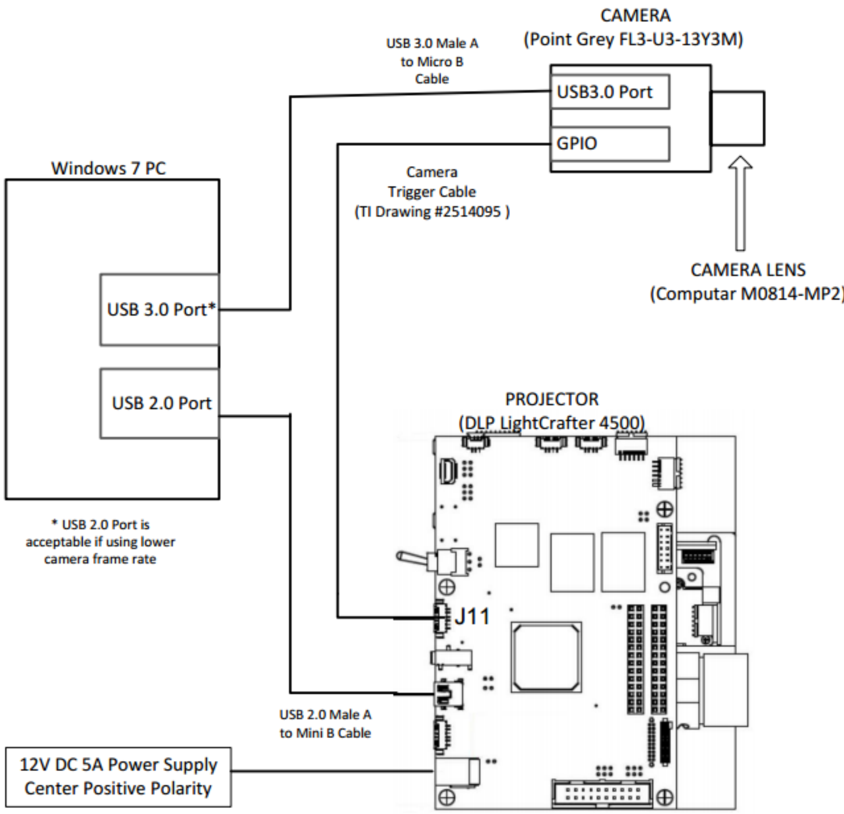
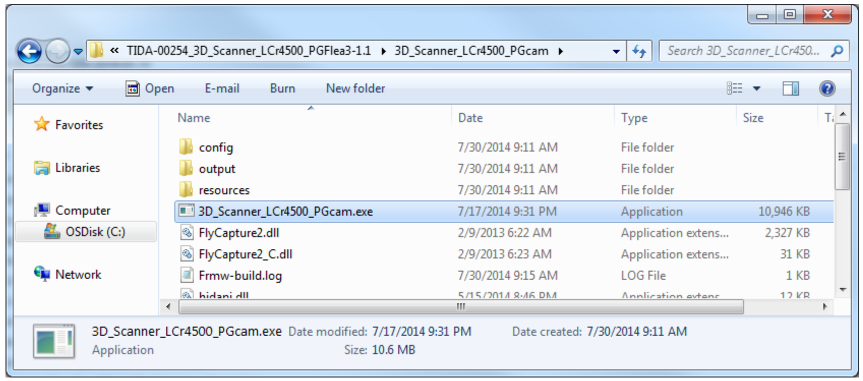
Connecting the Hardware

- 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

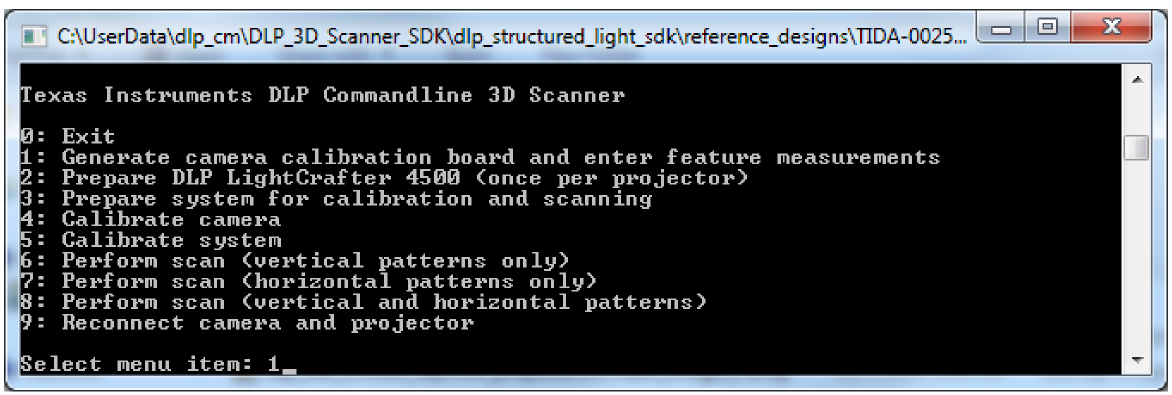


How to make the calibration board

- Open application directory and start executable

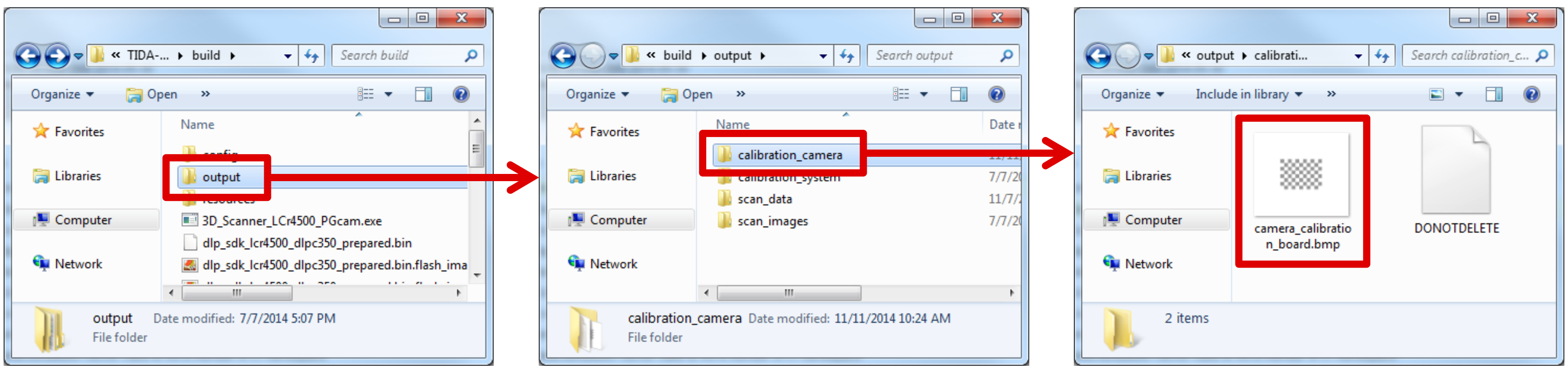


- Enter menu item “1: Generate camera calibration board and enter feature measurements”



How to make the calibration board

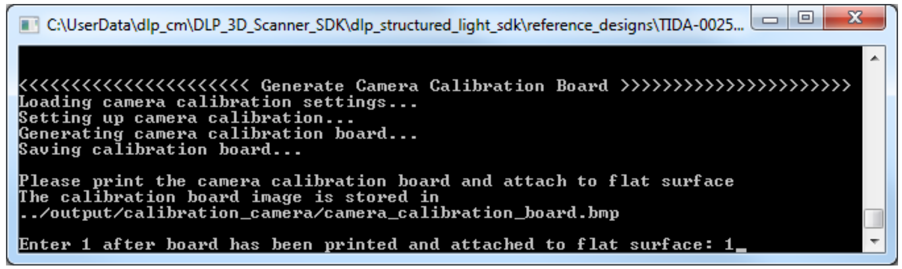
- After selecting menu item 1, a BMP file with the chessboard is generated in the "output/calibration_camera" directory



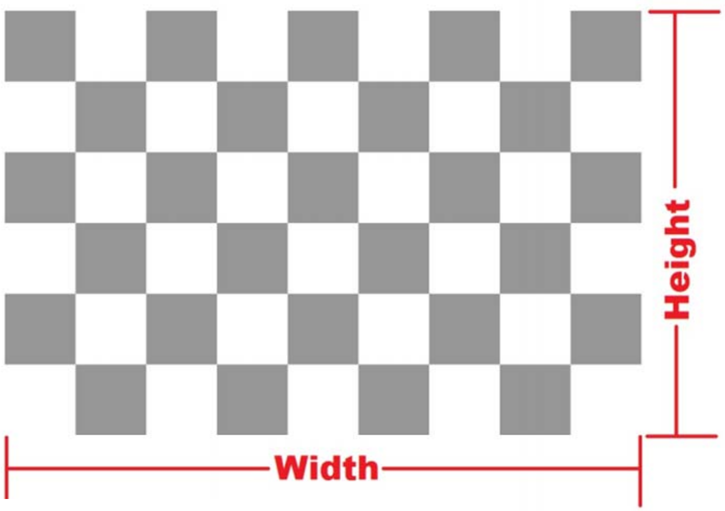
- Print the BMP file (at high DPI) and attach it to a flat surface
  - ¼" Foam core board, aluminum sheet stock, etc. all work well
  - Use spray adhesive to attach printed chessboard
  - **Your point cloud data will only be as good as your calibration board! Flatness is critical!**

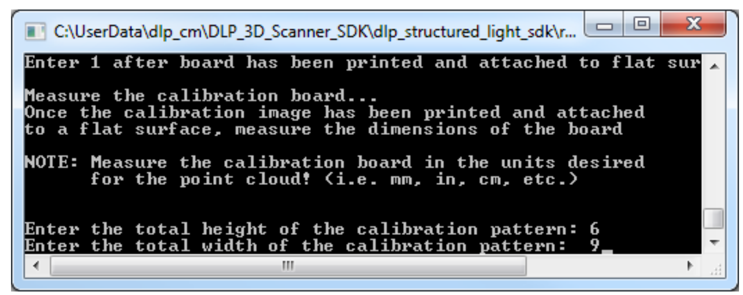
Entering calibration board measurements

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



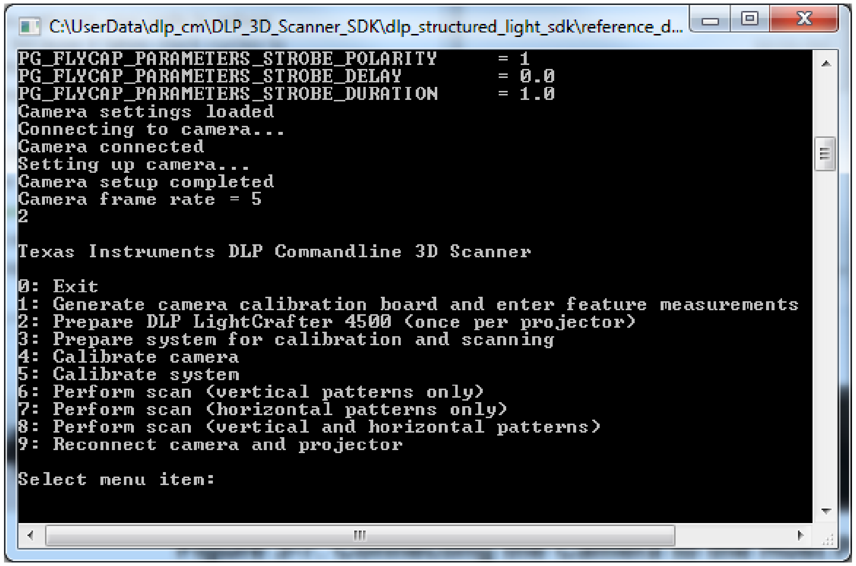
- Measure and enter the height and width of the calibration pattern
  - Note: Point cloud data units will be in the same units as are entered here





