

Intel® RealSense™ Product Family D400 Series Custom Calibration

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Revision History

Document Number	Revision Number	Description	Revision Date
XXXXXX	1.0	Initial Release	01/2018
	1.1	Update with Calibration API 2.5.2.0	01/2018
	1.2	Update with Calibration API 2.6.4.0	06/2018
	1.3	Update calibration frame image format details	08/2018
	1.4	Updated with Calibration API 2.6.7.0	10/2018
	1.5	Updated with Calibration API 2.6.8.0	12/2018
	1.7	Added instruction for target 540x480_60mm.pdf	01/2020
	1.8	Updated with Calibration API 2.11.0.0	05/2020



1 Introduction

1.1 Purpose and Scope of This Document

In order to operate Intel® RealSense™ D400 camera efficiently and accurately, users need to make sure the device is well calibrated. The Intel supplied calibration tools including Intel® RealSense™ Dynamic Calibrator and OEM Calibration Tool for Intel® RealSense™ technology are designed to calibrate the devices using Intel proprietary algorithms. Some customers or developers may choose to use their own calibration algorithms and update the device with their custom calibration data.

This document contains technical information to assist those developing custom calibration solutions for Intel® RealSense™ Product Family D400 series. The primary goal is to guide the user how to create a calibration application, using the D400 corresponding APIs. This includes a description how to configure the device under calibration, define the calibration parameters, and how to read/write these parameters from/into the device. In addition, a simple sample application based on OpenCV algorithm is provided as an example.

It is not in the scope of this document to discuss details of calibration algorithm or accuracy. Developing custom calibration requires knowledge in computer vision as well as good understanding of the RealSense device operating details. It is a complex topic and intended only for those with expert level knowledge.

1.2 Organization

This document is organized into four main parts: overview, setup, calibrating a device with custom calibration sample app, and developing custom solution:

- **Overview** – brief overview of the Calibration API and parameters.
- **Setup** – hardware and software setup for running the Custom Calibration Sample App to calibrate a device and developing custom calibration solutions.
- **Calibrating Device with Custom Calibration Sample App** – describes the necessary hardware and software setup required running the Custom Calibration Sample App and details steps to calibrate device.
- **Developing Custom Calibration Solution** – uses the sample application as an example to describe details of steps implementing a custom calibration solution for Intel® RealSense™ D400 series modules.

2 Overview

2.1 Calibration API and Calibration Data Read/Write/Restore

Intel provides a software interface in Calibration API to enable user uploading those calibration parameters to Intel® RealSense™ D400 cameras and read the parameter back from device:

- WriteCustomCalibrationParameters – write parameters to device
- ReadCalibrationParameters – read parameters from device

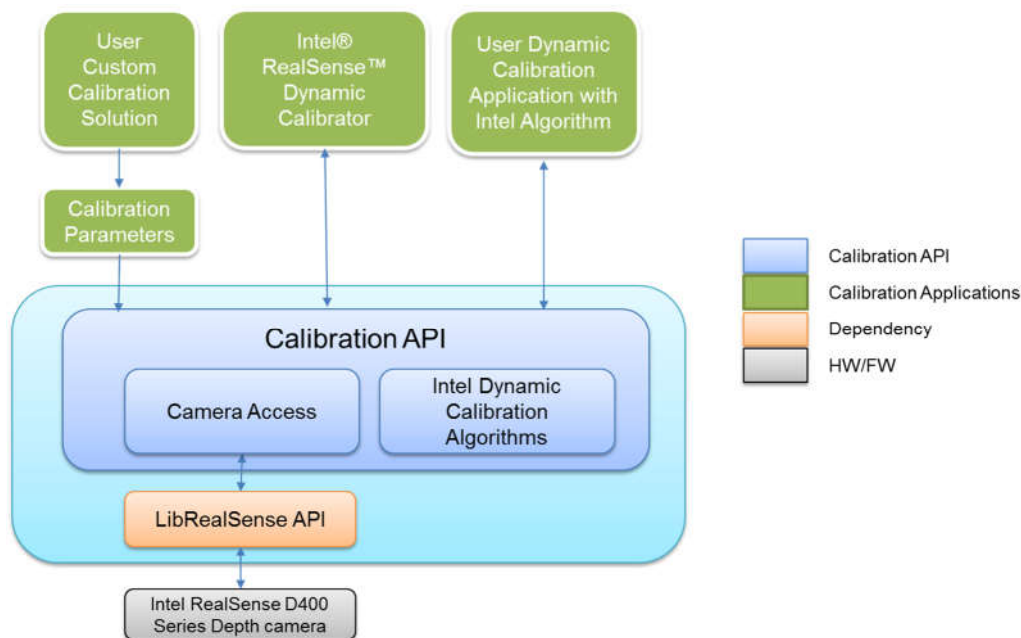


Figure 2-1 Software Stack with Dynamic Calibration API and Calibration Apps

An example tool CustomRW is also included in Calibration API to read calibration parameters from XML file and write them to the device.

A user custom calibration app can choose one of the two approaches to update the results to the device:

- To link to the WriteCustomCalibrationParameters and ReadCalibrationParameters and write directly to the device through the APIs.



- To write the results into a parameter XML file and then use CustomRW to read/write the parameters to the device.

In case user needs to restore the calibration data on the device, ResetDeviceCalibration in Calibration API can be called to programmatically restore the device calibration to gold settings.

- ResetDeviceCalibration – restore device calibration to gold settings

The CustomRW example tool also supports restore through command line option.

2.2 Calibration Parameters

Calibration parameters includes INTRINSICS and EXTRINSICS. Assume left camera is the reference camera and is located at world origin. RGB parameters only apply to cameras with RGB, e.g., D415 and D435.

Intrinsic includes

- Focal length - specified as [fx; fy] in pixels for left, right, and RGB cameras
- Principal point - specified as [px; py] in pixels for left, right, and RGB cameras
- Distortion - specified as Brown's distortion model [k1; k2; p1; p2; k3] for left, right, and RGB cameras

Extrinsic includes

- RotationLeftRight - rotation from right camera coordinate system to left camera coordinate system, specified as a 3x3 rotation matrix
- TranslationLeftRight - translation from right camera coordinate system to left camera coordinate system, specified as a 3x1 vector in millimeters
- RotationLeftRGB - rotation from RGB camera coordinate system to left camera coordinate system, specified as a 3x3 rotation matrix
- TranslationLeftRGB - translation from RGB camera coordinate system to left camera coordinate system, specified as a 3x1 vector in millimeters

The calibration data read/write API allows user to upload both INTRINSICS and EXTRINSICS. The user custom algorithm is free to optimize all these parameters. The sample in this document optimizes both intrinsic and extrinsic parameters.

The following table shows how the various calibration tools would impact calibration parameters for Intel® RealSense™ D400 series depth cameras.

	Factory Calibration	OEM Calibration	User Custom Calibration	Dynamic Calibration
--	---------------------	-----------------	-------------------------	---------------------



Intrinsic	x	x	x	
Extrinsic	x	x	x	x

2.3 Frame Formats Used in Custom Calibration

The Intel® RealSense™ Product Family D400 Series supply unrectified calibration frame formats for use in custom calibration. The device hardware provides unrectified left/right images in Y12I format and RGB sensor images in YUY2 format (on modules with RGB sensor). If user application streams through LibRealSense, the left/right images are transformed into Y16 format.

The Custom Calibration Sample App example uses LibRealSense for streaming from the device and the following image formats for calibration.

Table 2-1. Frame Formats Used in Custom Calibration*

Format	SKU	Used	Comment
Y16 (16-bit)	D400	Left and Right Sensors: 1920x1080 @ 15 FPS	Intel® RealSense™ Camera D400, D410, D415
	D410		
	D420	Left and Right Sensors: 1280x800 @ 15 FPS	Intel® RealSense™ Camera D430 D420, D435, D435i
	D430		
YUY2	D415	RGB Sensor: 1920x1080 @ 15 FPS	Intel® RealSense™ Camera D415, D435, D435i
	D435		

*Frame stream formats supported by librealsense

For details on Y12I and Y16 formats, please refer to *Appendix: Unrectified Left/Right Image Formats for Calibration*.

2.4 Frame Sync

The calibration frames are not synced. To avoid possible motion blur, calibrate the device with images captured at static positions. In this sample, a tripod is used to keep the camera device at fixed positions while capturing the images for calibration. This is same if you want to develop your own custom calibration app.



2.5 Accuracy

The calibration will not be accurate if the checkerboard doesn't sufficiently cover the field of view or the poses are not diverse enough between captures. The calibration will also not be accurate if the camera or board is handheld (or not completely still) as there is no frame sync in calibration mode.

3 Setup

This section describes the required hardware and software setup for running the Custom Calibration Sample Application to calibrate a device and developing a Custom Calibration Application.

3.1 Hardware

The hardware required including a calibration target, D400 series device to be calibrated, USB cable, and a Windows 10 computer. To ensure the images are synced, pictures are captured at static device positions, a tripod is used to support the device during calibration.

