Qualcomm Technologies, Inc.

# Stereo Camera Calibration Guide

80-NV559-1 B

March 18, 2015

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# Revision history

| Revision | Date | Description |
|---|---|---|
| A | Mar 2015 | Initial release |
| B | Mar 2015 | Numerous changes were made to this document; it should be read in its entirety. |

# Contents

# Figures

# 1 Introduction

## 1.1 Purpose

This document describes the procedure for mechanical placement and orientation of the stereo calibration components for use in conjunction with the supplied stereo calibration and depth map software libraries. The methodology described here is suitable for automated assembly line calibration of stereo camera modules. A validation procedure is also described based on computing metrics and assigning pass/fail thresholds.

Two separate charts are employed for stereo calibration, a nonplanar L-chart that is comprised of two perpendicular checkerboards, and a planar checkerboard chart. The L-chart is used to compute the projective calibration component, and the planar chart is used for geometric correction. The calibration charts used to create the test scenes, the chart placements relative to the stereo module containing the left and right cameras, and a brief overview of the subsequent calibration processes are described. The given mechanical procedure for calibration will serve as a guideline for capturing images to be used with Qualcomm's stereo camera calibration library.

## 1.2 Conventions

Function declarations, function names, type declarations, attributes, and code samples appear in a different font, for example, `#include`.

## 1.3 Technical assistance

For assistance or clarification on information in this document, submit a case to Qualcomm Technologies, Inc. (QTI) at https://support.cdmatech.com/.

If you do not have access to the CDMATech Support website, register for access or send email to support.cdmatech@qti.qualcomm.com.

# 2 Calibration Procedure

The procedure for calibrating a stereo camera system using QTI's calibration library consists of obtaining a suitable nonplanar calibration chart, orienting the camera module such that the Field of Views (FoV) coincide with the chart, and capturing and saving the left and right chart images for input into the calibration software. We refer to the two cameras equivalently as left and right, reference and auxiliary, or main camera and auxiliary interchangeably with the understanding that for asymmetric stereo systems the reference and/or main camera contains the higher resolution sensor.

Obtaining a stereo image pair with the test module of the planar chart is the second step in the calibration process. Images should be captured subsequent to capture of the L-chart with the exact same focal length settings. The planar chart may be placed adjacent to the L-chart as an additional precomposed factory calibration scene. The module may either be translated to this scene along a conveyor belt or rotated such that the new chart is viewed. The setup is shown in Figure 2-1 where the arrow implies that the module is moved to view scene two.