Preparing software and projector

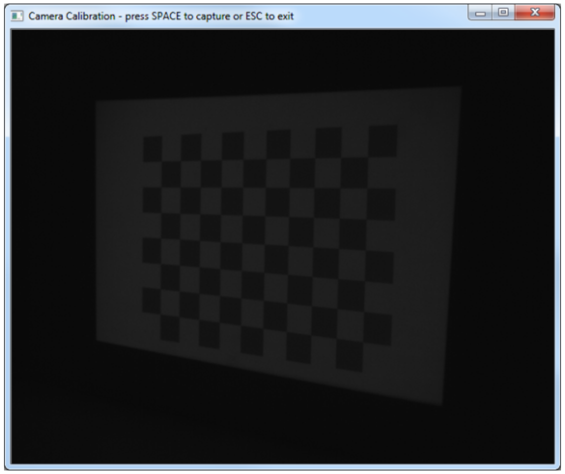
- Preparing the software and projector does the following:
  - Loads calibration and structured light settings
  - Generates projector calibration pattern
  - Generates structured light patterns
  - Uploads images to DLP LightCrafter™ 4500 EVM
- The first time you use the projector with the software 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 DLP LightCrafter 4500 EVM
  - Must be run every time the application is run



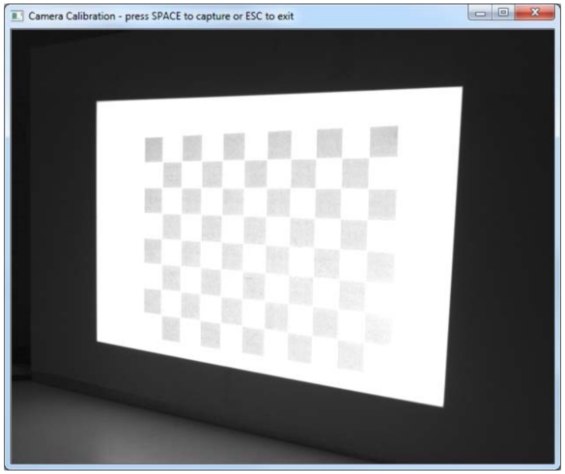
Calibrating the Camera - Setup

- 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!

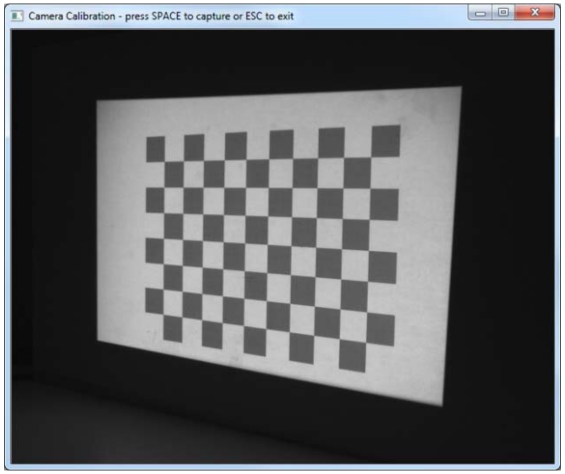
Under exposed



Over-exposed

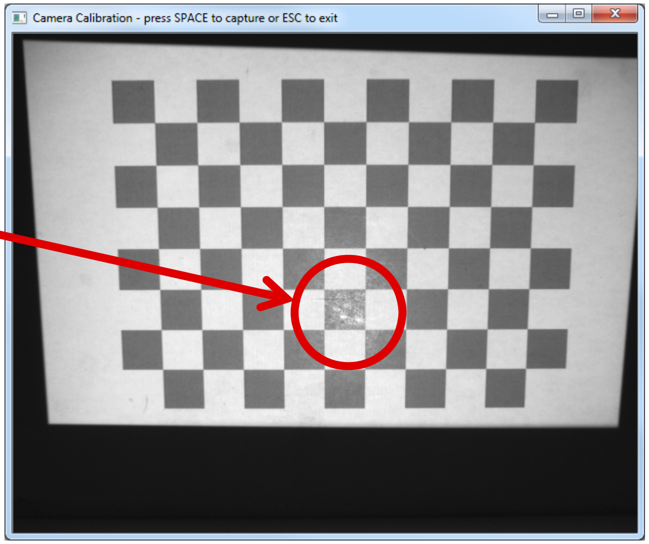


Good exposure

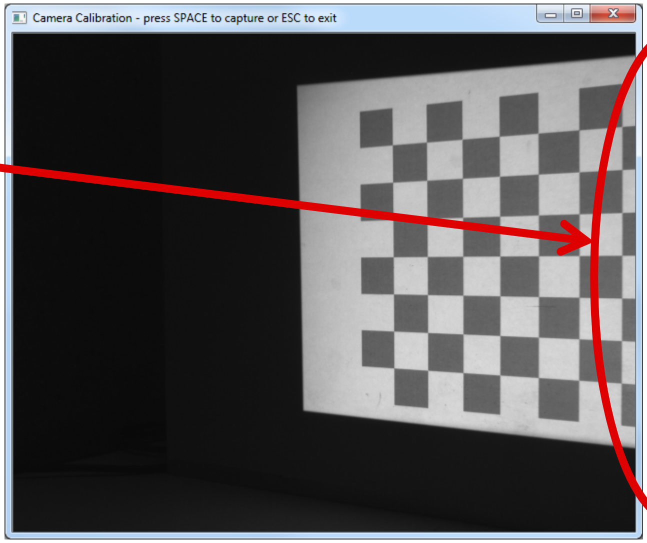


Calibrating the Camera – Watch out for…

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

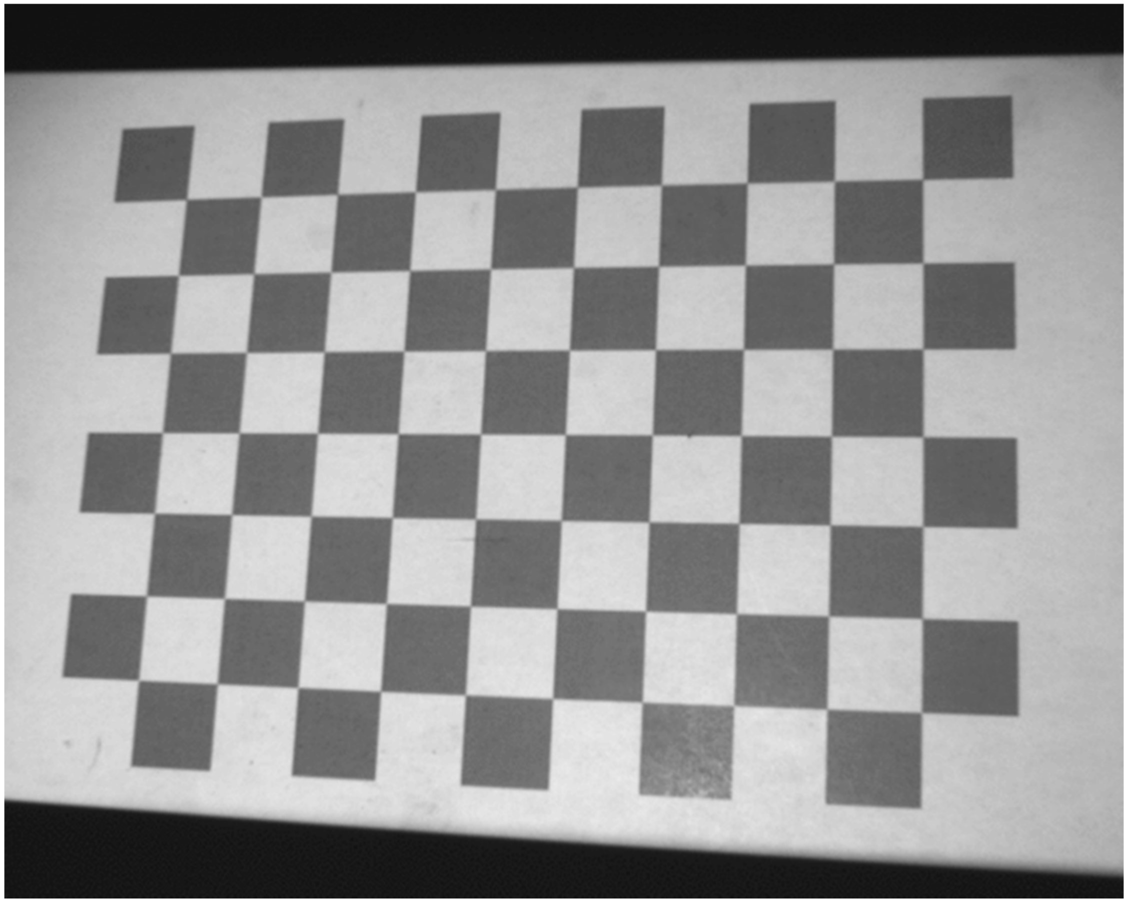


  - Part of the chessboard is missing from within the captured image
    - Parts of the squares on the border square can be cutout, so long as the inside corners are still visible



Calibrating the Camera – Example Images

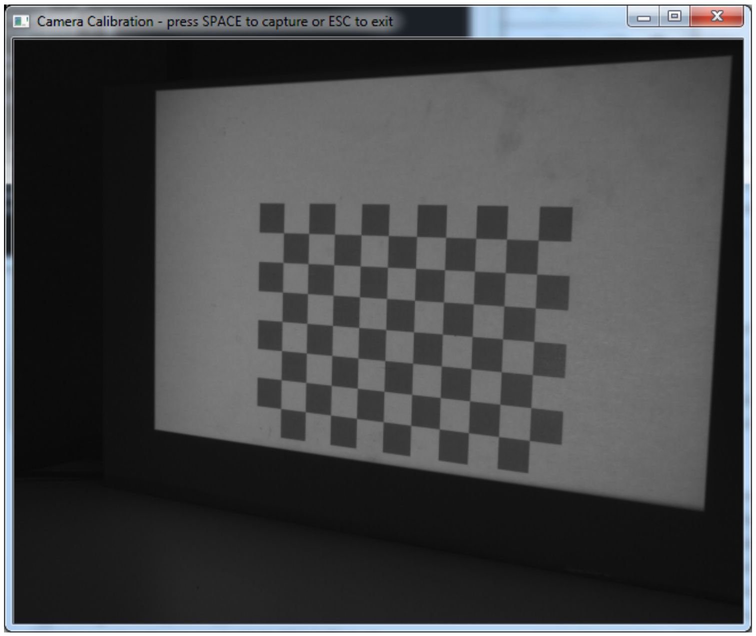
- Calibration image examples
- Measured camera reprojection error = 0.166341



