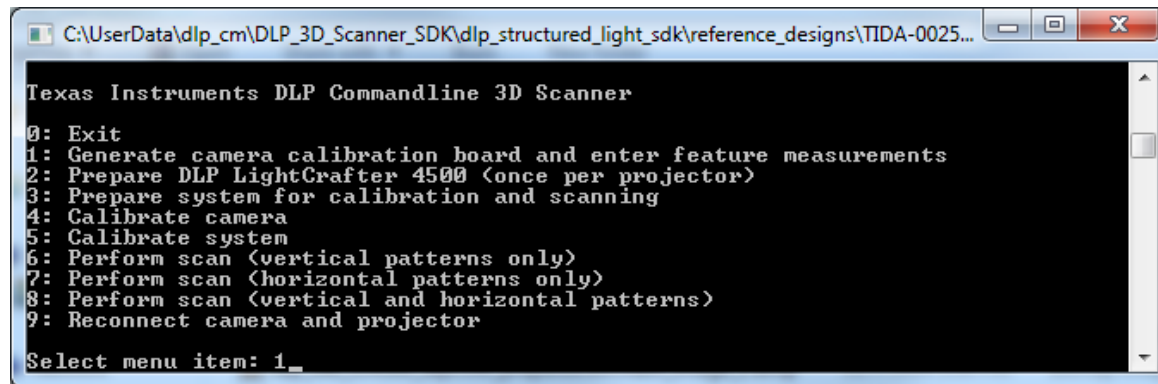


How to make the calibration board

- Open application directory and start executable

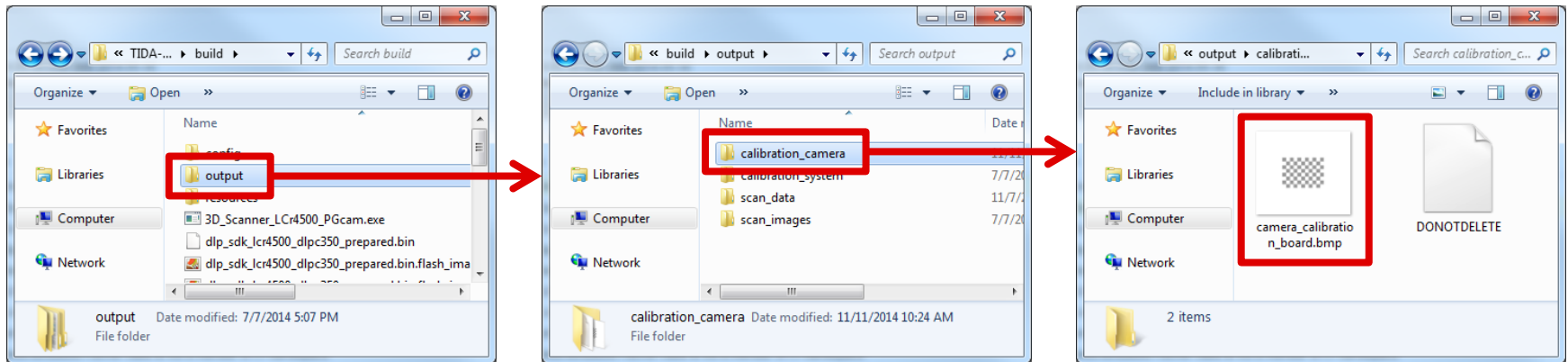


- Enter menu item “1: Generate camera calibration board and enter feature measurements”



How to make the calibration board

- After selecting menu item 1, a BMP file with the chessboard is generated in the “output/calibration_camera” directory



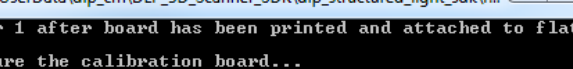
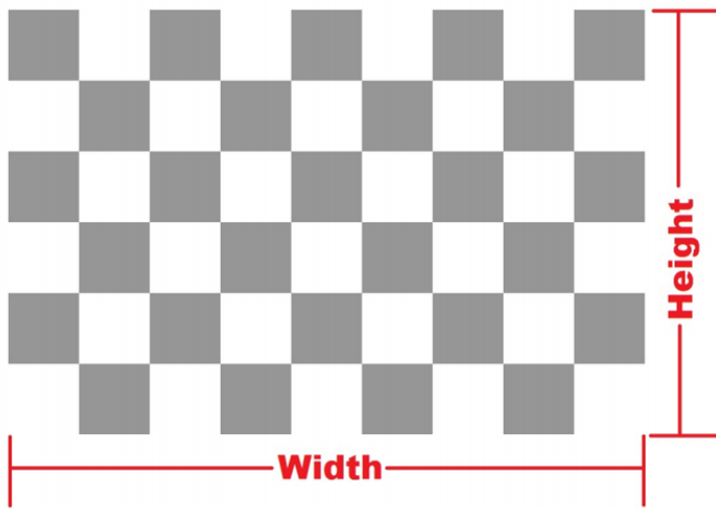
- Print the BMP file (at high DPI) and attach it to a flat surface
 - ¼” Foam core board, aluminum sheet stock, etc. all work well
 - Use spray adhesive to attach printed chessboard
 - **Your point cloud data will only be as good as your calibration board!**
- Flatness is critical!**