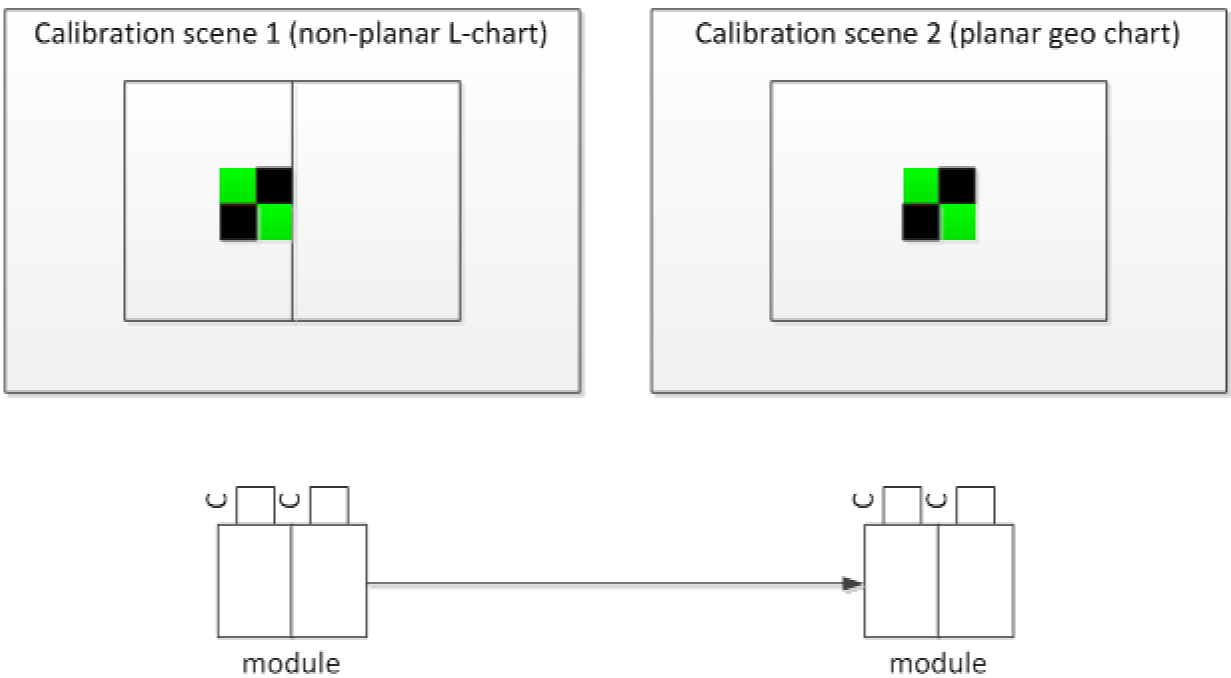



**Figure 2-1 Calibration scene diagram**

## 2.1 Construct the test chart

The test chart provides the calibration software with an orthogonal reference or measurement coordinate frame. This frame of reference is used to identify and associate position correspondences between the left and right images.

1. Print the calibration left and right checkerboard chart images on a quality printer. Attach them to firm surfaces, such as straight cardboard or other rigid substrate.

   It is recommended to affix the two charts to the corner of a room (two-walled intersection) or equivalent perpendicular surfaces. It is also possible to construct a mobile (nonplanar) calibration rig as shown in the following picture.

   The test chart consists of two planes sized 2 x 3 feet containing 12 x 18 black and white checkerboard squares 2 inches in length.

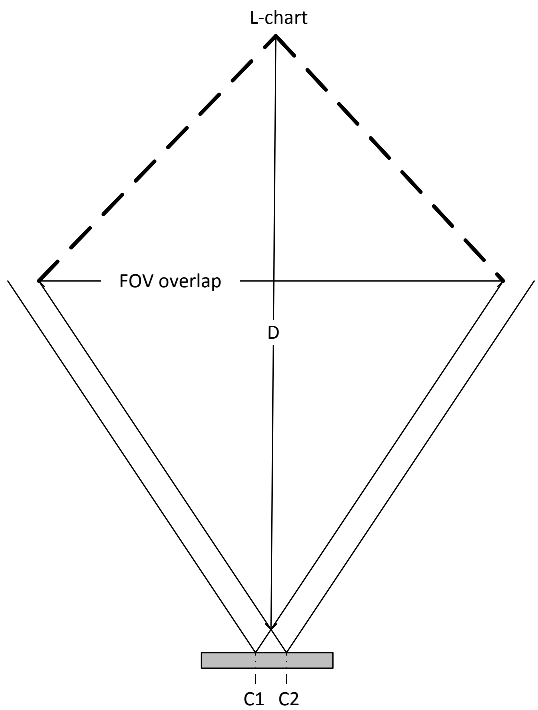
   

2. Once the chart is constructed, measure the size of the squares with a ruler and record the length for input to the calibration software.
3. Place the two planes at right angles so that the joining line is devoid of any interstitial gaps.

   The left plane contains two green patches that are used to identify the coordinate system origin. It is important that the charts are set up at right angles to each other to furnish the calibration software with a sufficiently orthogonal reference frame. The charts must be properly oriented in the vertical direction as they are not symmetric. Note that the left and right charts are not interchangeable, so be sure to properly place the charts.

## 2.2 Set up the test scene

1. Place the stereo camera pair at a distance so that the chart exclusively occupies the FoV of both the auxiliary and reference cameras as illustrated.




   The green patches, which serve as the origin for the world coordinate system, should be positioned in the center of the camera FoVs.