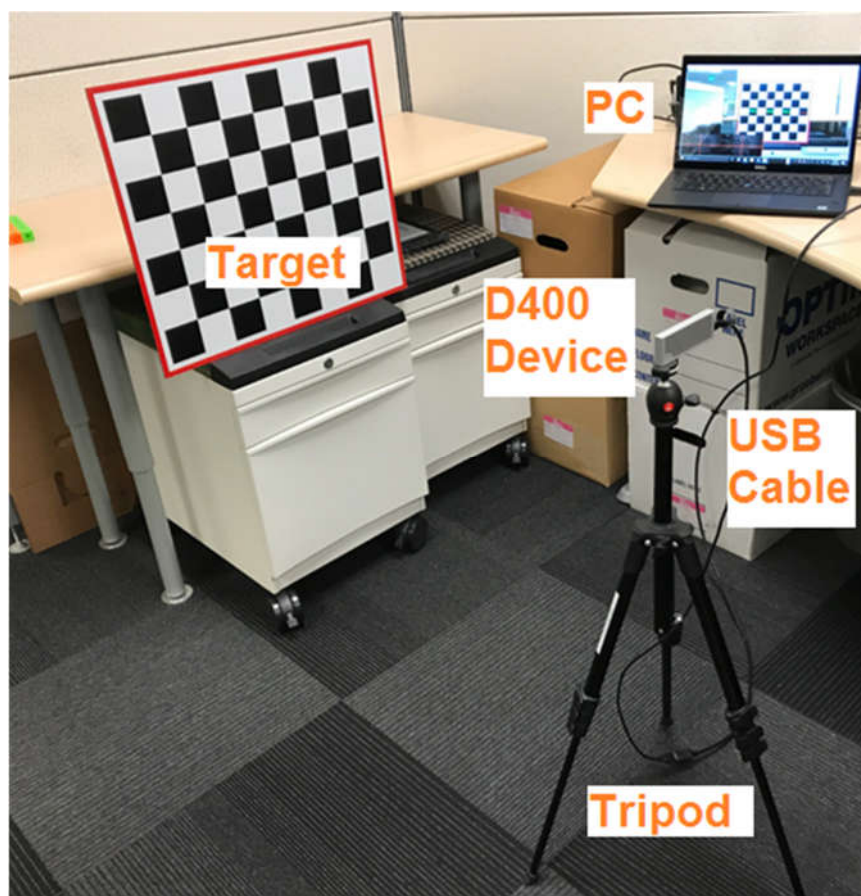


Figure 3-1 Hardware Setup



3.1.1 Device

Intel® RealSense™ Depth Camera D415 device as shown below is used to show case the custom calibration process. All D400 series devices can use the same process.



Figure 3-2 D415 Device

3.1.2 Target

The target used in this custom calibration example is an 8x7 checkerboard with a 60x60mm checker size. The target image pdf 540x480_60mm.pdf can be downloaded along with this document. It's also included in the sample source code. Users must ensure that when printing the target, the target is not scaled.

The specific target used in this application is for demonstration purpose only. A developer may choose to use a different target for their own calibration algorithm but will need to modify the sample application accordingly and recompile.

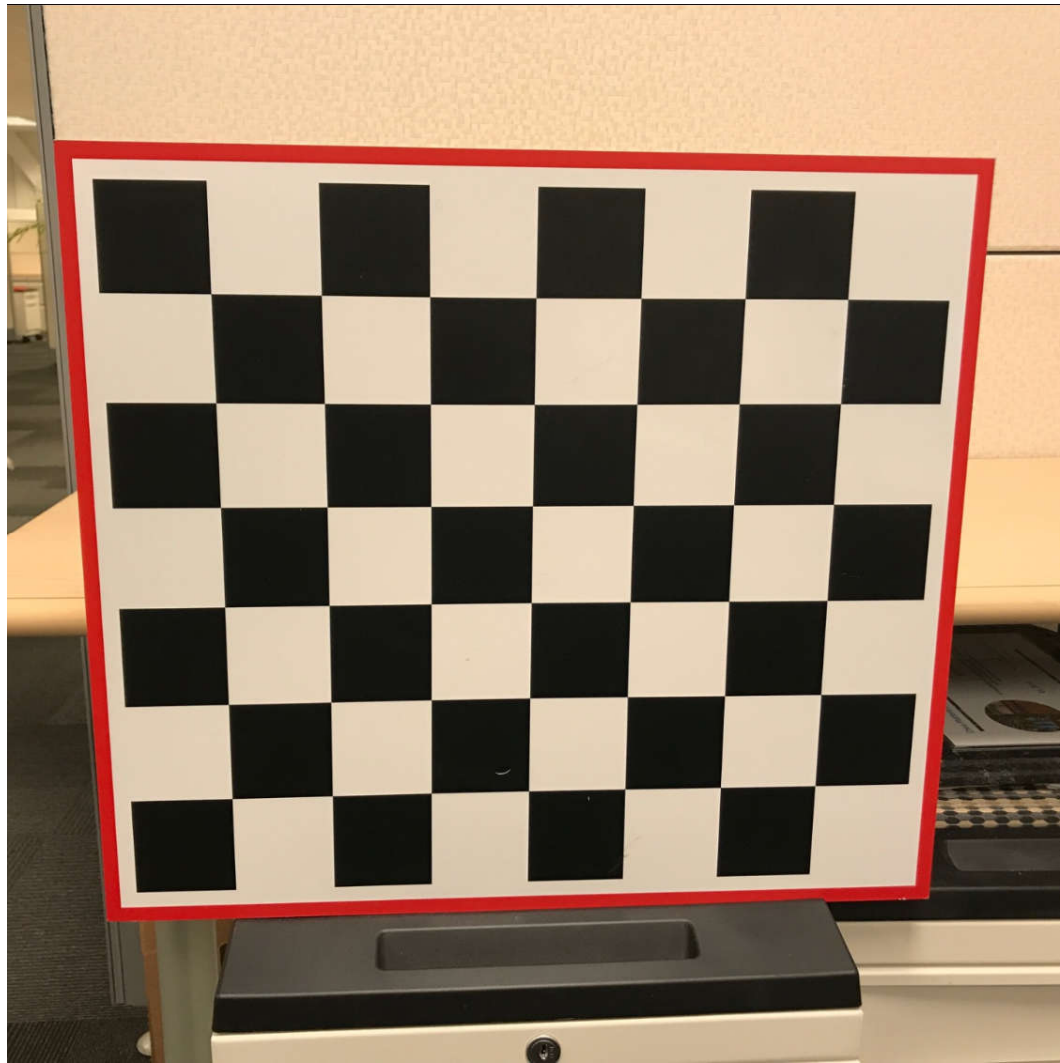


Figure 3-3 8x7 60x60 mm Checker Calibration Target

3.1.3 Tripod

Any medium sized tripod should be enough. In this example setup, we used a Manfrotto Compact Light Aluminum Tripod with ball head. The ball head makes adjustment to device orientation easier.



Figure 3-4 Tripod



3.1.4 USB

A long USB type C cable to connect the device to the host computer where the custom calibration sample application will run.

3.1.5 PC

A Windows 10 computer.

3.2 Software

Install the following to the windows computer.

3.2.1 Custom Calibration Sample Application

A CustomCalibration sample is provided and its source code is included in Intel® RealSense™ Calibration API package which is available for download at the Intel® RealSense™ download center (the download link is shown in Table 3-1).

3.2.2 Intel® RealSense™ Calibration Tool and API

The calibration example uses support functions provided by the Intel® RealSense™ Calibration API to store updated calibration parameters into the non-volatile storage on the Intel® RealSense™ Product Family D400 Series. Required functions were first introduced in version 2.6.5.0 of the Dynamic Calibration API, so install the latest version and ensure that it is version 2.6.5.0 or later.

Table 3-1 lists where to download the Intel® RealSense™ Calibration API software and associated documentation.



Table 3-1. Intel® RealSense™ Calibration API Resources

Resource	URL
Intel® RealSense™ Product Family D400 Series Dynamic Calibration Software Download	https://downloadcenter.intel.com/download/27415/?v=t
Intel® RealSense™ Product Family D400 Series Dynamic Calibration User Guide	https://www.intel.com/content/www/us/en/support/articles/000026723/emerging-technologies/intel-realsense-technology.html
Intel® RealSense™ Product Family D400 Series Dynamic Calibration Programmer Guide	https://www.intel.com/content/www/us/en/support/articles/000026724/emerging-technologies/intel-realsense-technology.html

Find **Calibration Tool** installer and follow instruction in the user's guide to install. For example, version 2.11.0.0, it's installed under C:\Program Files\Intel with the following directory structure:

CalibrationToolAPI

```

|
|----- 2.11.0.0
|       |----- bin
|       |       |----- Intel.Realsense.CustomRW.exe
|       |       |----- api
|       |       |----- DynamicCalibrationAPI.Zip
|       |
|

```



The API package DynamicCalibrationAPI.Zip contains various example source code, including the example described in this document.

DynamicCalibrationAPI

```
|----- Include
|----- attributions.txt
|----- release_notes.txt
|----- license.txt
|----- gimbal
|----- target
|----- examples
|           |----- CustomCalibration
|           |           |---- 540x480_60mm.pdf
|           |           |---- other source code
```

Intel.Realsense.CustomRW.exe under bin directory is the calibration data read/write tool. We will be using it to update the calibration parameters to the device after running the Custom Calibration Sample App and obtained optimized parameters for the device.

CustomCalibration under examples directory is the Custom Calibration Sample App source code and project solution files to compile it. We will go over it later in this document.

3.2.3 Intel® RealSense™ SDK

Install the latest release of the Intel® RealSense™ SDK so your custom calibration application can use LibRealSense to conveniently open and access Intel® RealSense™ D400 series modules. **Table 3-2** contains pointers to the SDK homepage, GitHub* repository where you can download the latest release, and the SDK documentation.

Table 3-2. Intel® RealSense™ SDK Resources

Resource	URL
Intel® RealSense™ SDK Home Page	https://software.intel.com/en-us/realsense/sdk
LibRealSense GitHub*	https://github.com/IntelRealSense/librealsense
SDK Documentation	https://github.com/IntelRealSense/librealsense/tree/master/doc



3.2.4 OpenCV 3.3.1

The calibration example presented in this document uses several OpenCV 3.3.1 libraries for computations, so OpenCV 3.3.1 must be installed. **Table 3-3** lists URLs for downloading OpenCV 3.3.1, and **Table 3-4** lists the specific OpenCV libraries that are required by the example code.