Entering calibration board measurements

- Enter “1” after printing and attaching the flat board

[illegible]

- Measure and enter the height and width of the calibration pattern
 - Note: Point cloud data units will be in the same units as are entered here

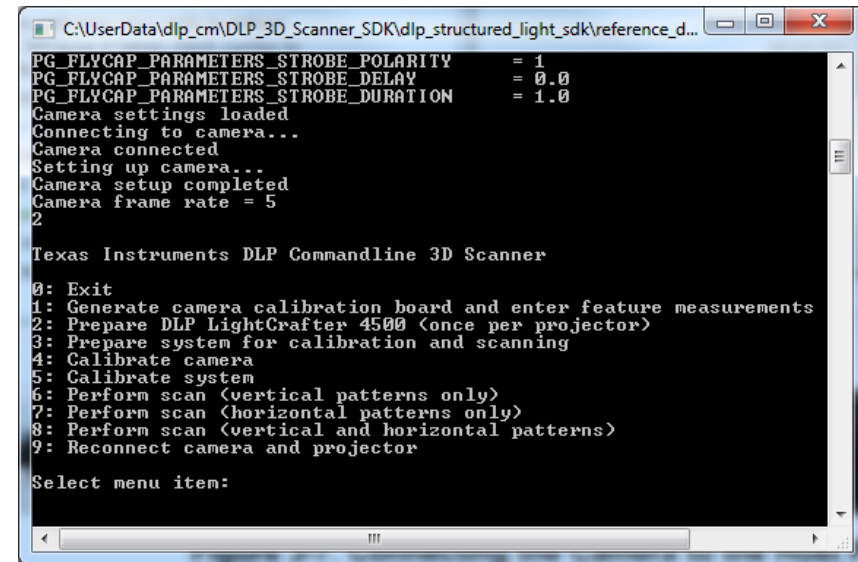


The screenshot shows a Windows command prompt window with the title bar "C:\UserData\dlp_cm\DLDP_3D_Scanner_SDK\dlp_structured_light_sdk\r...". The window contains the following text:

```
Enter 1 after board has been printed and attached to flat surface  
Measure the calibration board...  
Once the calibration image has been printed and attached  
to a flat surface, measure the dimensions of the board  
  
NOTE: Measure the calibration board in the units desired  
for the point cloud! (i.e. mm, in, cm, etc.)  
  
Enter the total height of the calibration pattern: 6  
Enter the total width of the calibration pattern: 9
```

Preparing software and projector

- Preparing the software and projector does the following:
 - Loads calibration and structured light settings
 - Generates projector calibration pattern
 - Generates structured light patterns
 - Uploads images to LightCrafter 4500
- The first time you use the projector with the software or change any structured light settings, use option 2: “Prepare DLP LightCrafter 4500 (once per projector)”
 - Performs all steps listed above
- If settings have not changed and the projector was previously prepared, use option 3: “Prepare system for calibration and scanning”
 - Performs all steps above, except uploading images to LightCrafter 4500
 - Must be run every time the application is run



```
C:\UserData\dlp_cm\DLP_3D_Scanner_SDK\dlp_structured_light_sdk\reference_d...
PG_FLYCAP_PARAMETERS_STROBE_POLARITY = 1
PG_FLYCAP_PARAMETERS_STROBE_DELAY = 0.0
PG_FLYCAP_PARAMETERS_STROBE_DURATION = 1.0
Camera settings loaded
Connecting to camera...
Camera connected
Setting up camera...
Camera setup completed
Camera frame rate = 5
2

Texas Instruments DLP Commandline 3D Scanner

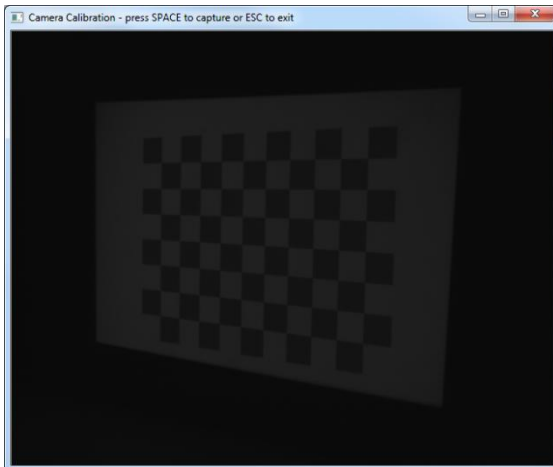
0: Exit
1: Generate camera calibration board and enter feature measurements
2: Prepare DLP LightCrafter 4500 (once per projector)
3: Prepare system for calibration and scanning
4: Calibrate camera
5: Calibrate system
6: Perform scan (vertical patterns only)
7: Perform scan (horizontal patterns only)
8: Perform scan (vertical and horizontal patterns)
9: Reconnect camera and projector

Select menu item:
```