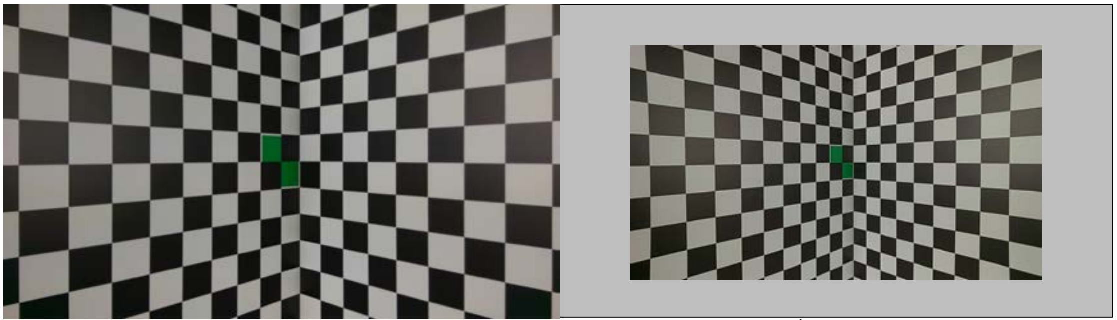
   The module should be placed equidistant from the two perpendicular planes, ideally 2 ft from each plane (horizontally) and 1.5 ft from the bottom of each plane (vertically).

2. Set position tolerances to ±2.5 in. in X, Y, and Z.

   Tolerances are sufficient to accommodate a high degree of flexibility when performing calibration as part of assembly line automation.

3. Set the baseline rotation < 5°.
4. Align the two green squares roughly in the middle of the image.
5. Record focal position and input into the calibration routine (lens can be in free focus).
6. Ensure the chart is well illuminated at +500 lux (or the mean value of the intensities at the 8 bit raw image stage around the center should be about 50 lux). Use D65 illuminant.

This is an example of a stereo image pair that satisfies this criteria.



Main camera Auxiliary camera

## 2.3 Perform calibration

1. Set up the chart as described in Section 2.1 and Section 2.2 and record the size parameters.
2. Capture reference and auxiliary images.
3. Input the chart square size, image pair, and focal position value to the calibration software.
4. Store the calibration parameters for input to the calibration software.
5. Run the calibration software to complete stereo calibration.

## 2.4 Algorithm

Once the left and right camera images of the calibration chart are captured, they are fed to the calibration program and the following automated process occurs:

1. Detection of key points within a boundary around the center, e.g., Figure 2-2 and Figure 2-3
2. Detection of coordinate system origin
3. Labeling of key points
4. Computation of key point real-world positions
5. Matching of key points image coordinates between the left and right cameras
6. Estimation of a scaling, rotation matrix, and yaw angle to minimize the vertical disparities between the matching key points, as well as set the disparity to the expected value at the center of the green patch
7. Alignment of the right image to make it parallel to the left image using a projective matrix derived from the rotation matrix and scale obtained above
8. Production of calibration accuracy metrics