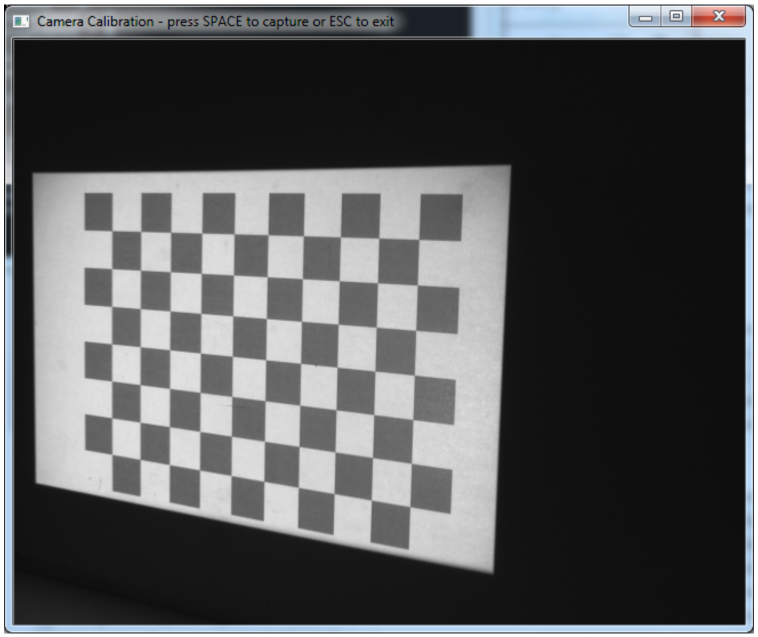
Calibrating the system - Setup

- 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

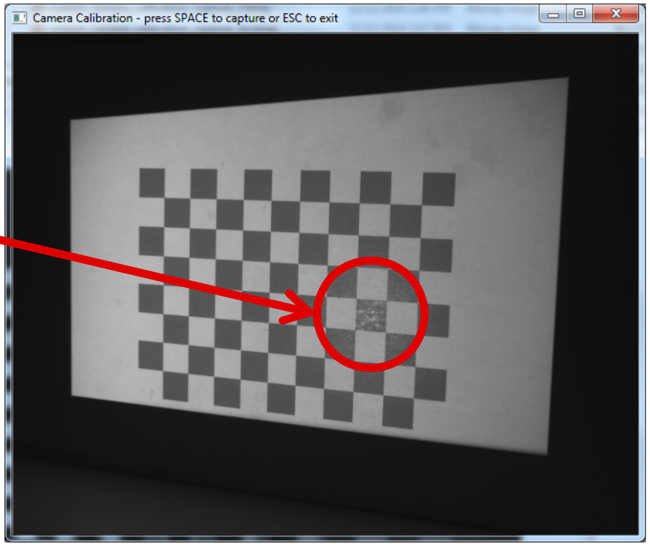


Closest distance

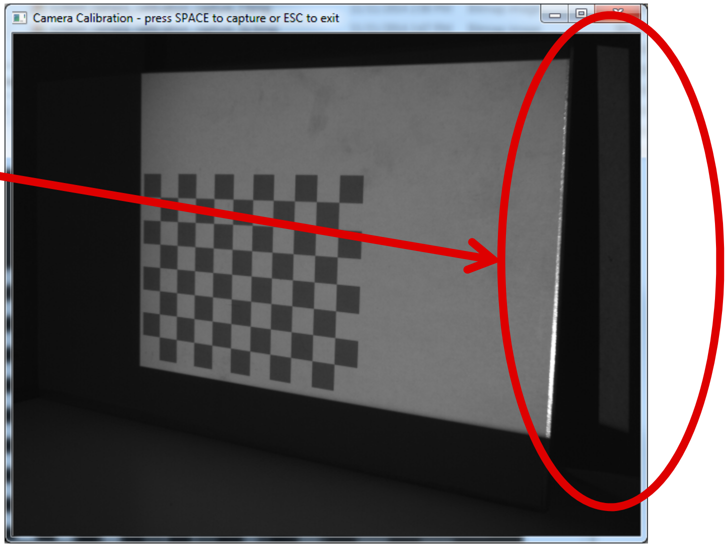


Calibrating the system – Watch out for…

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

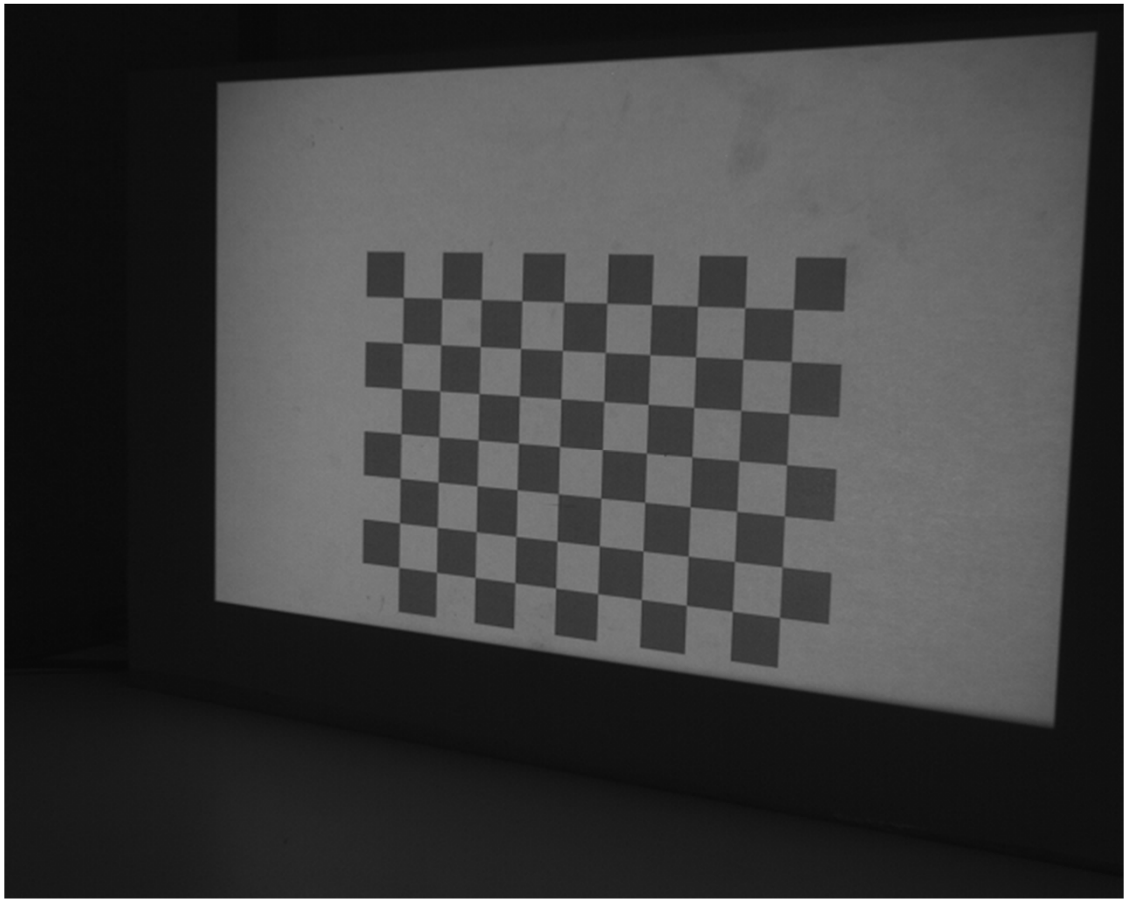


  - Part of the projected image falls off of the calibration board
    - This will cause squares to be missing on the projected chessboard calibration pattern



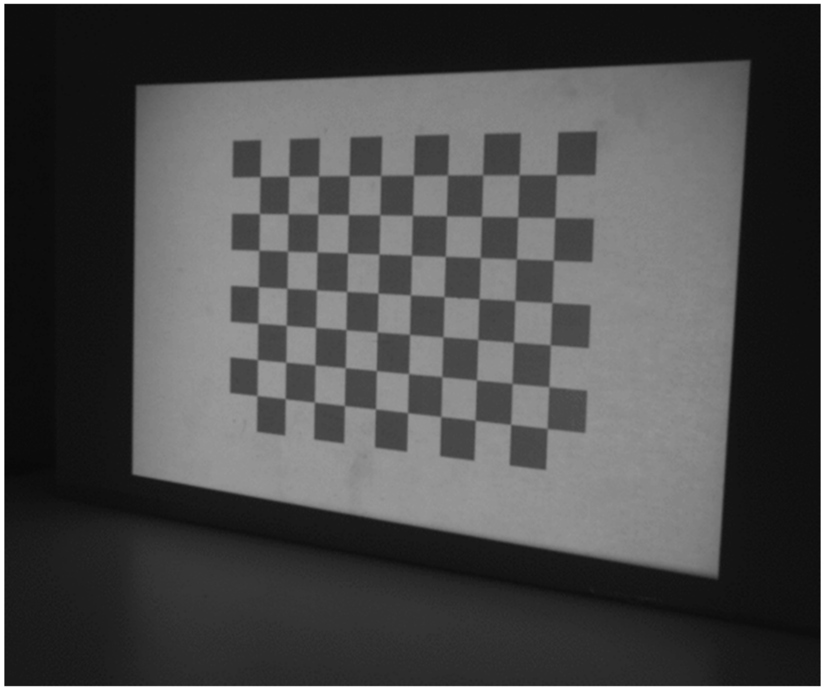
Calibrating the System – Example Images

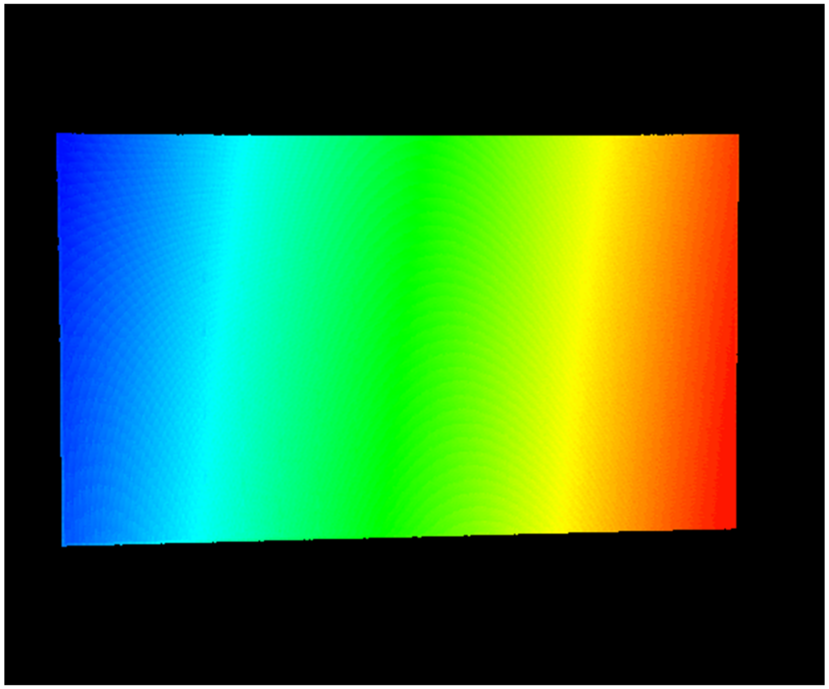
- Calibration image examples
- Measured projector reprojection error = 0.325859