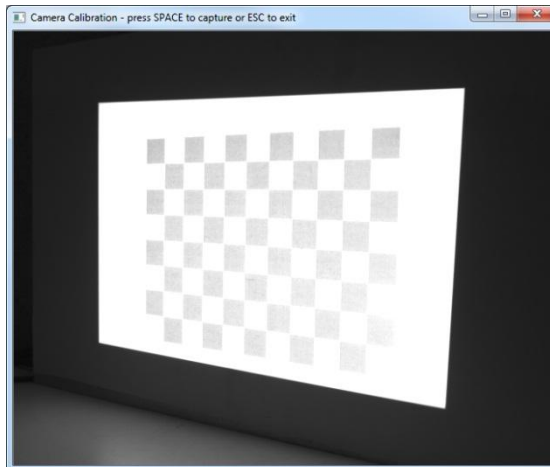
Calibrating the Camera - Setup

- Before capturing any board positions, set the aperture and focus
 - Aperture determines how much light reaches the sensor
 - Focus ensures the image plane is at the exact level of the sensor so that the image is sharp and not blurry
 - Lock everything into place!

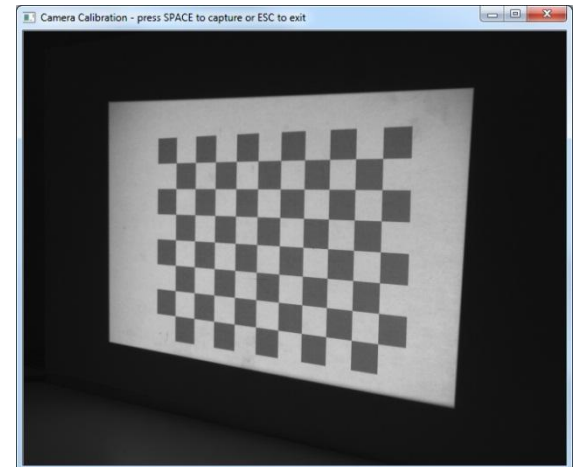
Under exposed



Over-exposed

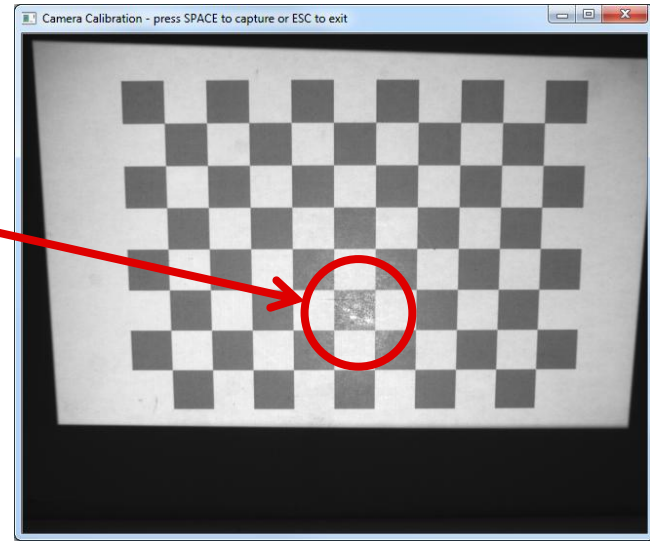