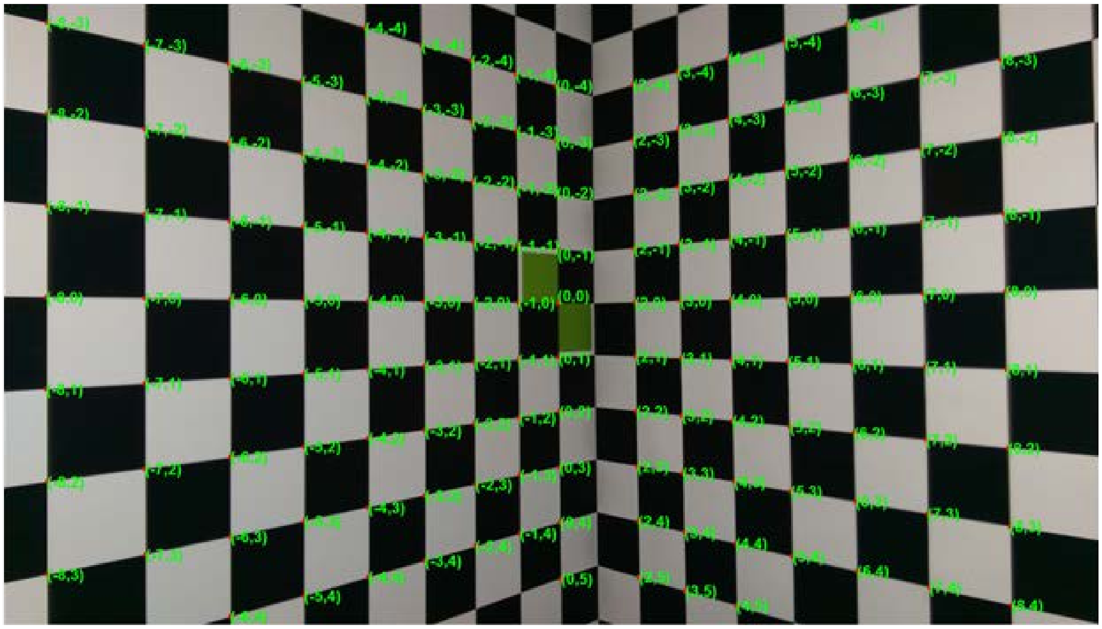


**Figure 2-2 Main camera key points at processing resolution**

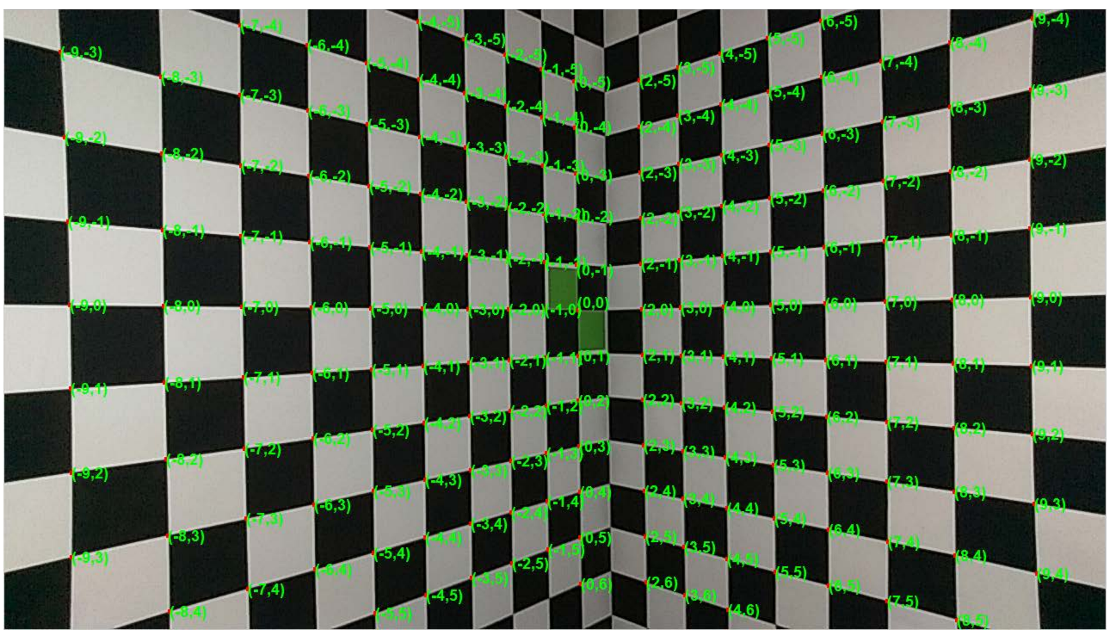


**Figure 2-3 Auxiliary camera key points at processing resolution**

# 3 Geometric Calibration Procedure

The procedure for performing geometric calibrations consists of taking stereo pairs of a flat checkerboard chart from which a 2D surface is calculated and which corrects for geometric distortion. We refer to the two cameras equivalently as left and right, reference and auxiliary, or main camera and auxiliary interchangeably with the understanding that for asymmetric stereo systems the reference and/or main camera contains the higher resolution sensor.

Obtaining a stereo image pair with the test module of the planar chart is the second step in the calibration process. Images should be captured subsequent to capture of the L-chart with the exact same focal length settings. The planar chart may be placed adjacent to the L-chart as an additional precomposed factory calibration scene. The module may be translated to this scene along a conveyor belt or rotated such that the new chart is viewed. The setup is shown in Figure 3-1 where the arrow implies that the module is moved to view scene two.

