BS ISO 17850:2015

BSI Standards Publication

Photography — Digital cameras — Geometric distortion (GD) measurements

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National foreword

This British Standard is the UK implementation of ISO 17850:2015.

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Photography — Digital cameras — Geometric distortion (GD) measurements

Photographie — Caméras numériques — Mesurages de distorsion géométrique (DG)

Reference number
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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

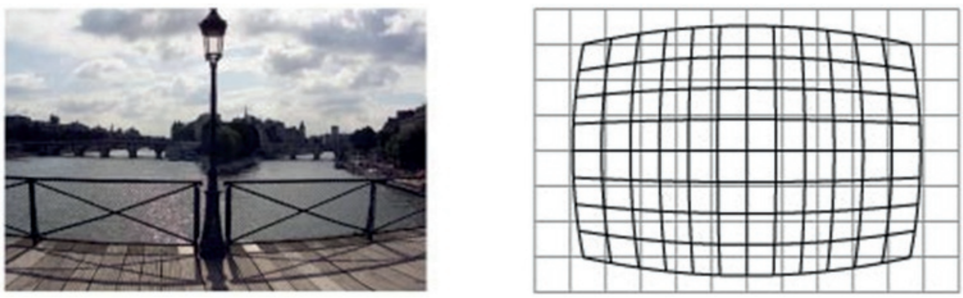
The committee responsible for this document is ISO/TC 42, *Photography*.

Introduction

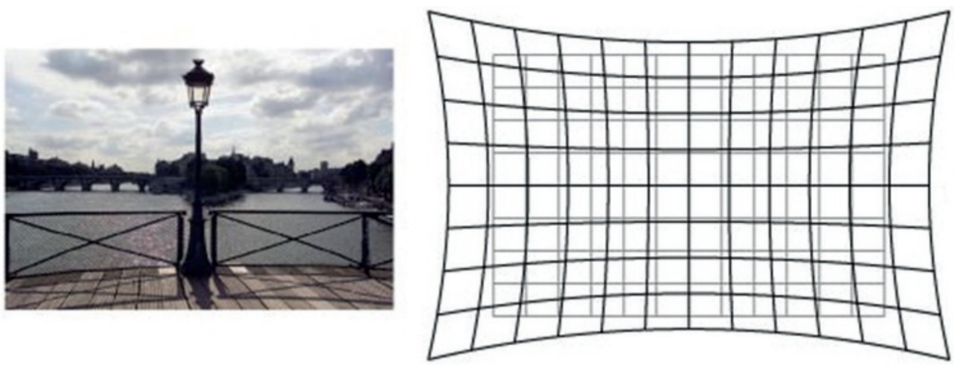
A digital still camera (DSC) typically employs a taking lens that is a rotationally symmetric optical system. Generally, the function of rotationally symmetric optical systems is to form an image that is geometrically similar to the object except some particular systems, such as fish-eye lenses and eyepieces, where this condition is deliberately not maintained. This function is accomplished ideally according to the geometry of perspective projection. Departures from the ideal image geometry are called distortion. The distortion is a position-dependent quantity which generally has a vectorial character. In a given image plane (which may also lie at infinity), this vector, representing the difference between theoretical and real image position, has a radial and a tangential component. In optical systems, the tangential component is basically conditioned by imperfect rotational symmetry. The systems manufactured in accordance with the present state of the art have a negligible tangential distortion.

Geometric distortion (GD) of DSCs is mainly caused by the variation of magnification in the image field of the camera lens. The most well-known effect of distortion is that straight lines appear curved. Generally speaking, the proportions between objects are not preserved in a distorted image, which can be very unpleasant for some natural scenes, architecture, or portraits. Distortion is fully described by a 2D map, giving the displacement from a point in an ideal undistorted image to the point in the actual distorted image. The image centre is usually assumed to be undistorted; the magnification factor at this position actually defines the focal distance.