Good exposure

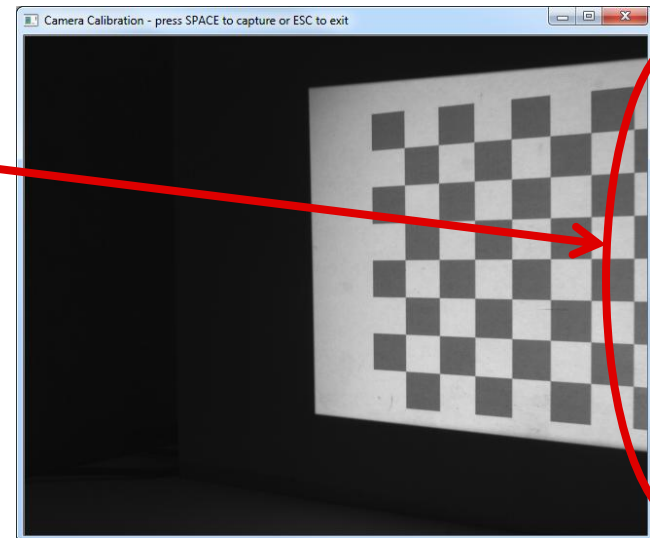


Calibrating the Camera – Watch out for...

- Software won't find the chessboard if...
 - There is too much glare
 - To remove glare, angle the calibration board

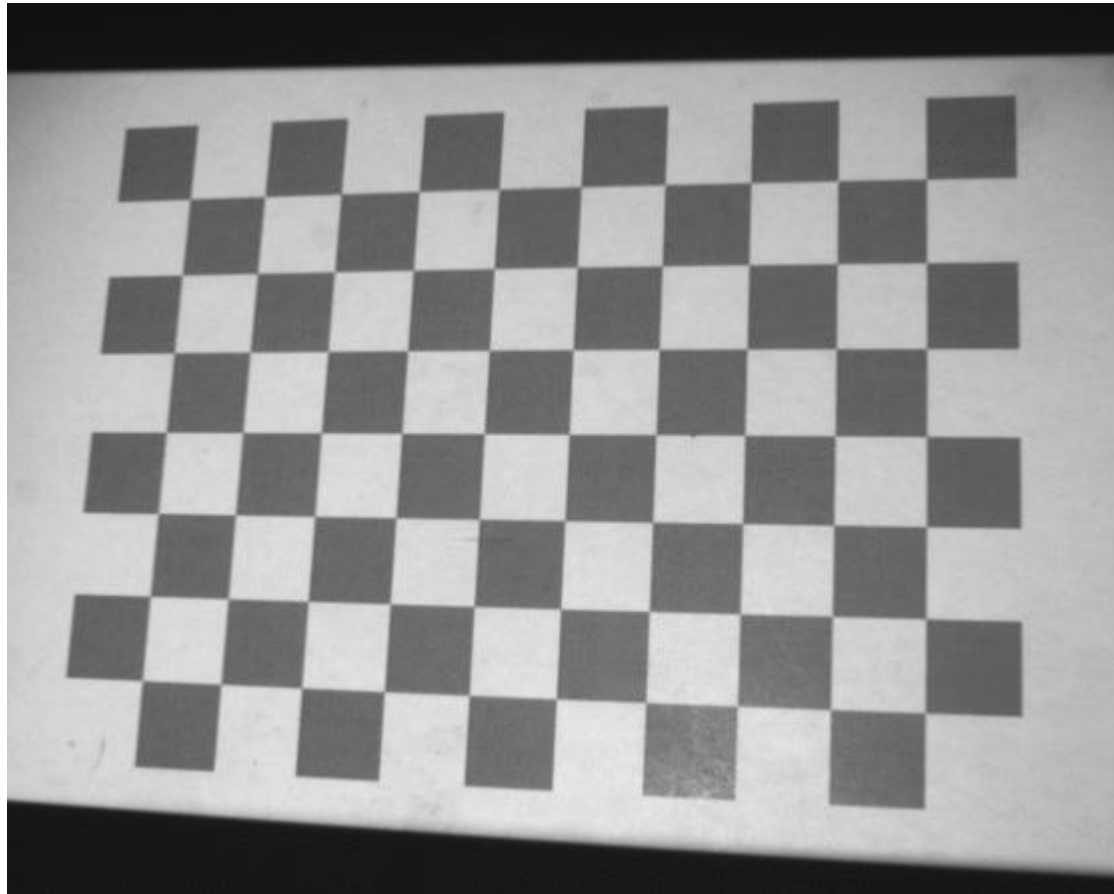


- Part of the chessboard is missing from within the captured image
 - Parts of the squares on the border square can be cutout, so long as the inside corners are still visible