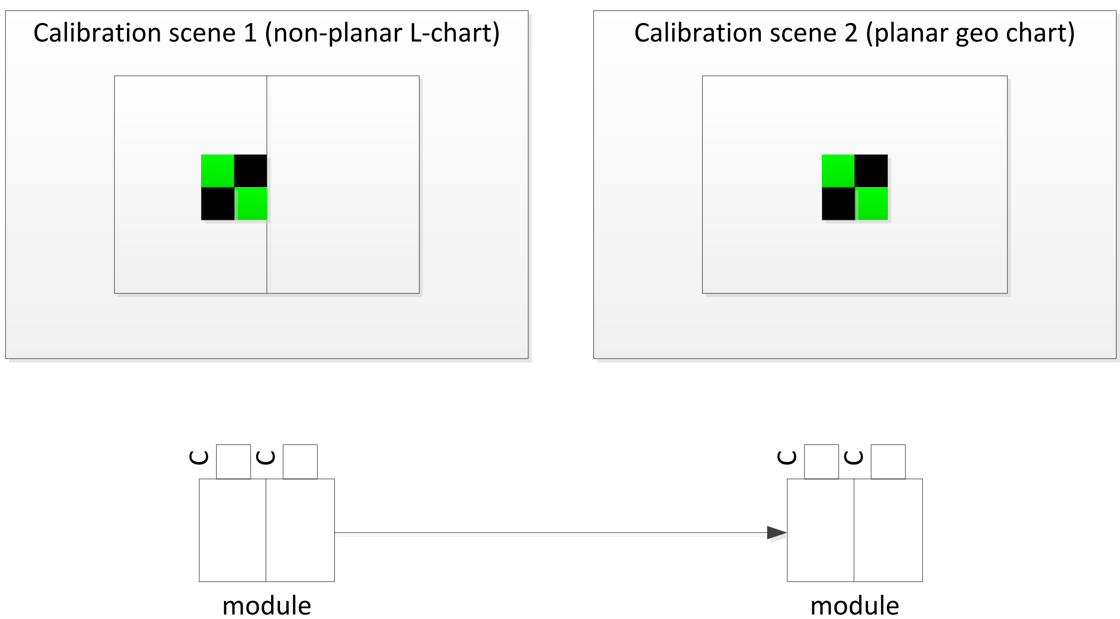


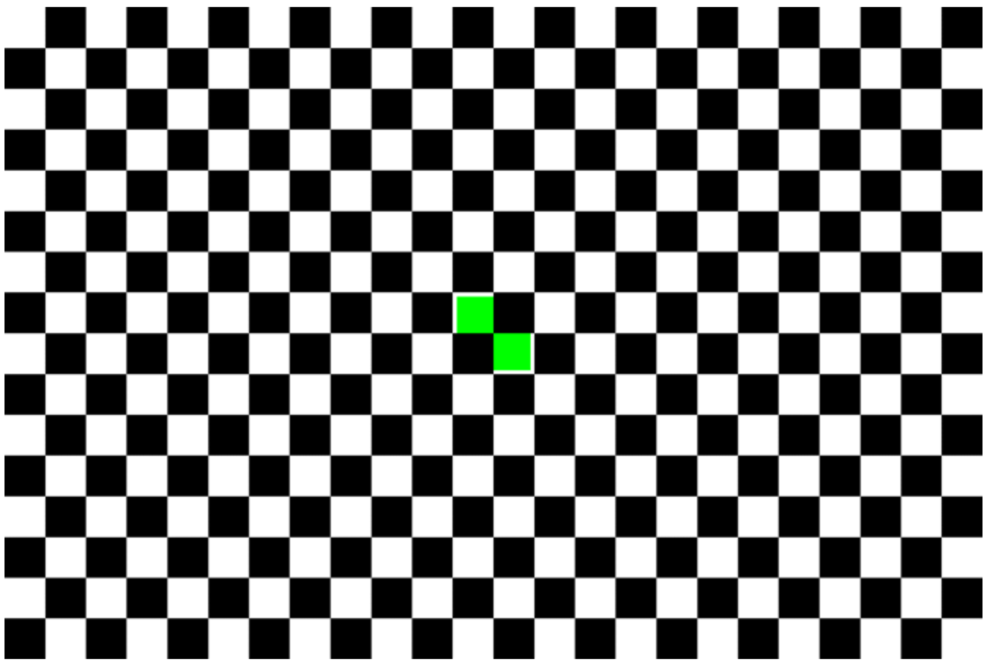

**Figure 3-1 Calibration scene diagram**

## 3.1 Construct the test chart

The test chart provides the calibration software with correspondence for lying on a known plane. This frame of reference is used to identify and associate position correspondences between the left and right images.