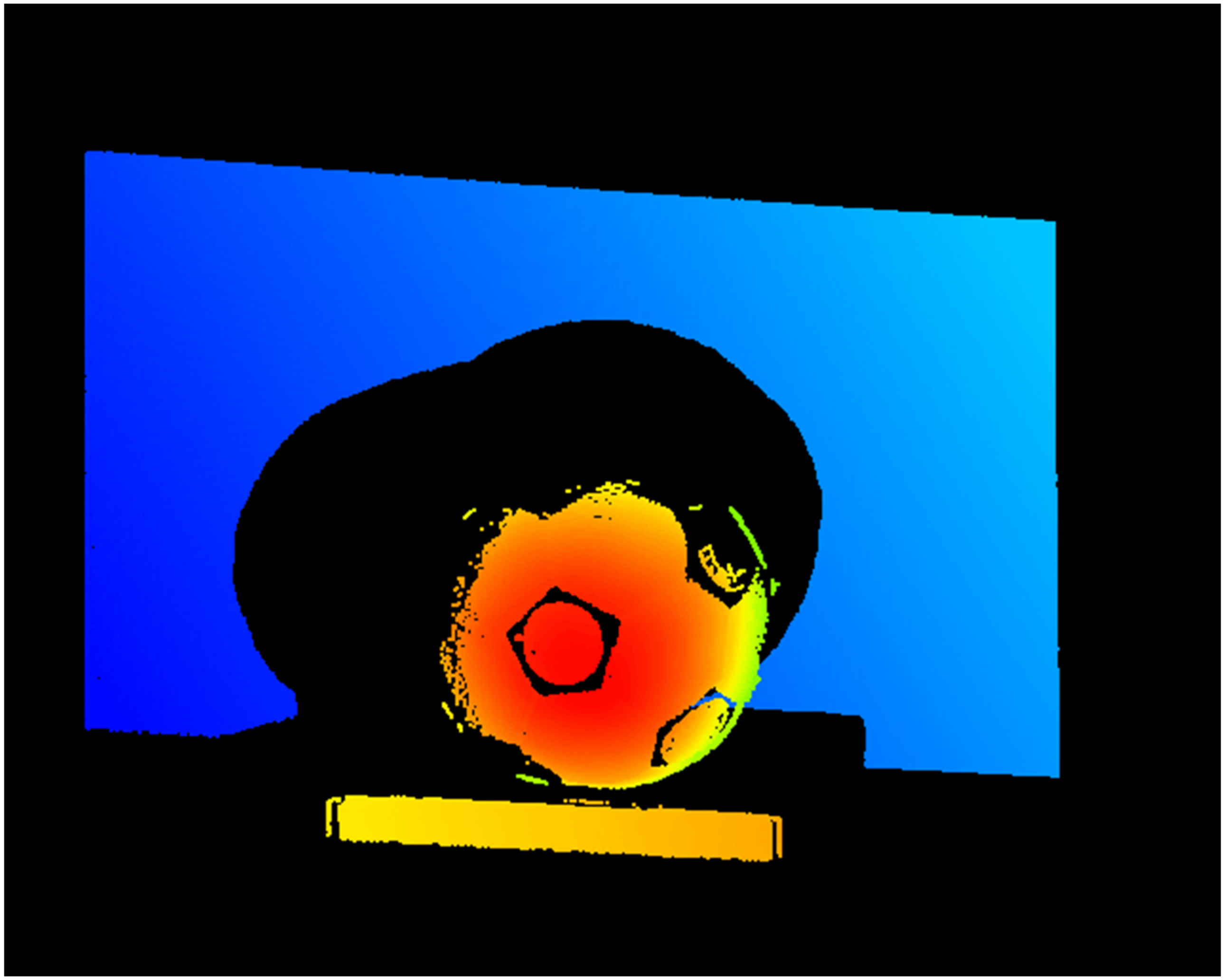
Perform Scan

- 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



Design Considerations for 3D 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

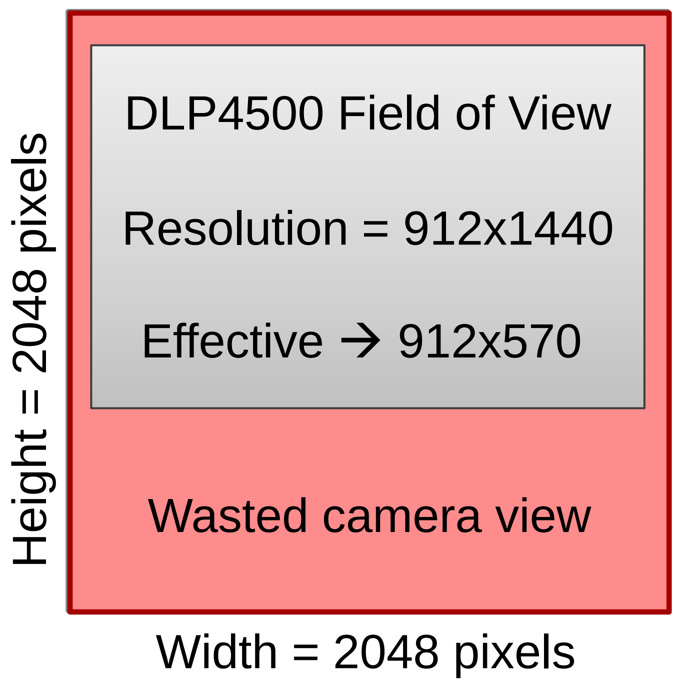
- Inversely proportional to field of view
  - Scanning larger areas worsens spatial resolution
  - Scanning smaller areas improves spatial resolution
- Proportional to camera and projector resolution
  - Increasing camera or projector resolution improves spatial resolution
  - Also increases number of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

$$2048\ pxls * 60\% = 1228\ effective\ pxls$$

Check pixel sampling…

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

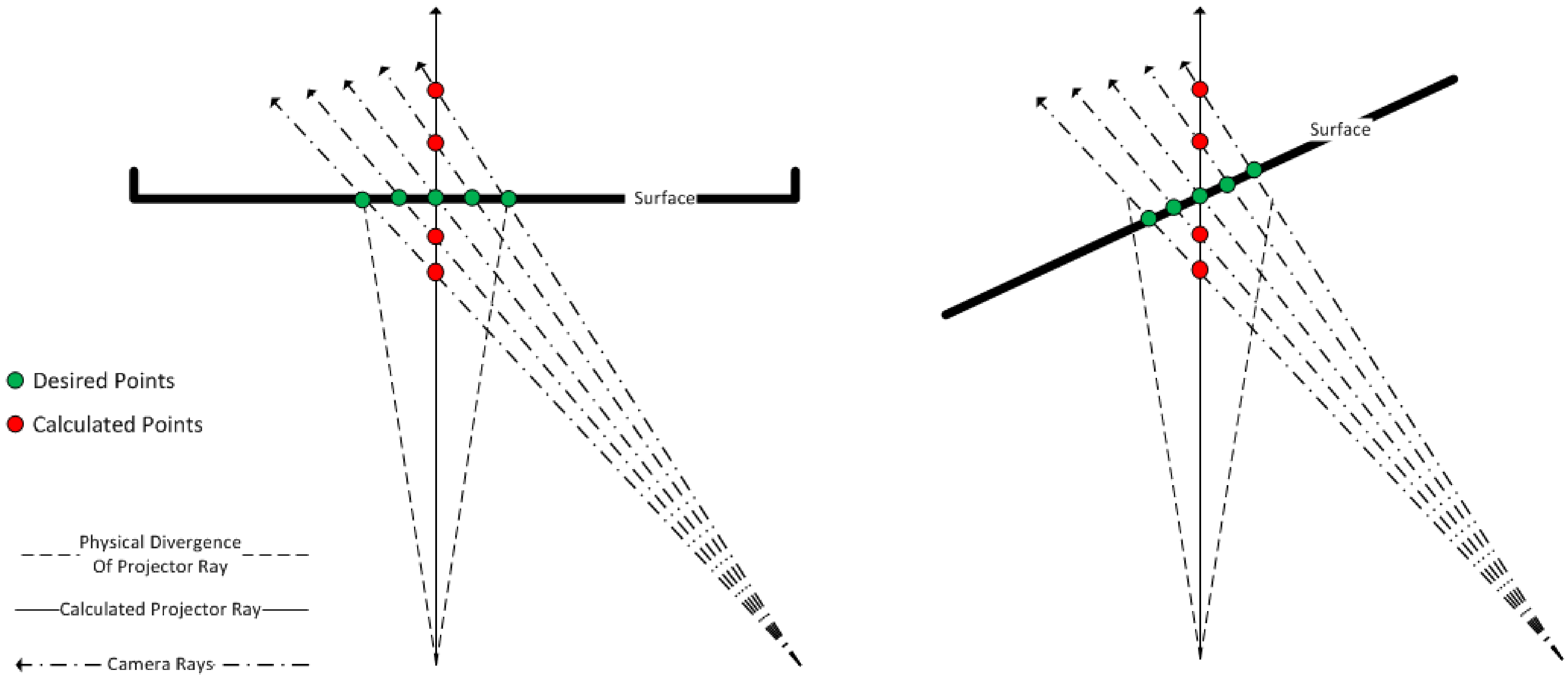
Cannot resolve all projector rows!!