Calibrating the Camera – Example Images

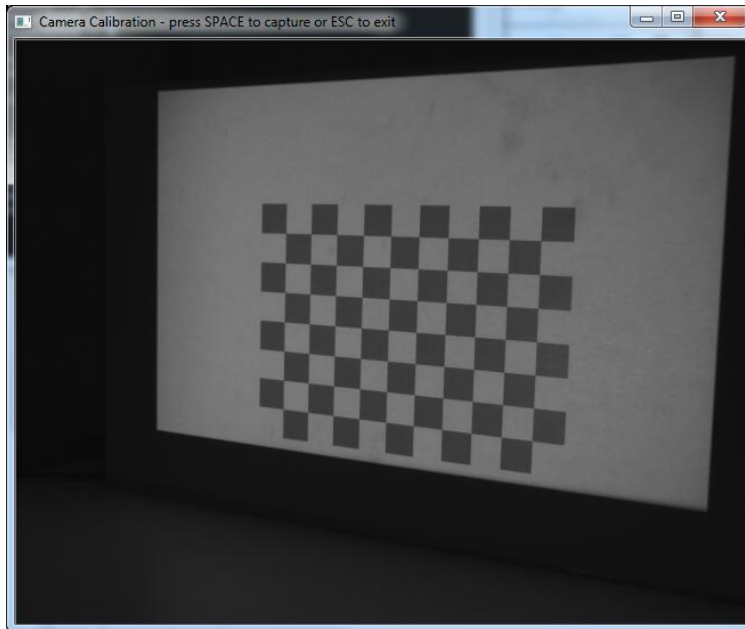
- Calibration image examples
- ?????? Measured camera reprojection error = 0.166341 ??????



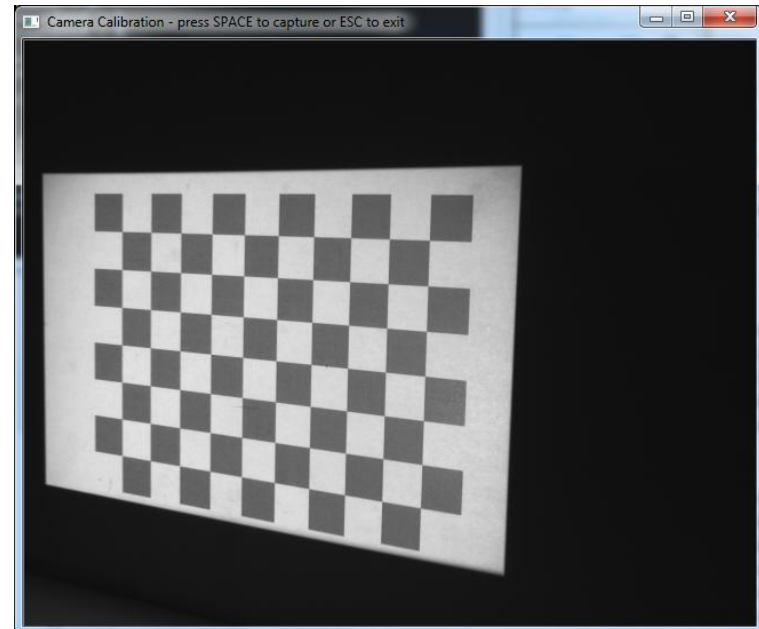
Calibrating the system - Setup

- Mount the camera so that the projected area can be seen within the camera at the minimum and maximum scanning distance
 - Try to utilize the entire camera frame if possible
- If the camera or projector are moved relative to each other, this calibration process must be redone