1. Print the calibration left and right checkerboard chart images on a quality printer.
2. Attach the images to firm surfaces, such as straight cardboard, foam board, or other rigid substrate.

   The test chart consists of 16 x 24 checkerboard squares of size 1.5 in. or 38.1 mm. The center white squares are marked in green.



## 3.2 Set up the test scene

1. Set the camera rig 15 to 30 in. from the chart ensuring that only the chart is present in the left and right camera FoVs.

   Ensure that both cameras only see the chart in their FoV (it is acceptable if they do not see the full chart). The green patches, which serve as the origin for the world coordinate system, should be positioned in the center of the camera FoVs.

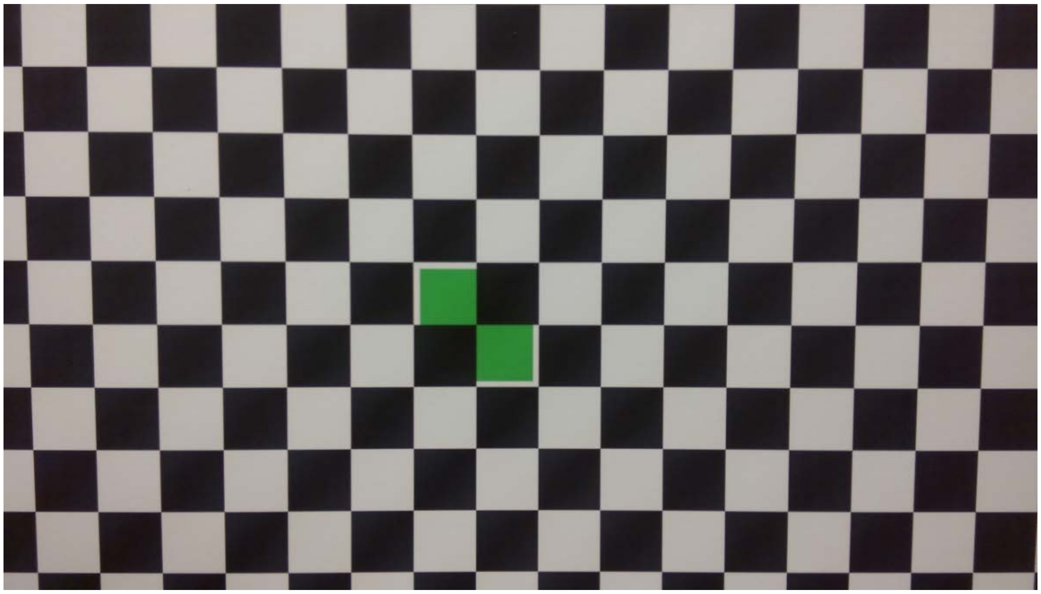
   The module should be placed equidistant from the two perpendicular planes, ideally 2 ft from each plane (horizontally) and 1.5 ft from the bottom of each plane (vertically).

2. Set position tolerances to ±2.5 in. in X, Y, and Z.

   Tolerances are sufficient to accommodate a high degree of flexibility when performing calibration as part of assembly line automation.

3. Set the baseline rotation < 5°.
4. Align the two green squares roughly in the middle of the image.

5. Record focal position and input into the calibration routine (lens can be in free focus).
6. Ensure the chart is well illuminated at +500 lux (or the mean value of the intensities at the 8 bit raw image stage around the center should be about 50 lux). Use D65 illuminant.



## 3.3 Perform calibration

Ensure that the stereo calibration is complete before this step (note the path of the stereo calibration .bin file).

1. Print and install the geometric chart as described in Section 3.1 and Section 3.2.
2. Capture the reference/aux images (color) of the geometric chart (note that the camera must be at the same focal position as that of stereo calibration).