Table 3-3. OpenCV 3.3.1 Resources

Resource	URL
OpenCV GitHub* Repository	https://github.com/opencv/opencv
OpenCV 3.3.1 Download	https://github.com/opencv/opencv/releases/tag/3.3.1

Table 3-4. OpenCV 3.3.1 Libraries Required for the Example

OpenCV 3.3.1 Library
itnotify.lib
opencv_calib3d331.lib
opencv_core331.lib
opencv_features2d331.lib
opencv_flann331.lib
opencv_imgproc331.lib
zlib.lib

3.2.5 Glut Library

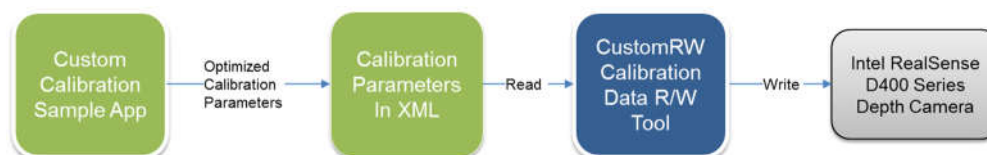
The FreeGLUT package is a convenient open source alternative to the OpenGL Utility Toolkit for displaying graphical output to the operator of the custom calibration application. You can download and install the FreeGLUT package at <http://freeglut.sourceforge.net/>.



4 Calibrating Device with Custom Calibration Sample Application

4.1 Process Overview

The general process to calibrate a device with the Custom Calibration Sample App involves running the app capturing images of the target from various viewpoints, the app optimizes the calibration parameters based on the captured images and writes the results to a XML file. The user then run CustomRW calibration data R/W tool to read the parameters from the XML file and write them to the device.



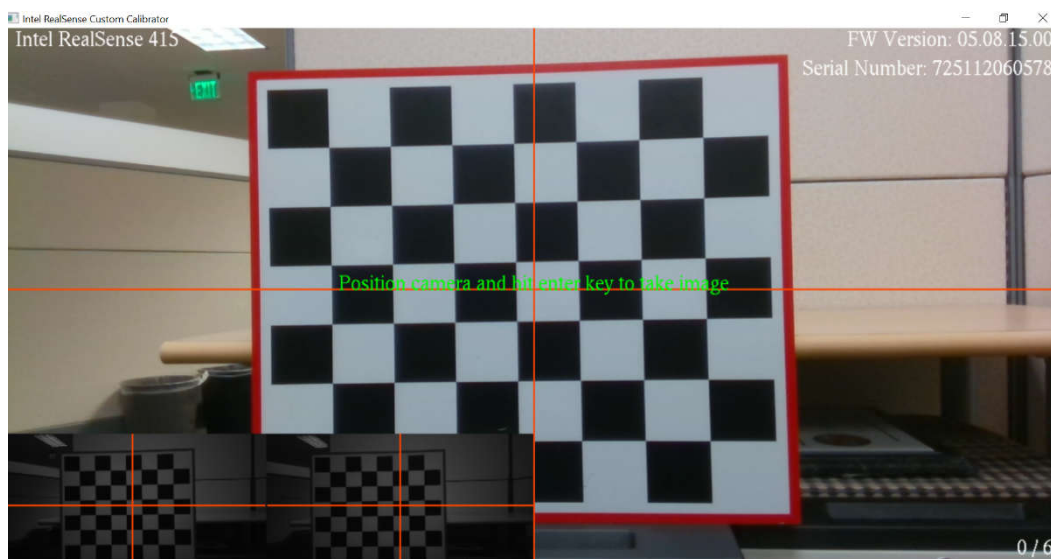
4.2 Connect Device to Computer

Connect the device through the USC cable to the PC where Custom Calibration Sample App locates.

4.3 Running Custom Calibration Sample Application

4.3.1 Starting Application

Use Windows explorer to browse to CustomCalibration\bin directory and find the CustomCalibrationTest.exe and double click it to start running.



The app runs with a simple UI. The main window displays the image from RGB imager, the lower left corner displays the left and right images. In case the device does not have RGB, only the left and right images display on the lower left corner.

A few text messages are overlay on top of the images:

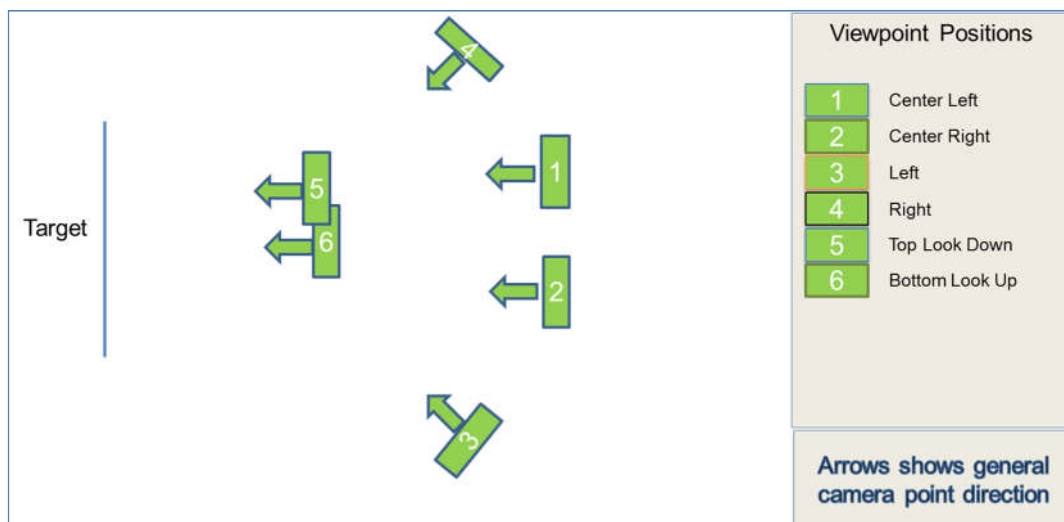
- On the top left corner, it displays the device model name, for example, Intel® RealSense™ Depth Camera D415.
- On the top right corner, it displays the FW version and serial number of the device.
- On the bottom right corner, it displays a progress counter in the form of x/6 where x is the number of images captured and accepted out of the total 6 images required.
- In the middle of the Window is a green help message to instruct the user to position the camera and press the enter key to capture image.
- In the top middle portion of the Window is an area where error message will display in red when the image is not accepted or other error conditions.

4.3.2 Capturing Images from 6 Viewpoints

The calibration algorithm in the Custom Calibration Sample Application requires 6 images of the target from different viewpoints. This is the minimum number of images for simplicity. The application UI will guide the user to go through the image capturing process.

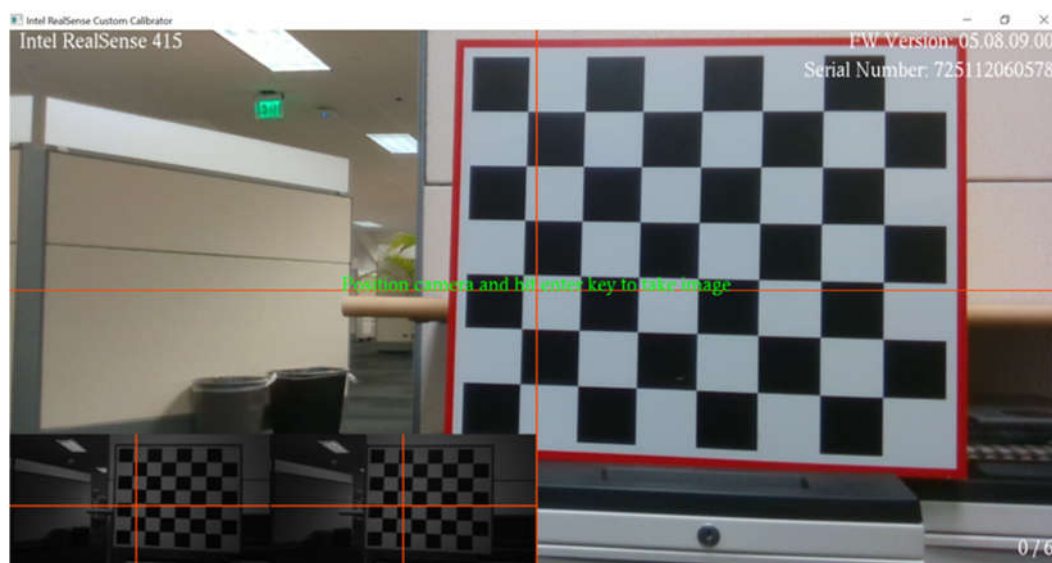


- **Viewpoints** - the choice of the viewpoint is critical to the accuracy of the calibration results. A general rule is that the target in these 6 images combined should cover as much as possible of the entire field of view and from different angles and distances from the target.