Different types of distortion are usually characterized by how the magnification radially varies within the image field. Barrel and pincushion are the most usual types of distortion for which magnification is respectively monotonously decreasing and monotonously increasing when moving along from the centre to the border of the image field. Other types which cannot be categorized into above two types are usually called wave distortion.



a) Barrel (or negative) distortion



b) Pincushion (or positive) distortion

NOTE The magnification is decreasing for barrel distortion and increasing for pincushion.

Figure 1 — Two main types of distortions

ISO 9039 defines methods to measure a lens that is separated from a camera. On the other hand, this International Standard was developed and defines methods to measure the total image distortion of a camera including a lens and signal processing.

This International Standard is based on both Reference [3] prepared by the Camera Phone Image Quality (CPIQ) group within the International Imaging Industry Association (I3A) and Reference [4] prepared by Camera and Imaging Products Association (CIPA).

Photography — Digital cameras — Geometric distortion (GD) measurements

1 Scope

This International Standard specifies a protocol to measure geometric distortion of a digital camera. It is applicable to the measurement of digital cameras including camera phones.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14524, *Photography — Electronic still-picture cameras — Methods for measuring opto-electronic conversion functions (OECFs)*.

IEC 61146-1, *Video cameras (PAL/SECAM/NTSC) — Methods of measurement — Part 1: Non-broadcast single-sensor cameras*

EBU Tech3249, *Measurement and analysis of the performance of film and television camera lenses*

3 Terms and definitions

3.1
geometric distortion
GD
<of DSC> displacement from the ideal shape of a subject (lying on a plane parallel to the image plane) in the recorded image

Note 1 to entry: Geometric distortion basically derives from variation of lateral magnification in the image field of a camera lens and results in straight lines being rendered as curves. There are other factors to induce geometric distortion, for example, rotational asymmetricity of a camera lens or position shift processing in a camera imaging process.

3.2
image height

3.2.1
image height
<of DSC> distance between an image point and the centre of the image area or its relative expression which is the value normalized by one half of the diagonal of the image area

Note 1 to entry: This is an extension of the definition in ISO 9039 which is a measurement for optical systems.

3.2.2
actual image height
<of DSC> image height of an actual recorded image point in the recorded image area

Note 1 to entry: "Actual recorded image point" corresponds to "observed image point" in ISO 9039.

Note 2 to entry: "Image height" in ISO 9039 basically means "actual image height" but the usage is sometimes confusing.

Note 3 to entry: The adjective "actual" is used in similar meaning, "actual point" and "actual position", for example.

3.2.3
ideal image height
<of DSC> image height of a theoretical corresponding point in the recorded image area, assuming a geometrically undistorted image formation

Note 1 to entry: This is an extension of the definition in ISO 9039 which is a measurement for optical systems.

Note 2 to entry: The adjective "ideal" is used in similar meaning, "ideal point" and "ideal position", for example.

3.3
image quality
impression of the overall merit or excellence of an image, as perceived by an observer neither associated with the act of photography nor closely involved with the subject matter depicted

Note 1 to entry: The purpose of defining image quality in terms of third-party (uninvolved) observers is to eliminate sources of variability that arise from more idiosyncratic aspects of image perception and pertain to attributes outside the control of imaging system designers.

3.4
noise
unwanted variations in the response of an imaging system

3.5
resolution
measure of the ability of a digital image capture system or a component of a digital image capture system to distinguish picture detail

3.6
TV distortion
line distortion measured by conventional method of TV field defined in IEC 61146-1 (24 Geometric distortions) or EBU Tech3249 (2.11. Picture height distortion)

4 Measurement methods

4.1 General

As defined in 3.1, geometric distortion basically derives from the variation of magnification in the image field. If this phenomenon occurs in an image, it means that a regular structure in an object does not appear to be regular in the image taken with the camera. There are two ways defined in this International Standard to quantify the amount of geometric distortion in an image. Both have their pros and cons.