## 3.4 Algorithm

Camera images of the calibration chart are captured and fed to the calibration program. The following automated process then occurs:

1. Detection of key points within a boundary around the center
2. Detection of coordinate system origin
3. Labeling of key points
4. Computation of key point real-world positions
5. Estimation of a scaling, rotation matrix, and yaw angle to minimize the vertical disparities between the matching key points, as well as set the disparity to the expected value at the center of the green patch
6. Alignment inter/extrapolated over the entire image grid; this surface (.bin) is to be read in and subtracted from the final depth map at resolution 720 x 1280 (in the depth map c code as released earlier)

# 4 Validation Procedure

The validation procedure describes the methodology used to verify that calibration was performed successfully. The prescribed metrics may also be used to measure the accuracy achieved by calibration and for part screening on the factory floor. Three metrics are used:

- Vertical scale ratio
- Distance from chart center
- Residual vertical disparity

The vertical scale ratio measures the degree of accuracy in the image zoom factor compensation afforded by calibration. The distance to chart center metric validates the correspondence between disparity and measured depth vs. known truth. The residual vertical disparity is a measure of the quality of the projective and geometric viewpoint matching transformation.

Table 4-1 summarizes the thresholds values for each metric. The calibration tool automatically provides these values at end time. If all values for each parameter are within their threshold guidelines, the calibration is deemed successful and the module may be accorded a passing grade.

**Table 4-1 Validation thresholds**

| Metric | Passing value |
|---|---|
| Vertical scale difference | <T1 |
| Center chart distance error | <T2 |
| Residual vertical disparity | <T3 |

## 4.1 Vertical scale ratio

The vertical scale ratio is the ratio of vertical lines in reference to the corresponding vertical lines in the auxiliary image. As depicted in Figure 4-1, the ratio at position y is

$$\overline{e}_s = \frac{1}{N}\sum_{k=1}^{N}\left|1-\frac{d_r(k)}{d_a(k)}\right| \tag{0.1}$$

and distances are:

$$d = \sqrt{(\hat{x}_a - x_r)^2 + (\hat{y}_a - y_r)^2} \tag{0.2}$$

Values close to 1 indicate proper scaling. Calibration is validated if the average ratio deviation across the image is less than T1%.

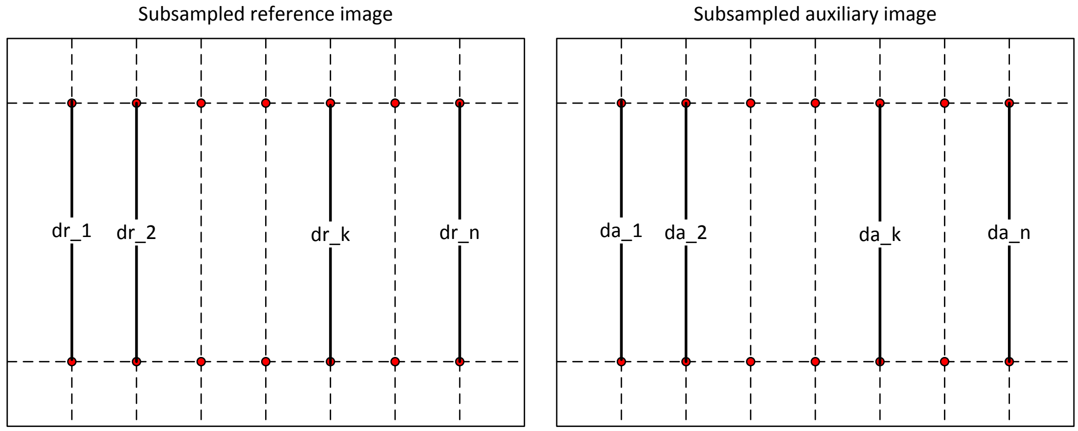



**Figure 4-1 Vertical scale ratio**

## 4.2 Center chart distance

The measured disparity at the L-chart center key point (green patch) as indicated in Figure 4-2 is compared with the known laboratory value. For baseline B in mm and normalized focal length *f*, the distance in mm is:

$$\hat{D}_0 = \frac{fB}{d_0} \qquad (0.3)$$

Where is the disparity at the center keypoint. For known distance D0 the error should not exceed T2% which is within the tolerance for chart placement errors. For example at 750 mm calibration is successful for measured values between 600 and 900 mm.