Furthest distance

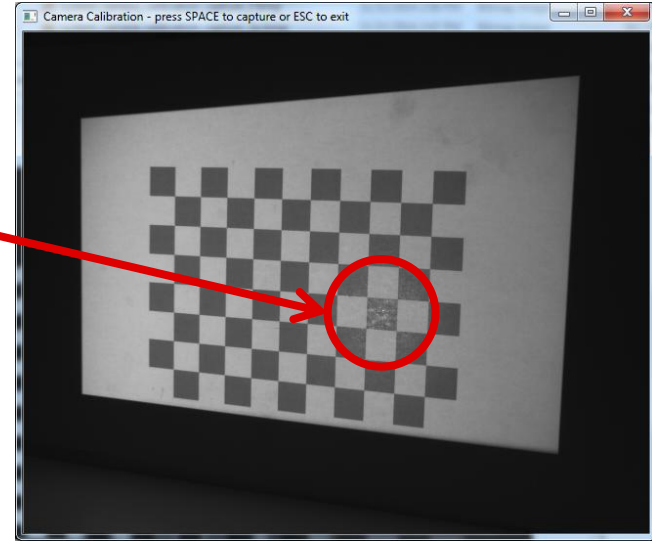


Closest distance

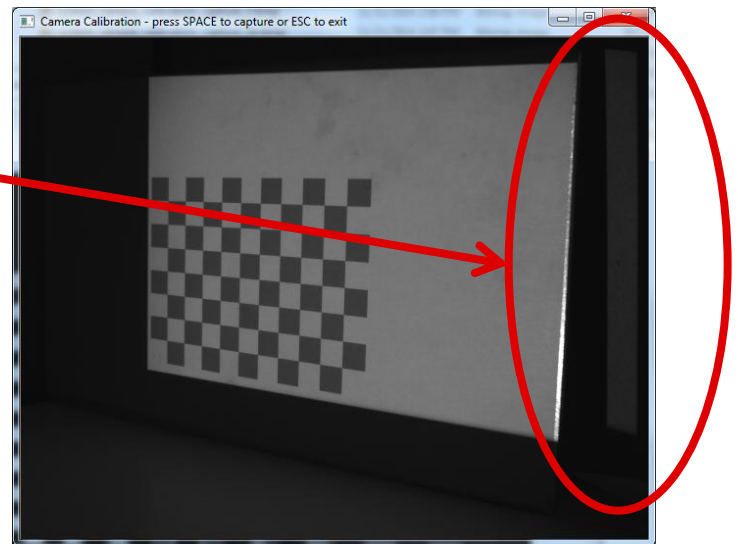


Calibrating the system – Watch out for...

- Software won't find the chessboard if...
 - There is too much glare
 - To remove glare, angle the calibration board