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

Can resolve projector row pairs

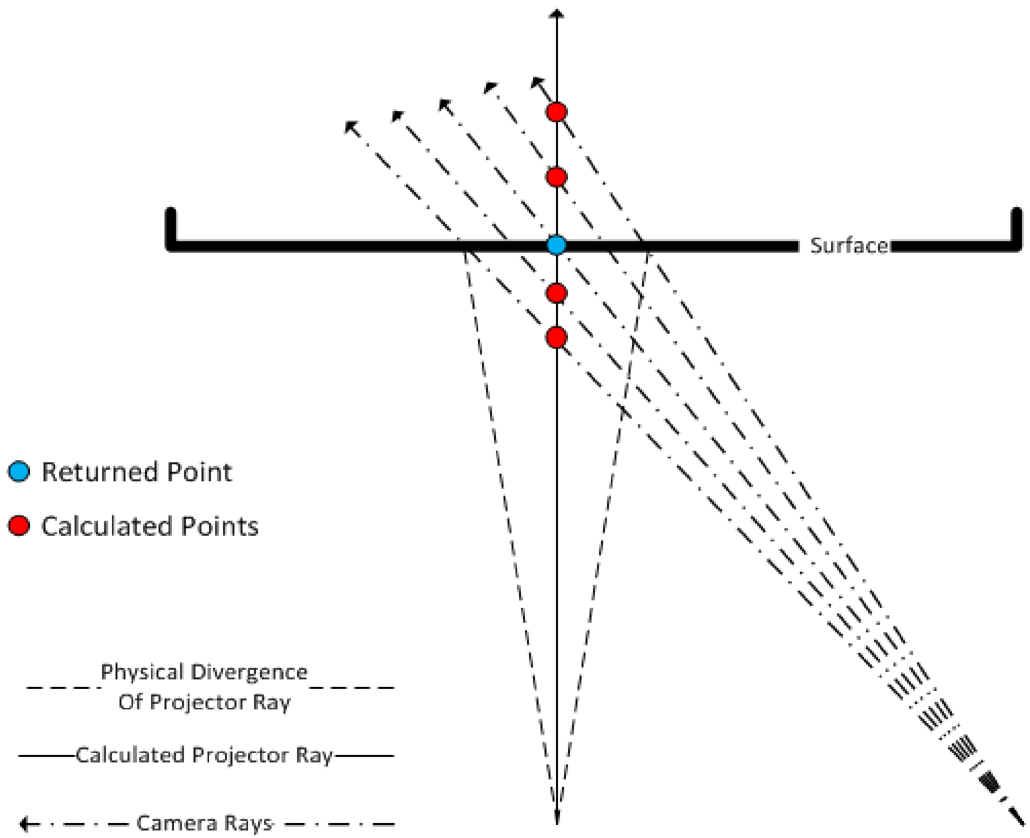
Effects of pixel over-sampling

- 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



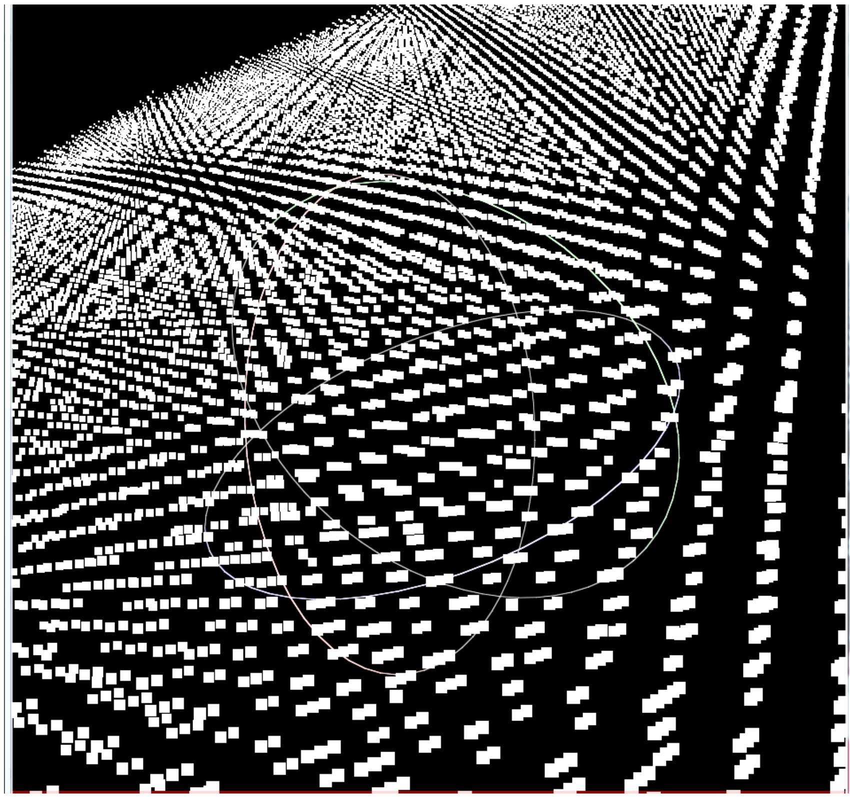
Overcoming pixel over-sampling

- 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

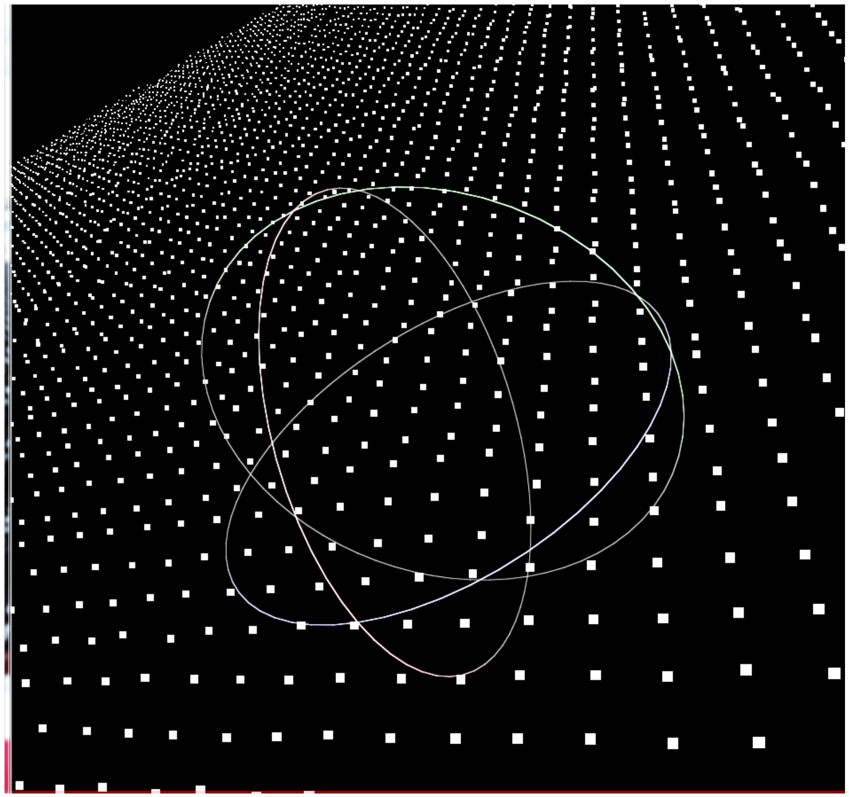


Example of filtering points by projector ray

No Filtering



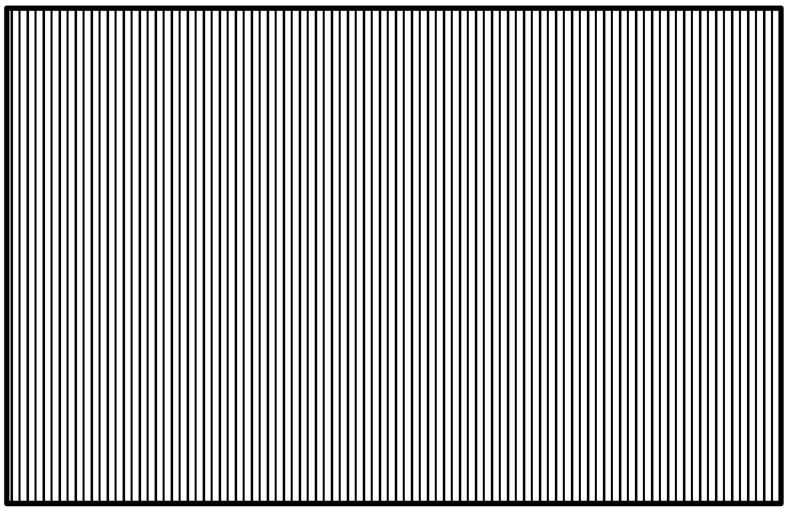
Points Filtered Per Projector Ray

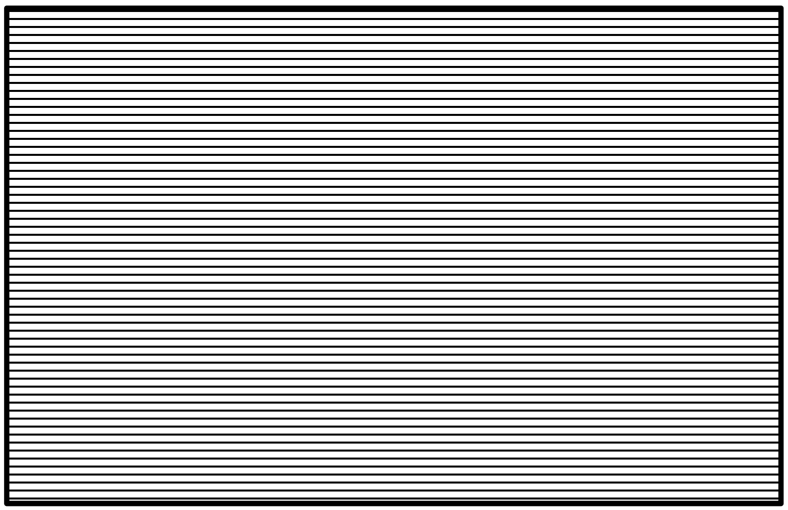


Note the lower density and higher accuracy of the point cloud

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

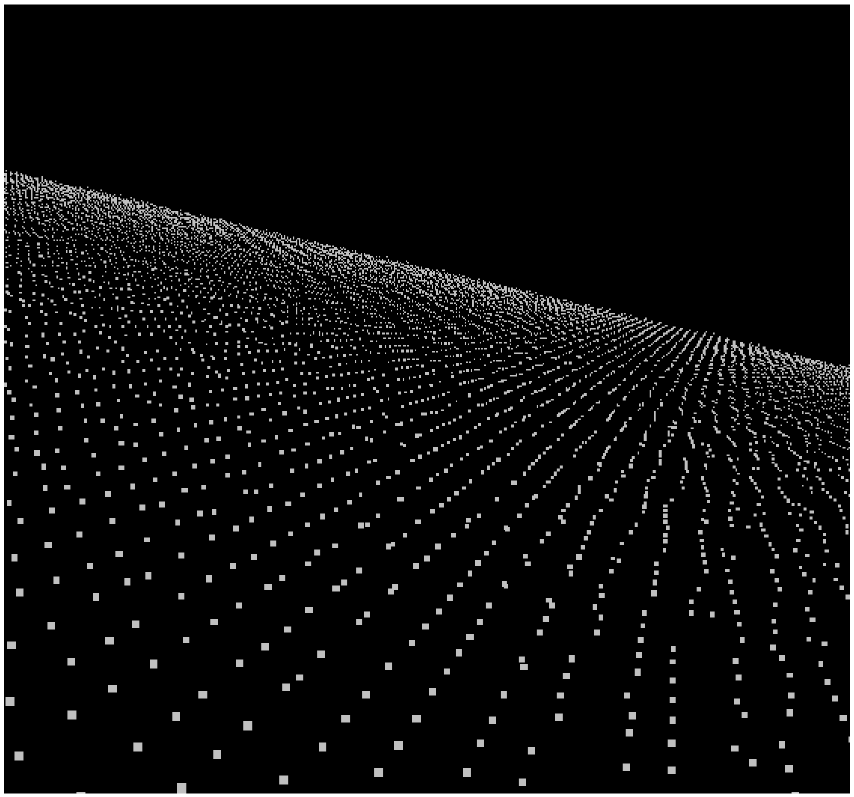




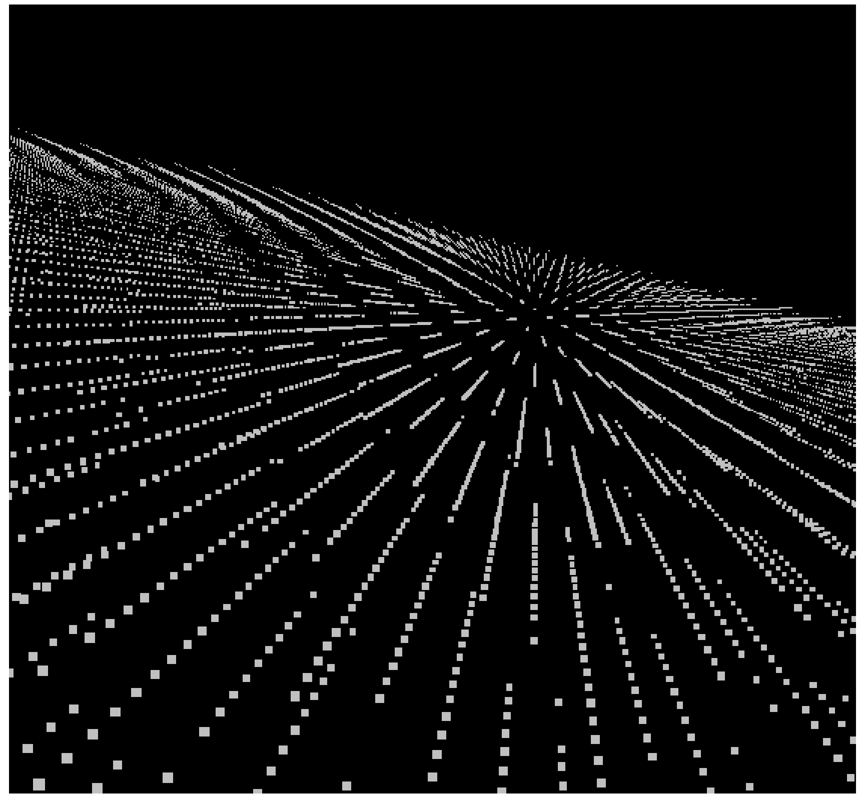