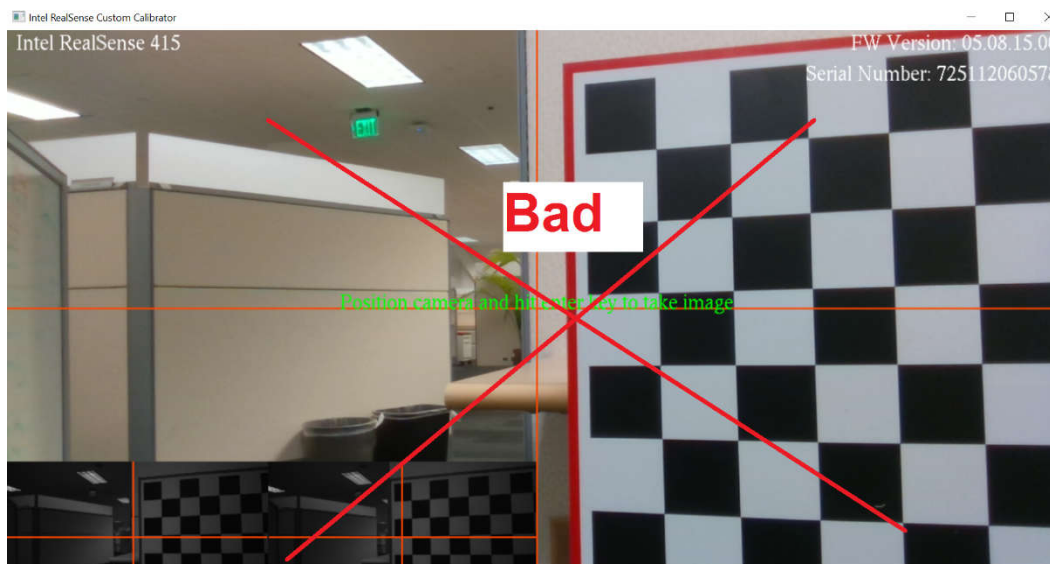
- **Cover whole target** - images from any of the viewpoints should cover the entire target in all imagers (Left, Right and RGB).

Good example – cover the entire target in all three imagers:





Bad example - cover only portion of the target in any of the three imagers:



Now, let's capture the images.

4.3.2.1 Viewpoint #1 – Center Right

Adjust the tripod and position the device on the center right facing directly to the target.



Figure 4-1 Center Right Position

The viewpoint should look like below with the target cover much of the right side the FOV.

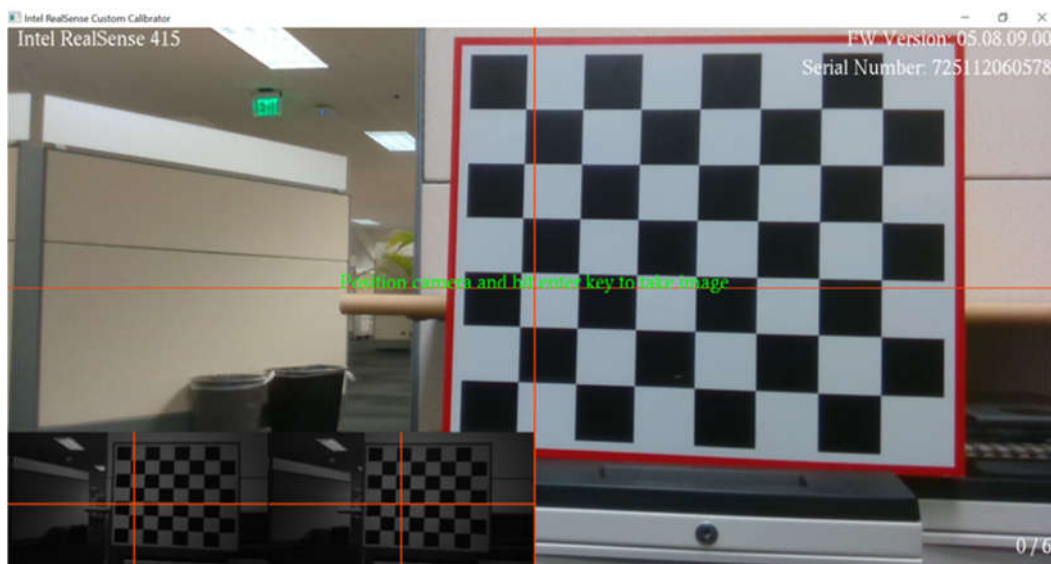


Figure 4-2 Viewpoint #1

Press enter to capture the image. If successful, the frame counter on the lower right corner will increase to 1/6 meaning 1 out of 6 images are captured. If it failed, a red error message will appear, and user is directed to retake a viewpoint.

4.3.2.2 Viewpoint #2 - Center Left

Move the device to the center left directly facing the target so the target covers much of the left portion of the FOV.



Figure 4-3 Center Right

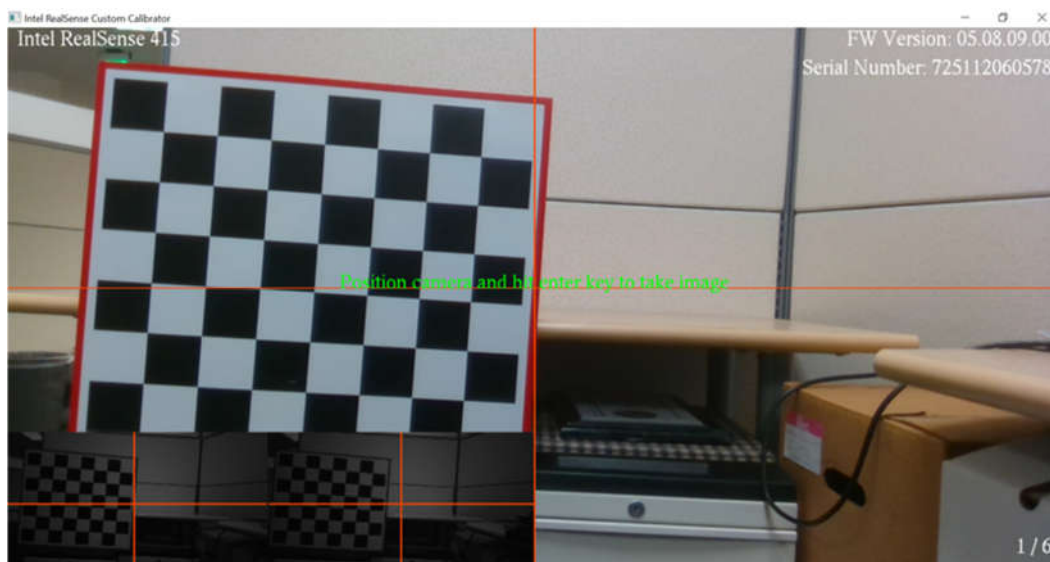


Figure 4-4 Viewpoint #2

Press enter to capture the image. If successful, the frame counter on the lower right corner will increase to 2/6 meaning 2 out of 6 images are captured. If it failed, a red error message will appear, and user is directed to retake a viewpoint.

4.3.2.3 Viewpoint #3 - Left

Move the device to the left of the camera facing the device at an angle. Use the viewpoint below for reference.



Figure 4-5 Left

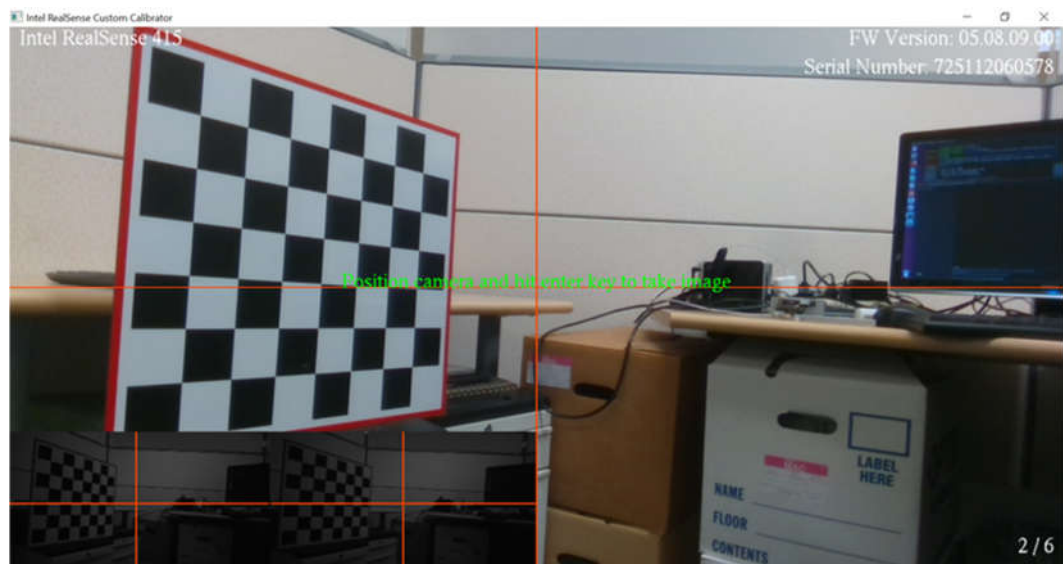


Figure 4-6 Viewpoint #3



Press enter to capture the image. If successful, the frame counter on the lower right corner will increase to 3/6 meaning 3 out of 6 images are captured. If it failed, a red error message will appear and user is directed to retake a viewpoint.

4.3.2.4 Viewpoint #4 – Right

Move the device to the right facing the target at an angle. Use the viewpoint below for reference.