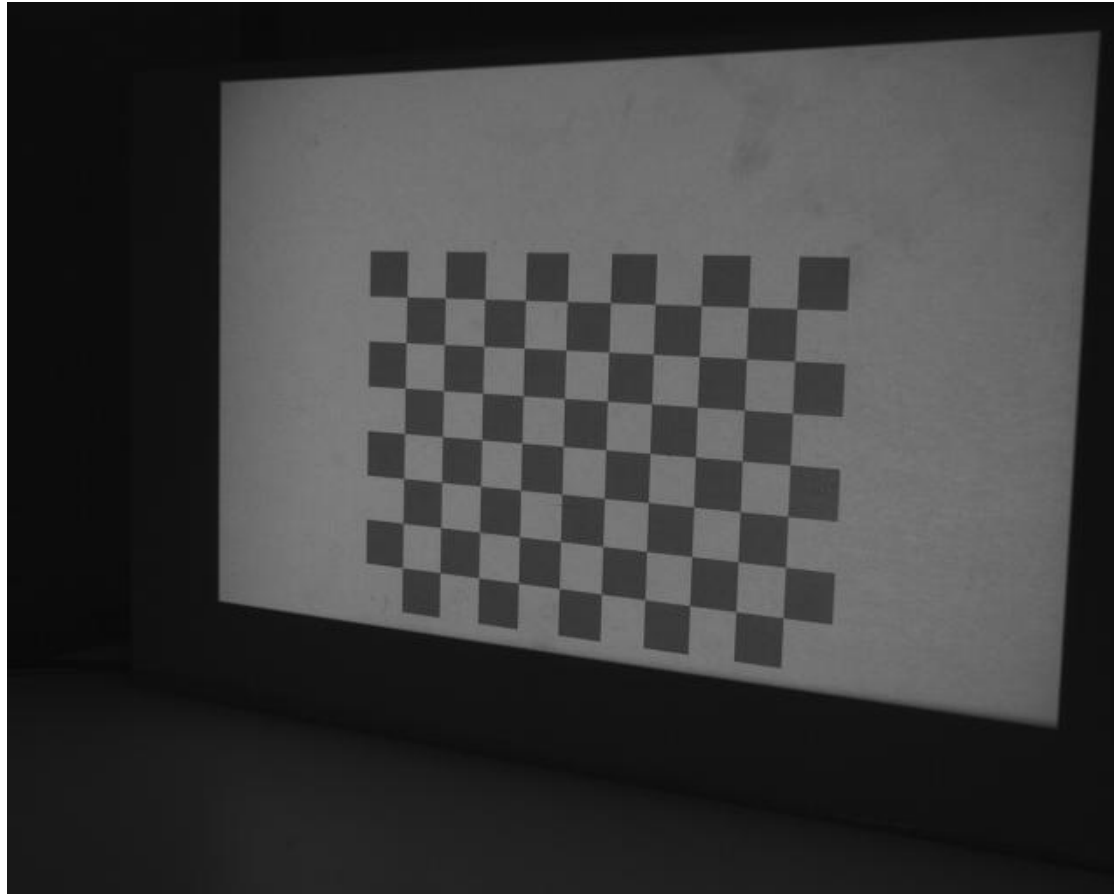


- Part of the projected image falls off of the calibration board
 - This will cause squares to be missing on the projected chessboard calibration pattern



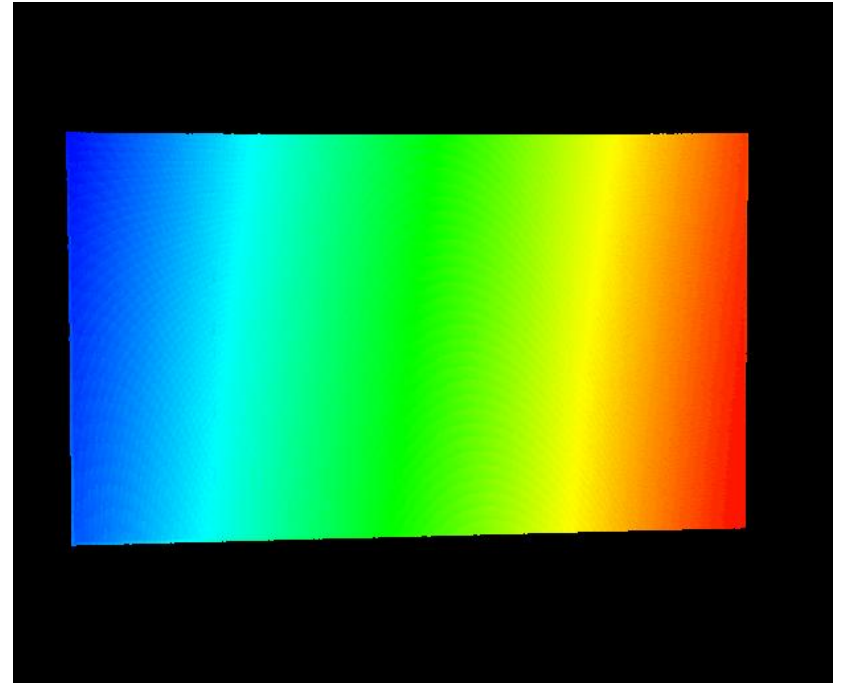
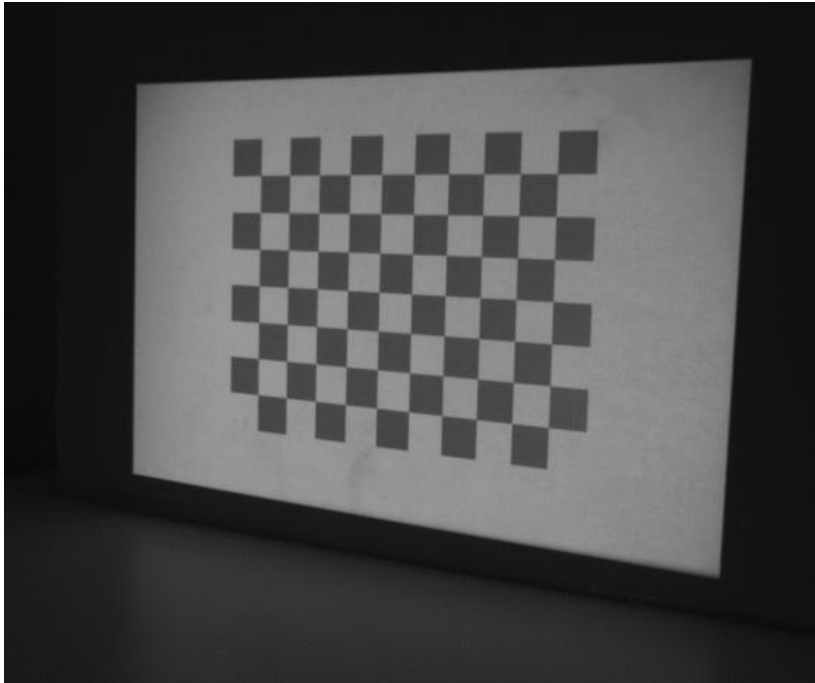
Calibrating the System – Example Images