- Single pattern orientation scans offer several advantages
  - Faster scan times
  - Point cloud density a function of projector planes (rows or columns) and camera resolution rather than only projector pixels

Example of Pattern Orientation Clouds

Filtering w/ Both Orientations



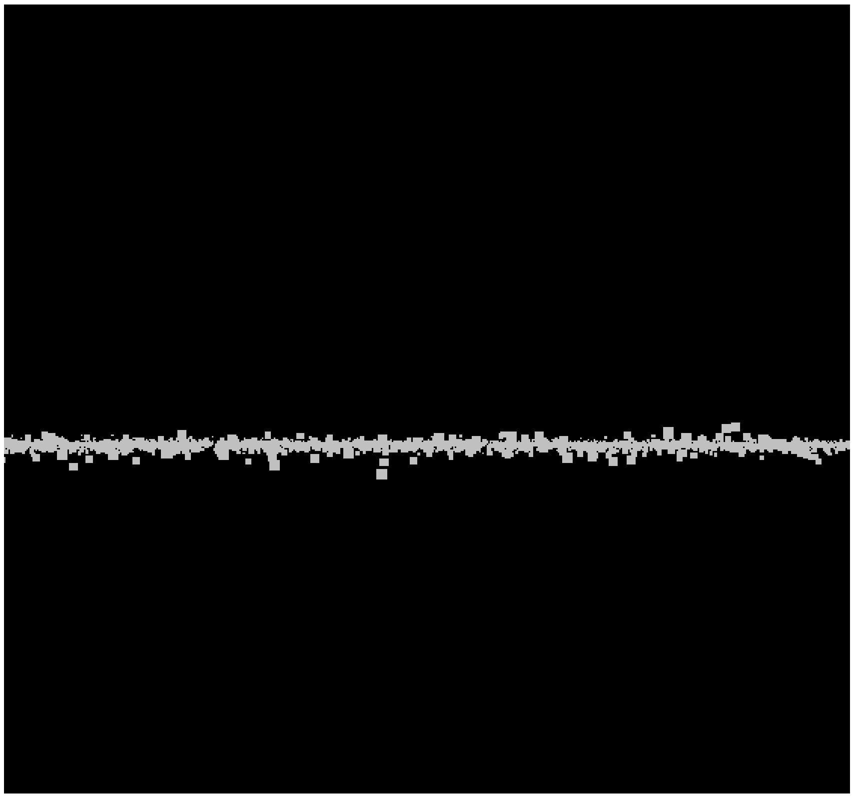
Only Vertical Orientation



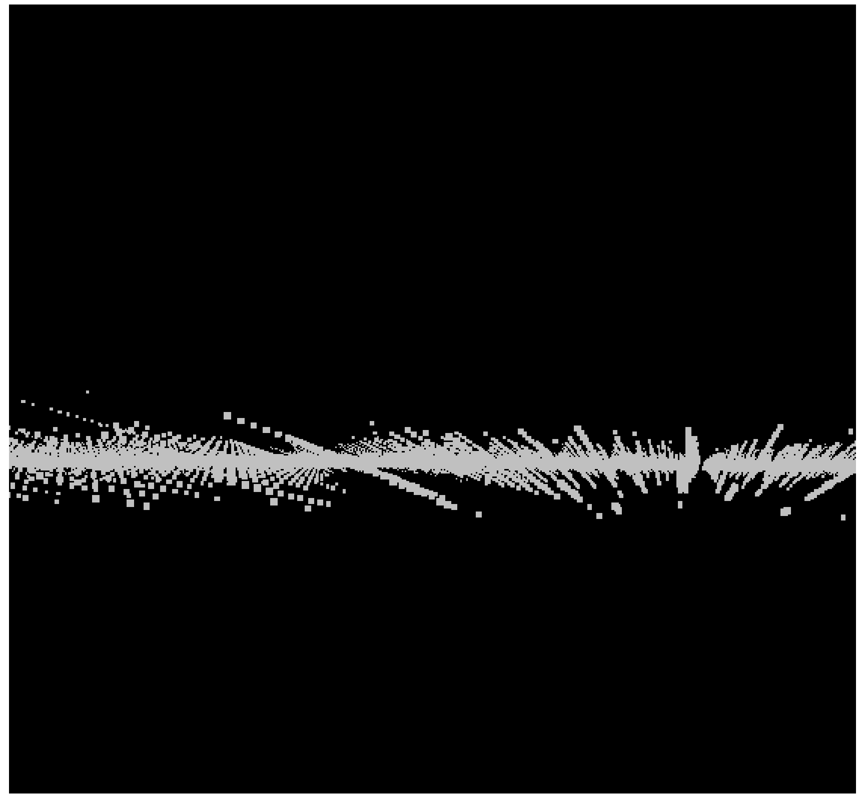
Note the higher point cloud density

Example of Pattern Orientation Clouds

Filtering w/ Both Orientations



Only Vertical Orientation

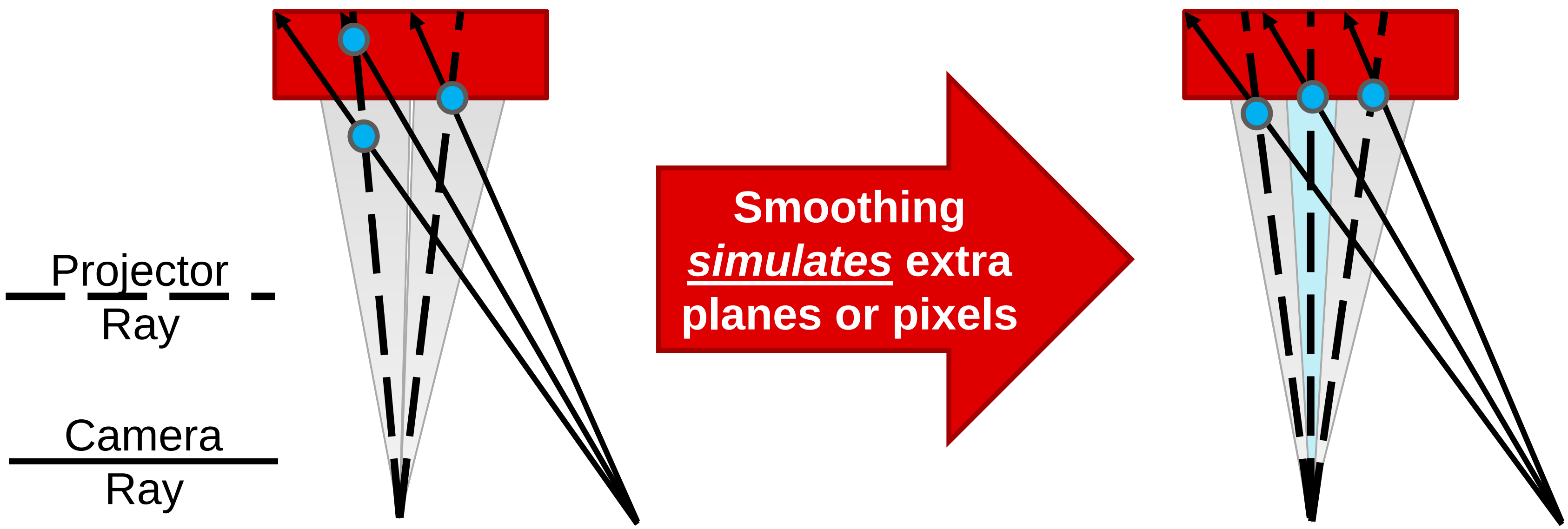


Note the higher point cloud density but lower depth accuracy

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, 1½ , 2 }



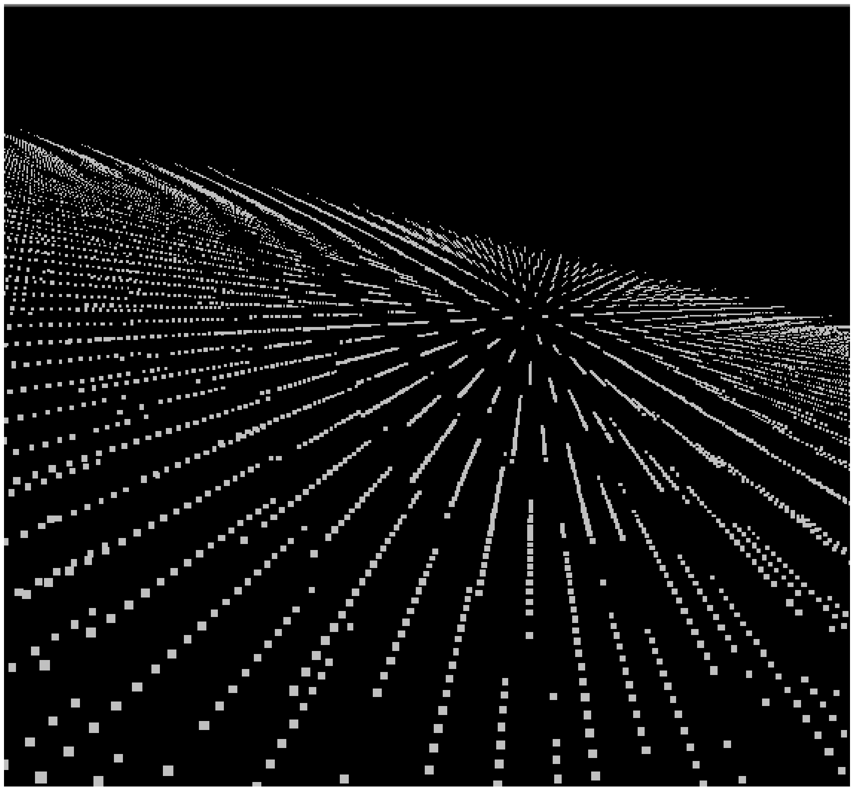
- Note: This can smooth edges that should be sharp!