Figure 4-7 Right

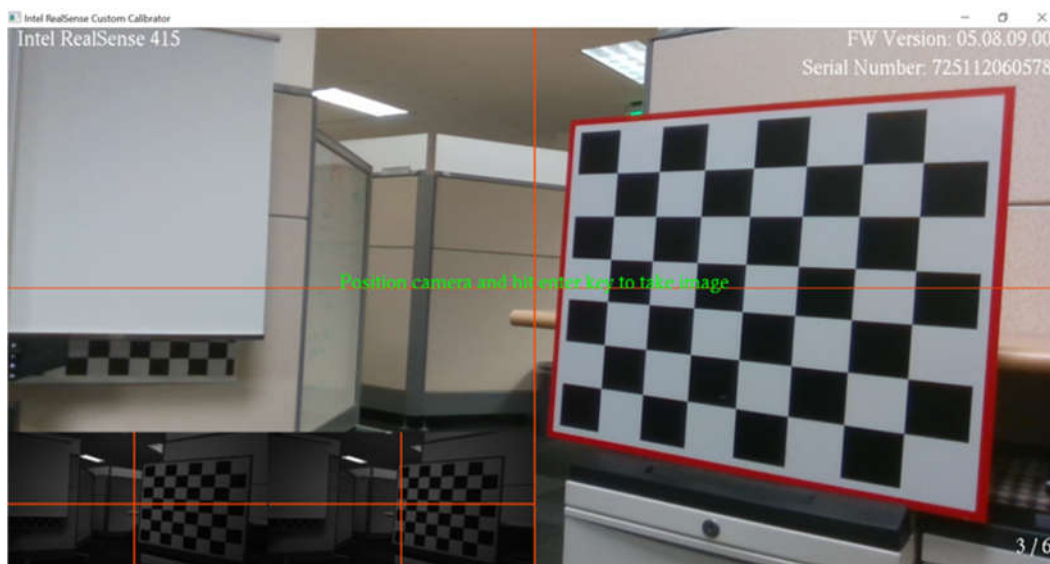


Figure 4-8 Viewpoint #4

Press enter to capture the image. If successful, the frame counter on the lower right corner will increase to 4/6 meaning 4 out of 6 images are captured. If it failed, a red error message will appear, and user is directed to retake a viewpoint.

4.3.2.5 Viewpoint #5 – Top Looking Down

Adjust the tripod so the device high enough to look down the target at an angle. Use the viewpoint below for reference.

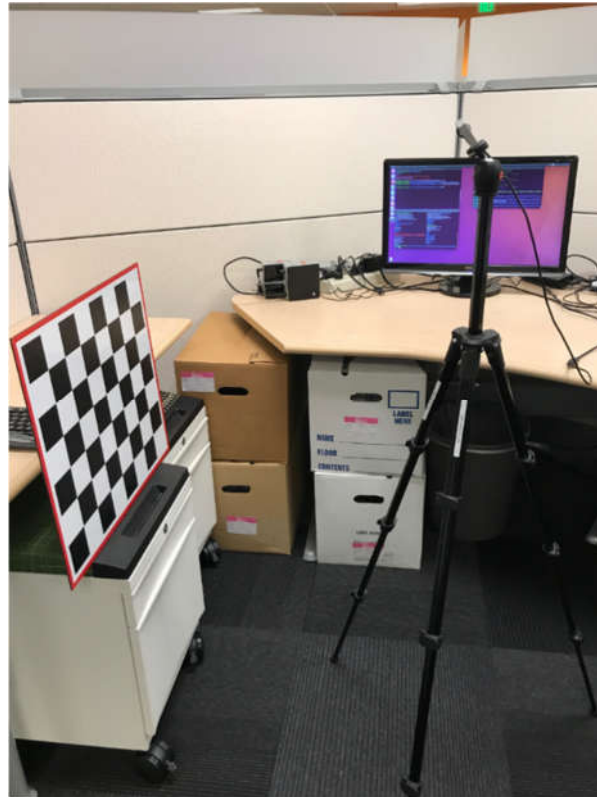


Figure 4-9 Top Looking Down

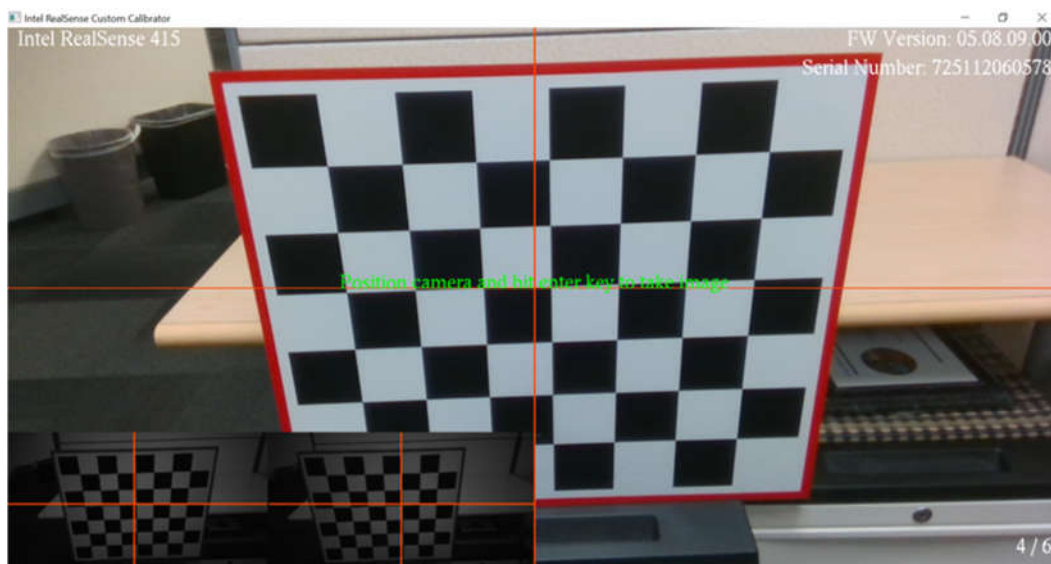


Figure 4-10 Viewpoint #5

Press enter to capture the image. If successful, the frame counter on the lower right corner will increase to 5/6 meaning 5 out of 6 images are captured. If it failed, a red error message will appear, and user is directed to retake a viewpoint.

4.3.2.6 Viewpoint #6 – Bottom Looking Up

Folding the tripod so that the device will be in a very low position looking up to the target. Use the viewpoint below for reference.



Figure 4-11 Bottom Looking Up

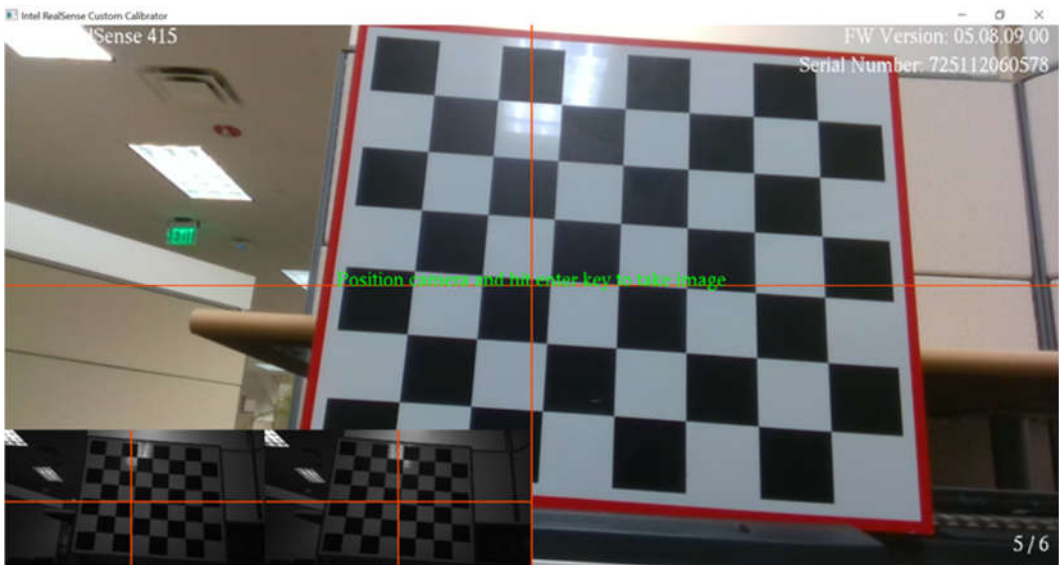


Figure 4-12 Viewpoint #6



Press enter to capture the image. If successful, the frame counter on the lower right corner will increase to 6/6 meaning 6 out of 6 images are captured. If it failed, a red error message will appear, and user is directed to retake a viewpoint.

4.4 Calibration Result

Once all 6 images captured, calibration will run and should finish very quickly. The results usually located under the CustomCalibrationSample\CustomResult folder with device serial number as the folder name. For example, CustomCalibrationSample\CustomResult\725112060578\DC1

6 RGB images:

- colorImage001.png
- colorImage002.png
- colorImage003.png
- colorImage004.png
- colorImage005.png
- colorImage006.png

6 left images:

- leftImage001.png
- leftImage002.png
- leftImage003.png
- leftImage004.png
- leftImage005.png
- leftImage006.png

Right RGB Images

- rightImage001.png
- rightImage002.png
- rightImage003.png
- rightImage004.png
- rightImage005.png
- rightImage006.png

Optimized calibration parameters in XML:

CalibrationParameters.xml

For example:

```
<?xml version="1.0"?>
<Config>
  <param name = "ResolutionLeftRight">
    <value>1920</value>
    <value>1080</value>
  </param>
  <param name = "FocalLengthLeft">
    <value>1378.69</value>
    <value>1379.13</value>
  </param>
```



```
<param name = "PrincipalPointLeft">
  <value>965.562</value>
  <value>542.603</value>
</param>
<param name = "DistortionLeft">
  <value>0.09689</value>
  <value>-0.0235634</value>
  <value>-5.05513e-05</value>
  <value>0.000105855</value>
  <value>-0.640377</value>
</param>
<param name = "FocalLengthRight">
  <value>1389.55</value>
  <value>1390.1</value>
</param>
<param name = "PrincipalPointRight">
  <value>957.402</value>
  <value>553.108</value>
</param>
<param name = "DistortionRight">
  <value>0.123289</value>
  <value>-0.290911</value>
  <value>0.000149083</value>
  <value>0.000723527</value>
  <value>0.0992178</value>
</param>
<param name = "RotationLeftRight">
  <value>0.999983</value>
  <value>0.00150008</value>
  <value>-0.00558928</value>
  <value>-0.00150249</value>
  <value>0.999999</value>
  <value>-0.000428313</value>
  <value>0.00558863</value>
  <value>0.000436704</value>
  <value>0.999984</value>
</param>
<param name = "TranslationLeftRight">
  <value>-55.3888</value>
  <value>0.0448052</value>
  <value>1.52189</value>
</param>
<param name = "HasRGB">
  <value>1</value>
</param>
<param name = "ResolutionRGB">
  <value>1920</value>
  <value>1080</value>
</param>
<param name = "FocalLengthRGB">
  <value>1376.09</value>
  <value>1376.4</value>
```



```

</param>
<param name = "PrincipalPointRGB">
  <value>947.958</value>
  <value>531.068</value>
</param>
<param name = "DistortionRGB">
  <value>0.109862</value>
  <value>-0.122685</value>
  <value>-0.000453445</value>
  <value>-8.61456e-05</value>
  <value>-0.396171</value>
</param>
<param name = "RotationLeftRGB">
  <value>0.999994</value>
  <value>0.00346622</value>
  <value>0.000876088</value>
  <value>-0.00346642</value>
  <value>0.999994</value>
  <value>0.000222113</value>
  <value>-0.000875313</value>
  <value>-0.000225148</value>
  <value>1</value>
</param>
<param name = "TranslationLeftRGB">
  <value>14.6987</value>
  <value>-0.0644999</value>
  <value>0.448085</value>
</param>
</Config>

```

4.5 Updating Results to Device

We will use Intel.Realsense.CustomRW to read the CalibrationParameters.xml and write the parameters to the device. Checking the depth quality before and after updating the calibration data on the device.

4.5.1 Depth Quality Check before Updating Calibration

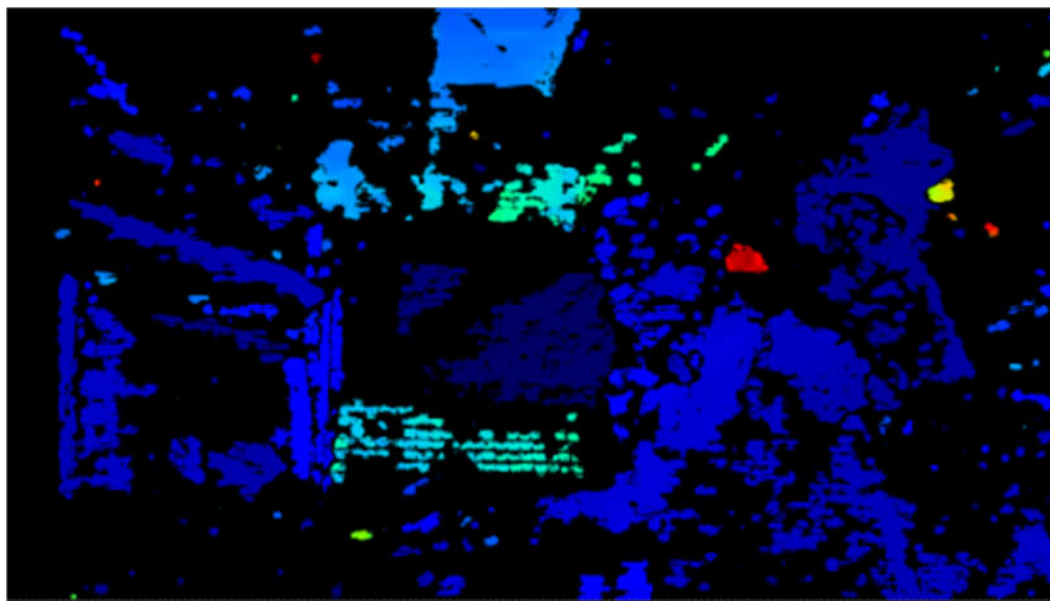


Figure 4-13 Depth Quality before Updating Calibration

4.5.2 Writing Optimized Calibration to Device

Change directory to Calibration Tool API bin:

```
Cd C:\CalibrationToolAPI\2.6.8.0\bin
```

Dump the current parameters on the device into before.txt:

```
Intel.Realsense.CustomRW.exe -r > before.txt
```

Writing the parameters in the XML result file into device:

```
Intel.Realsense.CustomRW.exe -w -f CalibrationParameters.xml
```



```
C:\Windows\System32\cmd.exe
C:\CalibrationToolAPI\2.5.2.0\bin>Intel.Realsense.CustomRW.exe -w CalibrationParameters.xml
CustomRW for Intel RealSense D400, Version: 2.5.2.0

Calibration data updated successfully.
Calibration parameters from the device:
resolutionLeftRight: 1920 1080

FocalLengthLeft: 1378.689941 1379.130005
PrincipalPointLeft: 965.561951 542.602966
DistortionLeft: 0.096890 -0.023563 -0.000051 0.000106 -0.640377

FocalLengthRight: 1389.549927 1390.099976
PrincipalPointRight: 957.402039 553.108032
DistortionRight: 0.123289 -0.290911 0.000149 0.000724 0.099218

RotationLeftRight: 0.999983 0.001500 -0.005589
                  -0.001502 0.999999 -0.000428
                  0.005589 0.000437 0.999984
TranslationLeftRight: -55.388802 0.044805 1.521890

HasRGB: 1

resolutionRGB: 1920 1080

FocalLengthColor: 1376.089966 1376.400024
PrincipalPointColor: 947.958008 531.067993
DistortionColor: 0.109862 -0.122685 -0.000453 -0.000086 -0.396171
RotationLeftColor: 0.999994 0.003466 0.000876
                  -0.003466 0.999994 0.000222
                  -0.000875 -0.000225 1.000000
TranslationLeftColor: 14.698700 -0.064500 0.448085

C:\CalibrationToolAPI\2.5.2.0\bin>
```

Figure 4-14 Updating Calibration Parameters to Device

Dump the parameters from device into after.txt:

Intel.Realsense.CustomRW -r > after.txt

Compare the parameters changed:

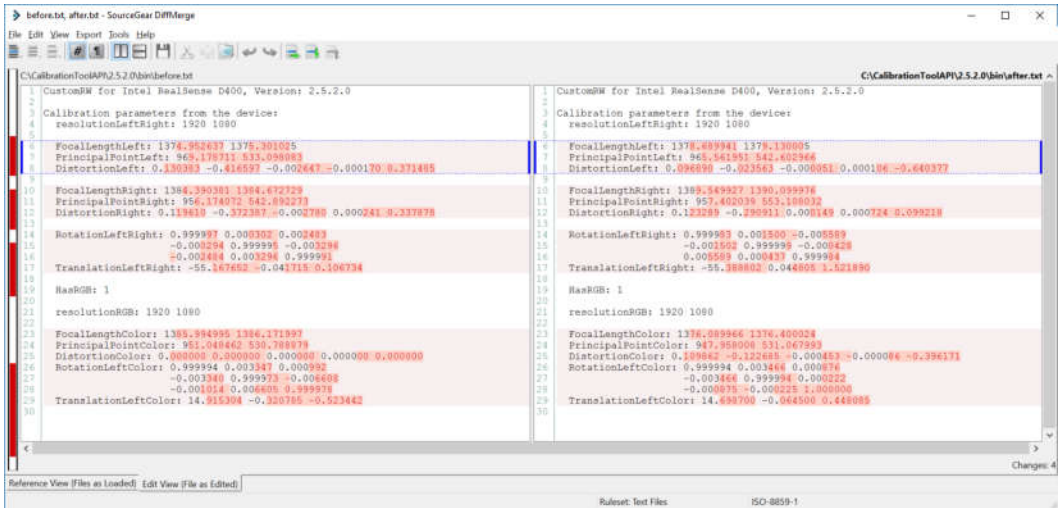
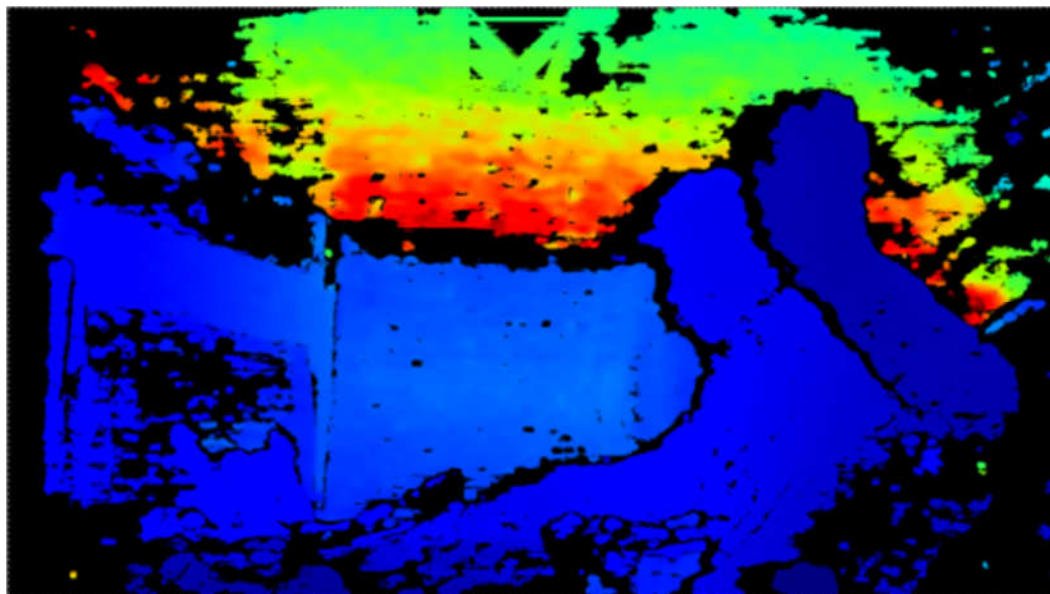


Figure 4-15 Calibration Parameter Change

4.5.3 Depth Quality Check after Updating Calibration







5 Developing Custom Calibration Application

This section demonstrates how to develop custom calibration application through key aspects of the sample app we used in *Calibrating Device with Custom Calibration Sample Application*. The sample app uses OpenCV algorithm as example.