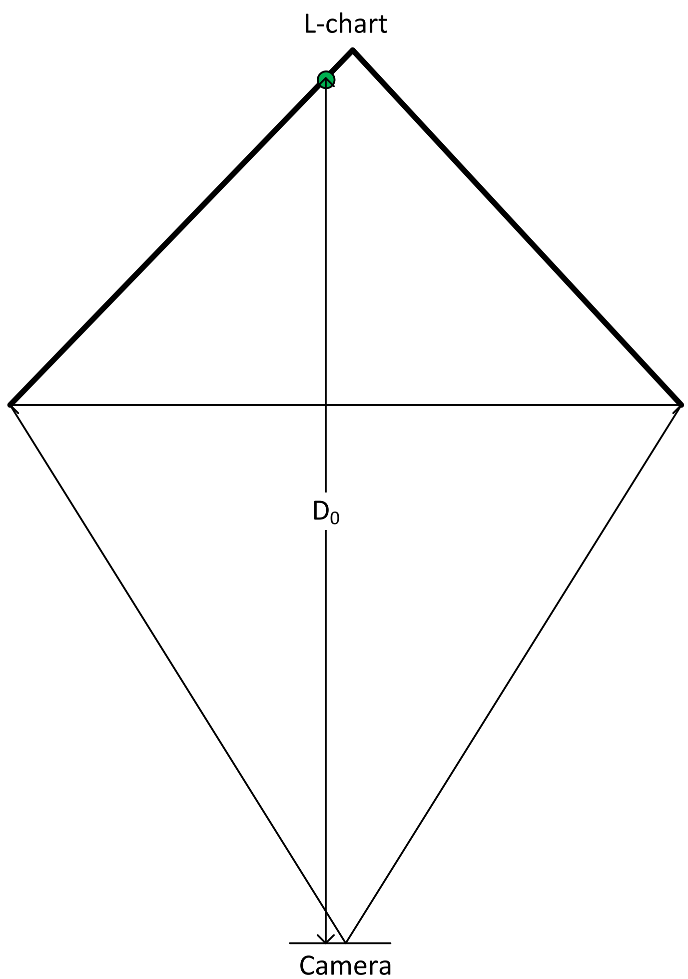



**Figure 4-2 Center chart distance**

## 4.3 Residual vertical disparity

The remaining vertical disparity after reprojecting the key points using the projective transformation is used to assess the quality of the fit. Values of this metric > T3 pixels are considered validated. The mean absolute residual vertical disparity is:

$$\overline{e}_v = \frac{1}{N}\sum_{k=1}^{N}\left|\hat{y}_a(k) - y_r(k)\right| \tag{0.4}$$

Where $\hat{y}_a(k)$ is the projected vertical position of the kth key point. The geometry of this metric is illustrated in Figure 4-3.

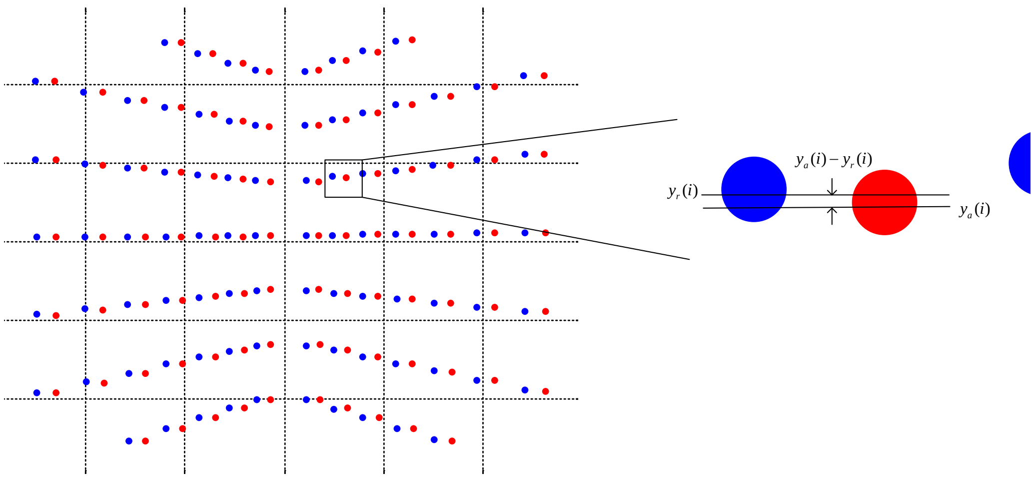



**Figure 4-3 Residual vertical disparity**