Smoothing a Disparity Map Example

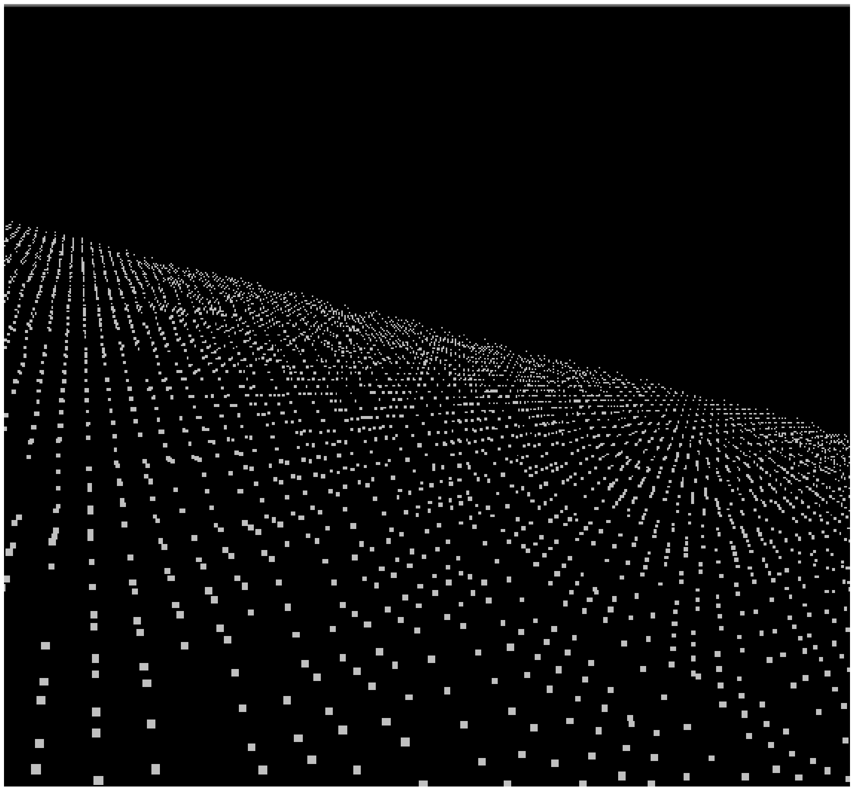
Note: This is an **extreme** example

Example of Disparity Smoothing

No Smoothing



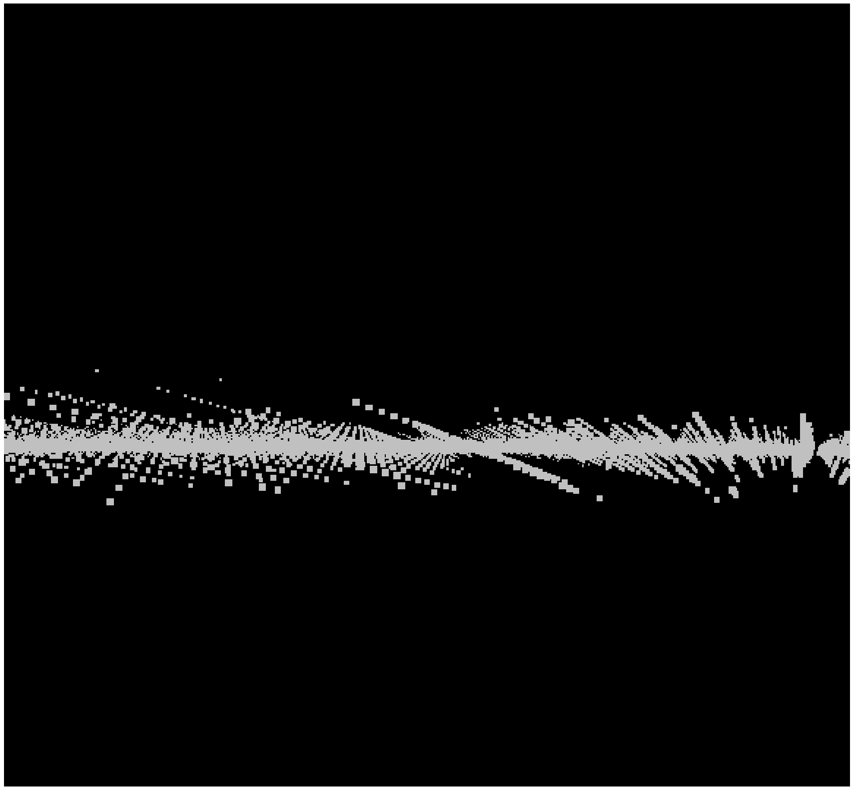
Smoothing Applied



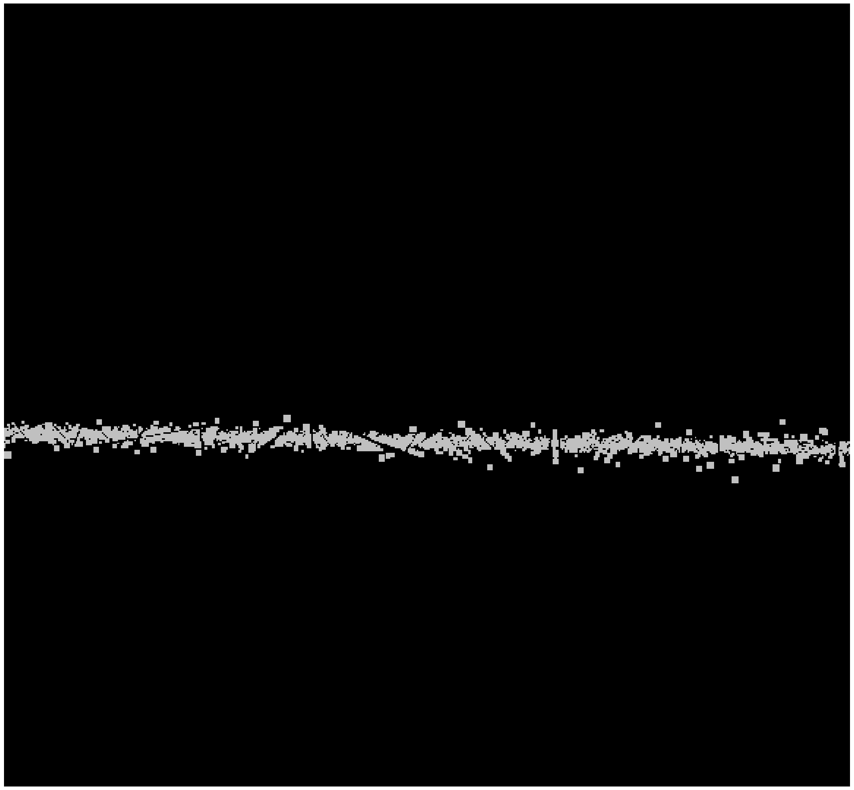
Helps but does not completely remove cloud "thickness"

Example of Disparity Smoothing

No Smoothing



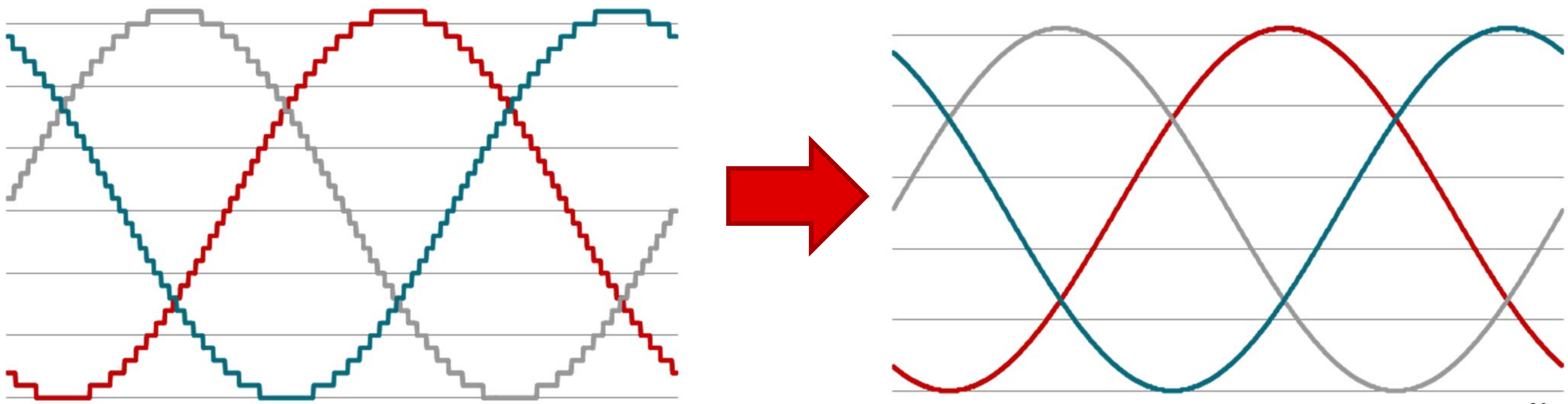
Smoothing Applied



Helps but does not completely remove cloud “thickness”

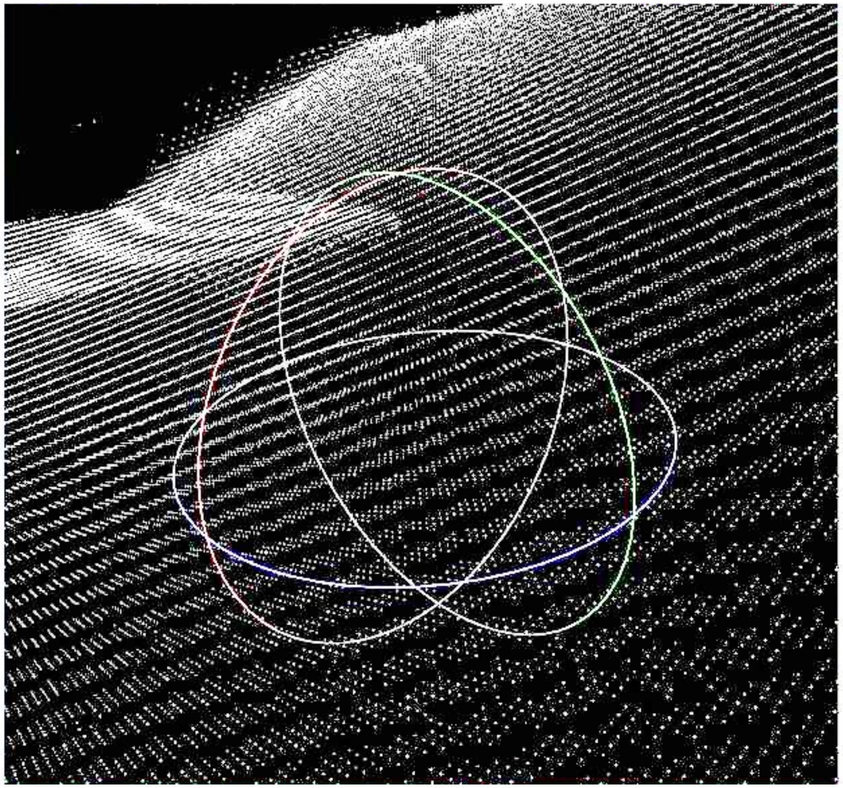
Alternative to Disparity Map Smoothing?