The general process is to configure the Intel® RealSense™ camera for calibration, capture images from the camera module, perform the desired calibration computations with OpenCV, and to write the new calibration parameters back to the cameras using routines from the Intel® RealSense™ calibration library.

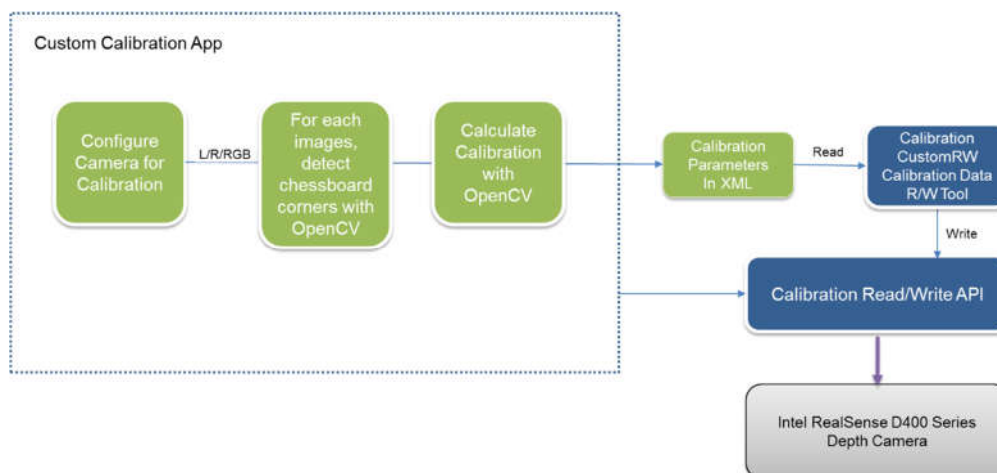


Figure 5-1 General Process for custom Calibration

5.1 Sample Application Source Code and Compile

The source code for Custom Calibration Sample Application is included in the Calibration API package as example. The packages are described in section 3.2.2 “Intel® RealSense™ Calibration Tool and API”.

The following directory structure is related to the sample app:

```

CalibrationToolAPI
|
|----- 2.6.8.0
|         |----- bin
  
```



```

|
|
|          |----- DSDynamicCalibrationAPI.dll
|          |----- freeglut.dll
|          |----- realsense2.dll
|
|----- Include
|          |----- DSDynamicCalibration.h
|          |----- DSOSUtils.h
|          |----- DSShared.h
|
|----- lib
|          |----- DSDynamicCalibrationAPI.lib
|
|----- librealSense
|          |----- include
|          |----- lib
|
|----- examples
|          |----- CustomCalibration
|          |          |----- CalibrationManager.cpp
|          |          |----- CalibrationManager.h
|          |          |----- CustomCalibration.cpp
|          |          |----- CustomCalibration.h
|          |          |----- CustomCalibrationWrapper.cpp
|          |          |----- CustomCalibrationWrapper.h
|          |          |----- Rs400Dev.cpp
|          |          |----- Rs400Dev.h
|          |          |----- FileOp.h
|          |          |----- Main.cpp
|          |          |----- CustomCalibrationTest.vcxproj
|          |          |----- CustomCalibrationTest.sln
|
|          |----- Common
|          |          |----- CalibParamXmlWrite.h
|
|          |----- ThirdParty
|          |          |----- glut

```

The sample app depends on a few third party libraries, including GLUT, LibRealSense, and OpenCV 3.3.1. GLUT is included under examples\ThirdParty\glut. LibRealSense is included under librealSense.

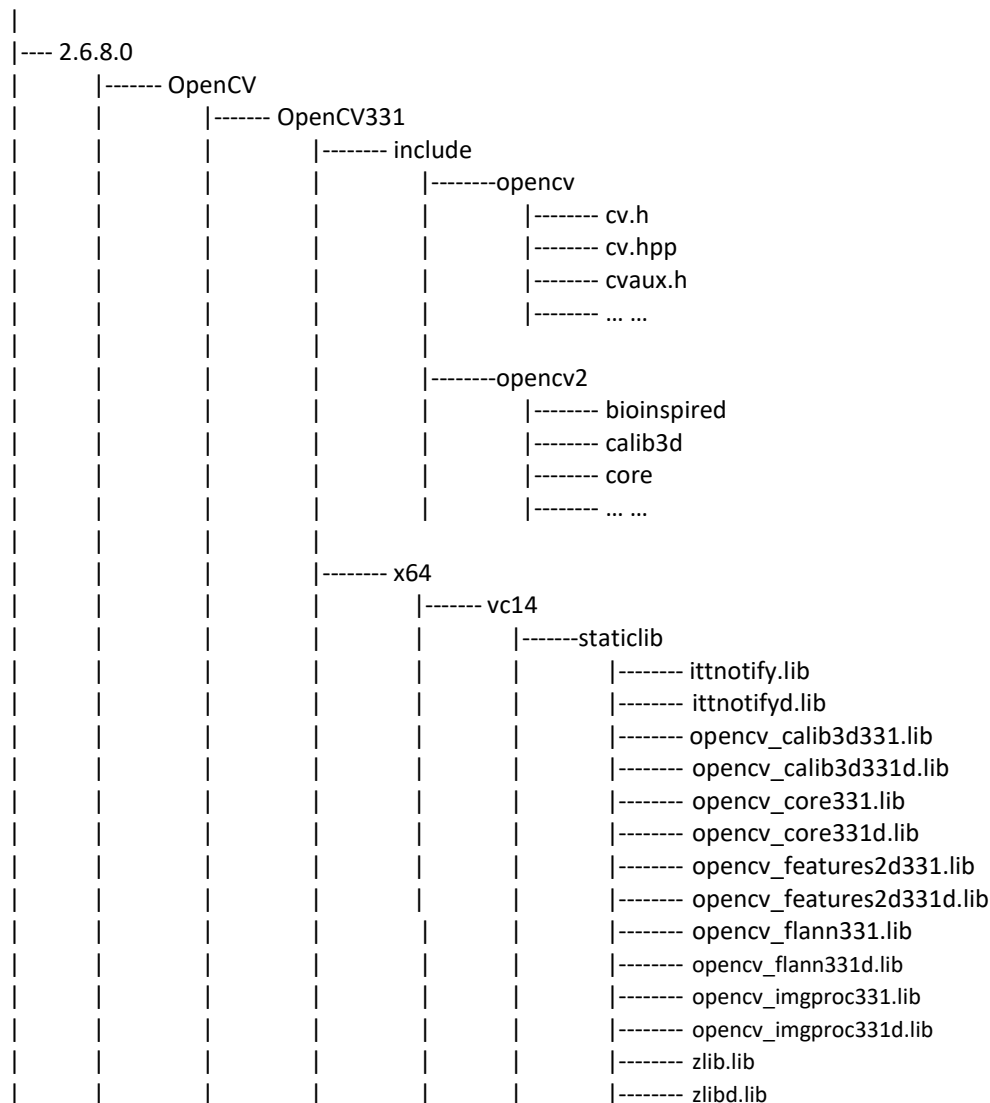
- **bin** contains the runtime libraries for Calibration API, GLUT, and LibRealSense.
- **Include** contains header files for Calibration API.
- **lib** contains Calibration API library.
- **librealSense** contains the header files and libraries for LibRealSense



- **examples** contains all Calibration API examples and related files. The CustomCalibration sample app source is under CustomCalibration folder.

OpenCV 3.3.1 is not included. To compile the CustomCalibration sample app, user will need to download sources from <https://github.com/opencv/opencv/releases/tag/3.3.1>, compile, and set it up so that the OpenCV header files and libraries is under CalibrationToolAPI\2.6.8.0 as below. OpenCV setup is discussed in section 3.2.4 “OpenCV 3.3.1” earlier in this document.

CalibrationToolAPI





To build the project, open the **CustomCalibrationTest.sln** under `examples\CustomCalibration` with **Visual Studio 2015 Update 3** and build “Release” “x64”.

5.2 Calibration Mode Camera Configuration

For calibration, the camera needs to be configured to capture calibration images for both depth and RGB camera using LibRealSense. Basic device operations are defined in `Rs400Dev.h` and `Rs400Dev.cpp`. The Configurations for the device is defined in `CalibrationManager.h` and `CalibrationManager.cpp`.

5.2.1 Emitter

The emitter should be turned off during calibration to avoid interference.