- Calibration image examples
- Measured projector reprojection error = 0.325859

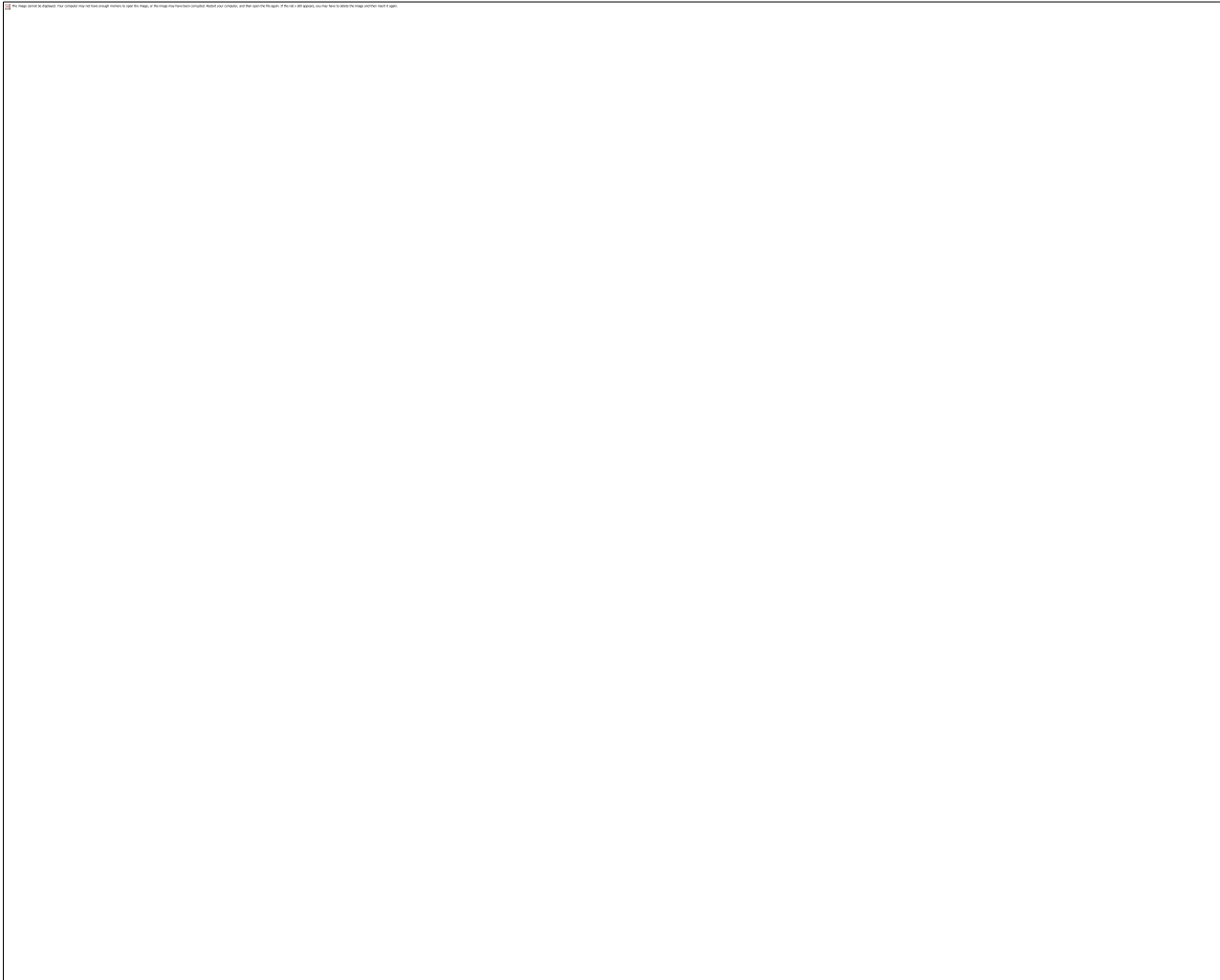


Perform Scan

- After preparation and calibration, the system is ready for scanning!
 - Use one of the “Perform Scan” menu options 6, 7, or 8



Point Cloud Example



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