- 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

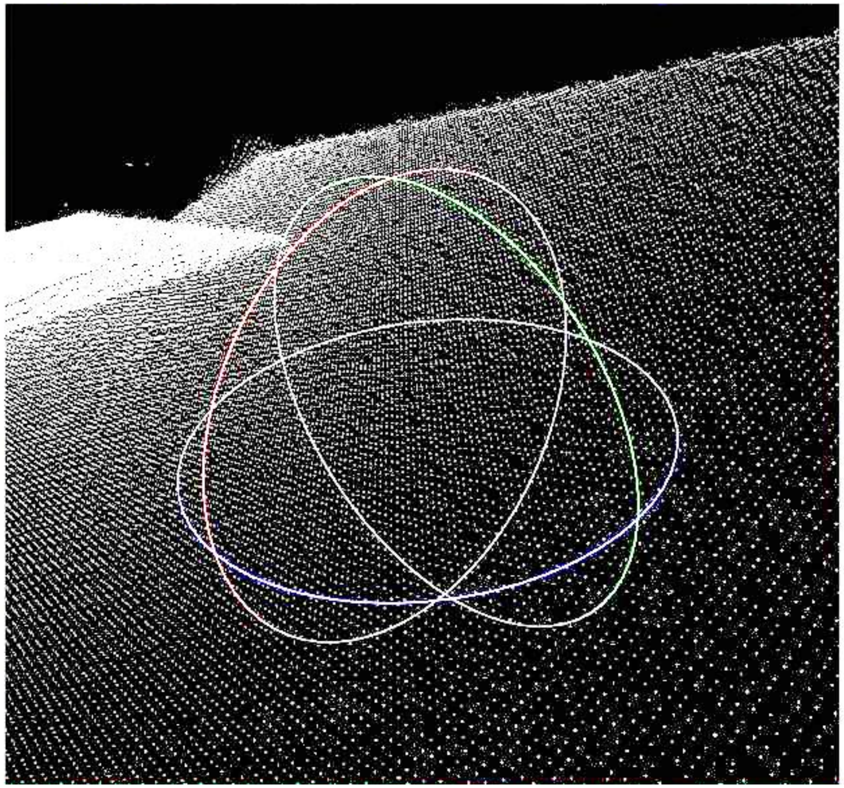


Example of Three Phase with Sub-Pixels

No Sub-Pixels



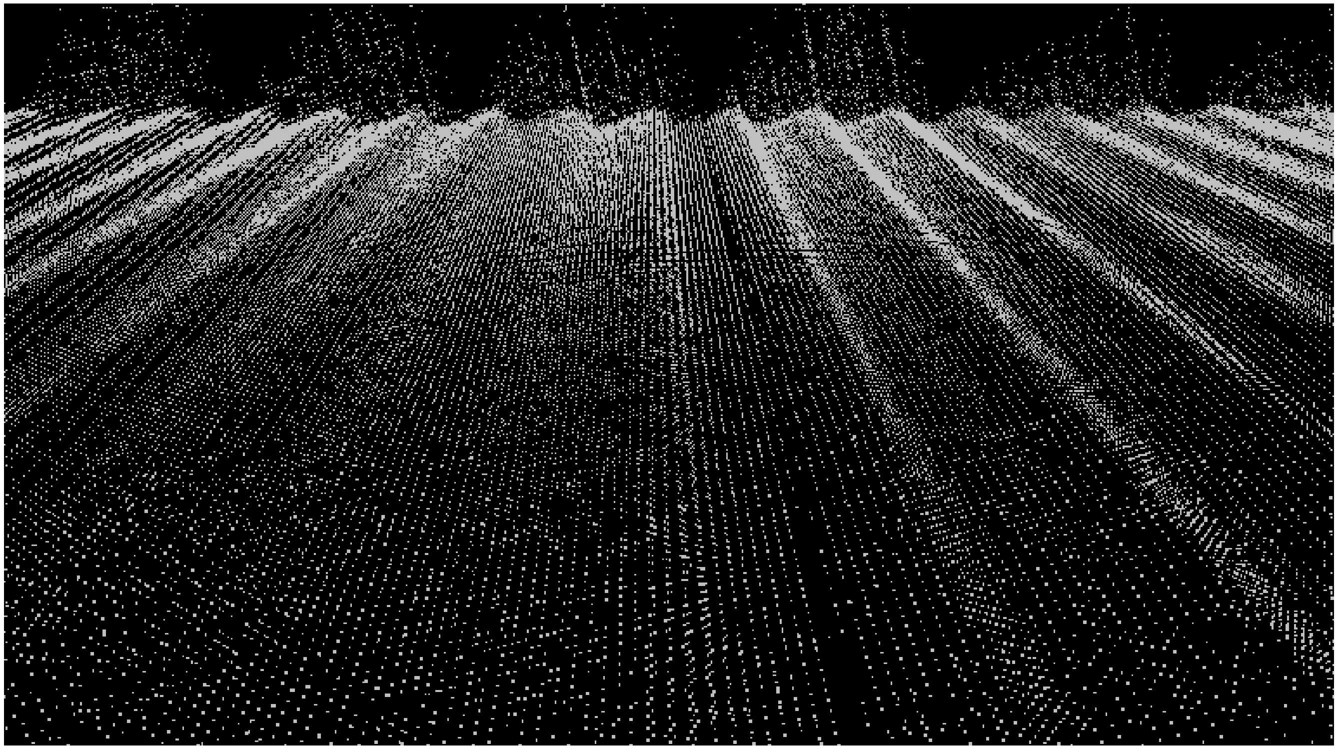
Sub-Pixels Calculated



No loss in point cloud density or edge definition!

Phase Shift Scans and Ambient Light

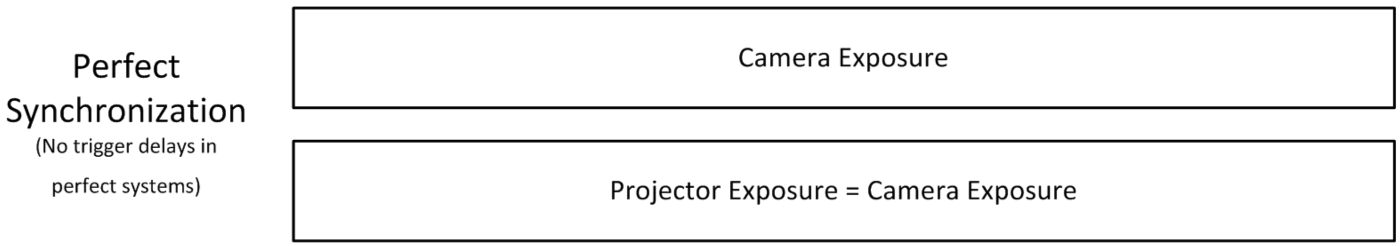
- Many indoor light sources pulse a 60 Hz!
- Notice the effect of fluorescent lighting on this 120 Hz speed scan



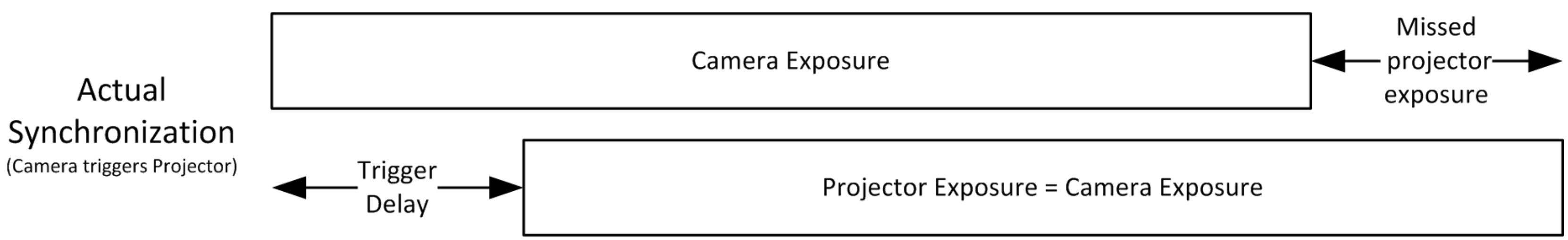
- Camera and pattern exposures must be very long to average the ambient light pulses or scan must be taken in darkness

Synchronizing the Camera with Projector

- Ideally everything matches up perfectly



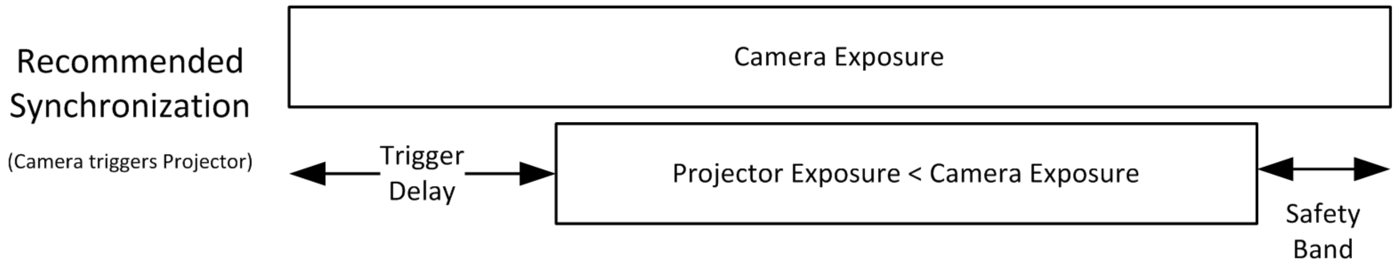
- There is ***always*** a delay in the triggers



  – 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