Sample code in `Rs400Device`:

```
m_rsDevice->EnableEmitter(0.0f);
```

5.2.2 Auto Exposure

Auto exposure should be turn on and the AE setpoint be adjusted according to lighting condition. In indoor room lighting, a setpoint value around 500 – 800 should be sufficient. In outdoor, 1200 or higher.

```
m_rsDevice->EnableAutoExposure(1.0f);
if (m_cameraInfo.isWide)
    m_rsDevice->SetAeControl(800);
else
    m_rsDevice->SetAeControl(500);
```

5.2.3 Streaming Resolution and Format

Calibration frame resolutions and formats are described in *Table 2-1 Frame Formats Used in Custom Calibration*, for example, in this sample, or D415 device, the resolution is 1920x1080 with frame rate of 15 fps. The L/R format is Y16 and the RGB format is YUY2.

```
m_rsDevice->SetMediaMode(m_width, m_height, m_fps, m_rgbWidth,
m_rgbHeight, m_cameraInfo.isRGB);

m_rsDevice->StartCapture([&](const void *leftImage, const void *rightImage,
const void *colorImage, const uint64_t timeStamp)
```



5.2.4 Image Captures

The sample app captures 6 images. More images from different positions may improve accurate. The number of images is defined in CalibrationManager.h:

```
const int NUM_SHOTS = 6;
```

5.2.5 Demosaic Left/Right Images for ASR / PSR SKUs

For ASR/PSR SKUs, left and right images need to be **demosaiced**.

5.3 Detecting the Chessboard in an Image with OpenCV

For each of the captured images, find the chessboard corners with OpenCV findChessboardCorners.

```
#include <opencv2/opencv.hpp>
#include <opencv2/core/core.hpp>
#include <opencv2/calib3d.hpp>
#include <vector>

using namespace std;
using namespace cv;

bool DetectChessboard(const Mat& image, const Size& chessboardSize, vector<Point2f>&
corners)
{
    // Find chessboard corners
    if (!findChessboardCorners(image, chessboardSize, corners,
CALIB_CB_ADAPTIVE_THRESH | CALIB_CB_NORMALIZE_IMAGE | CALIB_CB_FILTER_QUADS))
        return false;

    // Refine them
    cornerSubPix(image, corners, Size(11, 11), Size(-1, -1),
TermCriteria(CV_TERMCRIT_EPS | CV_TERMCRIT_ITER, 30, 0.1));
    return true;
}
```

5.4 Calculating Depth Camera Calibration with OpenCV

```
#include <opencv2/opencv.hpp>
#include <opencv2/core/core.hpp>
#include <opencv2/calib3d.hpp>
#include <vector>
```



```
using namespace std;
using namespace cv;

static void CreateCorners3D(const Size& chessboardSize, float checkerSize, size_t
numImages, vector<vector<Point3f> >& corners3D)
{
    corners3D.resize(numImages);
    corners3D[0].resize(chessboardSize.width * chessboardSize.height);

    for (int i = 0; i < chessboardSize.height; i++)
        for (int j = 0; j < chessboardSize.width; j++)
            corners3D[0][i * chessboardSize.width + j] = Point3f(j *
checkerSize, i * checkerSize, 0.0f);

    for (size_t i = 1; i < numImages; i++)
        corners3D[i] = corners3D[0];
}

double CalibrateDepthCamera(const vector<vector<Point2f> >& cornersLeft, const
vector<vector<Point2f> >& cornersRight, const Size& chessboardSize, float checkerSize,
const Size& imageSizeLR, Mat& K1, Mat& D1, Mat& K2, Mat& D2, Mat& R1, Mat& T1)
{
    CV_Assert(cornersLeft.size() != 0 && cornersLeft.size() == cornersRight.size());
    CV_Assert(checkerSize > 0.0f);

    // Create 3D prototype of the corners
    vector<vector<Point3f> > corners3D;
    CreateCorners3D(chessboardSize, checkerSize, cornersLeft.size(), corners3D);

    // Calibrate each camera individually
    calibrateCamera(corners3D, cornersLeft, imageSizeLR, K1, D1, noArray(),
noArray(), CV_CALIB_FIX_ASPECT_RATIO, TermCriteria(TermCriteria::COUNT +
TermCriteria::EPS, 60, DBL_EPSILON));
    calibrateCamera(corners3D, cornersRight, imageSizeLR, K2, D2, noArray(),
noArray(), CV_CALIB_FIX_ASPECT_RATIO, TermCriteria(TermCriteria::COUNT +
TermCriteria::EPS, 60, DBL_EPSILON));

    // Calibrate the extrinsics between them
    return stereoCalibrate(corners3D, cornersLeft, cornersRight, K1, D1, K2, D2,
Size(-1, -1), R1, T1, noArray(), noArray(), CV_CALIB_FIX_INTRINSIC |
CV_CALIB_USE_INTRINSIC_GUESS, TermCriteria(TermCriteria::COUNT + TermCriteria::EPS, 300,
DBL_EPSILON));
}
```

5.5 Calculating RGB Camera Calibration with OpenCV

Note: Assumes good depth camera calibration

```
double CalibrateRGBCamera(const vector<vector<Point2f> >& cornersLeft, const
vector<vector<Point2f> >& cornersRGB, const Size& chessboardSize, float checkerSize,
const Size& imageSizeRGB, const Mat& K1, const Mat& D1, Mat& Kc, Mat& Dc, Mat& R1c, Mat&
T1c)
{
    CV_Assert(cornersLeft.size() != 0 && cornersLeft.size() == cornersRGB.size());
    CV_Assert(checkerSize > 0.0f);

    // Create 3D prototype of the corners
```




```
vector<vector<Point3f> > corners3D;
CreateCorners3D(chessboardSize, checkerSize, cornersLeft.size(), corners3D);

// Calibrate RGB camera
calibrateCamera(corners3D, cornersRGB, imageSizeRGB, Kc, Dc, noArray(),
noArray(), CV_CALIB_FIX_ASPECT_RATIO, TermCriteria(TermCriteria::COUNT +
TermCriteria::EPS, 60, DBL_EPSILON));

// Calibrate the extrinsics between them
return stereoCalibrate(corners3D, cornersLeft, cornersRGB, K1, D1, Kc, Dc, Size(-
1, -1), R1c, T1c, noArray(), noArray(), CV_CALIB_FIX_INTRINSIC |
CV_CALIB_USE_INTRINSIC_GUESS, TermCriteria(TermCriteria::COUNT + TermCriteria::EPS, 300,
DBL_EPSILON));
}
```

5.6 Calculating RGB Camera Calibration Extrinsics with OpenCV

Note: Assumes good depth camera calibration and intrinsics for the RGB camera.

The `CustomCalibration.h` header file in the sample code contained the following unimplemented prototype:

```
double RecalibrateRGBCamera(const std::vector<std::vector<cv::Point2f> >& cornersLeft,
const std::vector<std::vector<cv::Point2f> >& cornersRGB, const cv::Size& chessboardSize,
float checkerSize, const cv::Mat& K1, const cv::Mat& D1, const cv::Mat& Kc, const
cv::Mat& Dc, cv::Mat& R1c, cv::Mat& T1c);
```

5.7 Writing Calibration Parameters

A user custom calibration app can choose one of the two approaches to update the results to the device:

- To link to the `WriteCustomCalibrationParameters` and `ReadCalibrationParameters` and write directly to the device through the APIs.
- To write the results into a parameter XML file and then use `CustomRW` to read/write the parameters to the device.

Custom Calibration Sample Application write the results into a parameter XML file and use CustomRW to update the calibration parameters to the device.



6 Appendix: Unrectified Left/Right Image Formats for Calibration

D400 series devices stream unrectified frames from left and right imagers in advanced mode. These streams are usually used in calibrating the devices. Y12I is the native format from the hardware. If users access the streams through LibRealsense, these unrectified frames are exposed in Y16 format.



6.1 Unrectified Calibration Format

Both Y12I and Y16 are unrectified. In Y12I, the left and right frames are interleaved in the same file in 3 bytes every two pixels format. In Y16, the left and right frames are separated buffers and each in two bytes per pixel format.

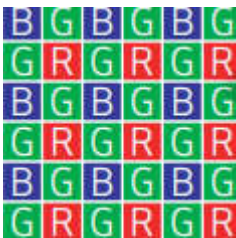
Table 6-1. Left/Right Unrectified Calibration Image Formats

Device	Sensor	Unrectified Frame Resolution	From Device HW	From LibRealsense	Note
D400/D410/D415	Bayer pattern	1920x1080	Y12I	Y16	Data is in BG/GR Bayer pattern. User will need to demosaic the image before using in calibration.
D420/D430/D435	Monochrome	1280x800	Y12I	Y16	Data is monochrom.



					No need to demosaic.
--	--	--	--	--	----------------------

On devices with regular lens, for example, D400/D410/D415, the left and right imager sensors are colored, and data is in BG/GR bayer pattern. User will need to demosaic the data before using them in their calibration algorithms.



On devices with wide angle lens, for example, D420/D430/D435, the left and right imager sensors are monochrome. Demosaic is not needed.

6.2 Y12I Format

The device outputs the unrectified frames in Y12I format with left and right images interleaved in the same frame. This mode interleaves 12 bits of data from the left imager and 12 bits of data from the right imager as described below:

Table 6-2 Y12I Format

7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0
RY0 [0..7]								LY0 [0..3]				RY0 [8..11]				LY0 [4..11]								RY1 [0..7]							
LY1 [0..3]				RY1 [0..3]				LY1 [4..11]								RY2 [0..7]								LY2[0..3]				RY2 [8..11]			
LY2 [4..11]								RY3 [0..7]								LY3 [0..3]				RY3 [8..11]				LY3 [4..11]							

Y12I data is 12-bit per pixel.



6.3 Y16 Format

Librealsense outputs the unrectified calibration frames in Y16 format. Each pixel is represented by 16-bits of intensity or bayer pattern data from the left or right imagers. The data is scaled to the full 16-bit value range. The organization of the pixels in the image buffer is from left to right and top down, i.e, the first 16 bits of the image buffer corresponds to the first pixel of the first line of the image and the second 16 bits represent the second pixel, etc.

Table 6-3 Y16 Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Y0 [0..15]																Y1 [0..15]															

Y16 data is 16-bit per pixel and is scaled to the full 16-bit 0 – 65535 range.