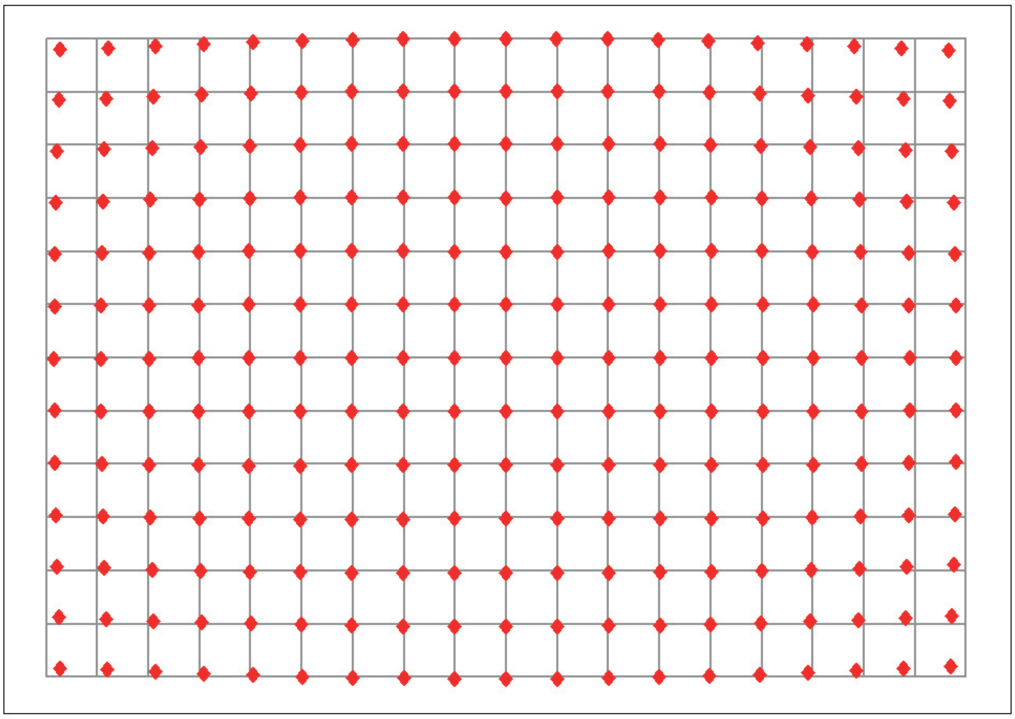


Figure 2 — Regular grid (solid lines) in the scene is distorted and the red diamonds mark the position of the intersections in the image produced by the camera

4.2 Local geometric distortion

Geometric distortion can be measured on a white chart containing black dots at the position of a regular grid or on a grid chart formed by straight lines. The local geometric distortion method analyses the grid formed by the test chart in the centre of the image and calculates the ideal positions of the structure based on the measured distances. After that, it analyses the rest of the image and locates all actual positions of the grid. The distance between the ideal position and the actual position is the geometric distortion at that location in the image.

The distance between the two positions can be plotted as a function over the distance to the image centre. This curve indicates the variation of image magnification versus the actual image height, which is an expression of the geometric distortion called local geometric distortion. In order to limit the result to a single value that might get reported with the cameras specifications, the maximum (peak to peak) value shall be reported.

The manufacturing tolerances, such as lens tilt or off-centring, can result in a non-rotationally symmetric GD behaviour. If the system is not rotationally symmetric, it can lead to increased distortion levels in the image corners. In this case, the measured geometric distortion is correct for the camera under test but might not represent a standard camera of the tested model.

4.3 Line geometric distortion

The principle of line geometric distortion is to measure the bending of a straight horizontal or vertical line at defined distances from the image centre and to report the maximum of the measured bending. This bending is preferably measured on a chart with a regular line grid.

Line geometric distortion is the direct measured result of this method and it is easy to understand intuitively for consumers. However, it can also be interpreted from the measured result using the local geometric distortion method.

NOTE The line geometric distortion has a long history and it has been used in the video technology for decades. The reason is that it was easy to determine this value with standard measurement equipment used in the analogue video world. The fundamental concept of this method was first standardized by the IEC in IEC 61146–1 in 1994.

5 Requirements

5.1 Apparatus and hardware

The following hardware is necessary to control and report the test conditions:

— dot target or a grid chart;

— two light sources;

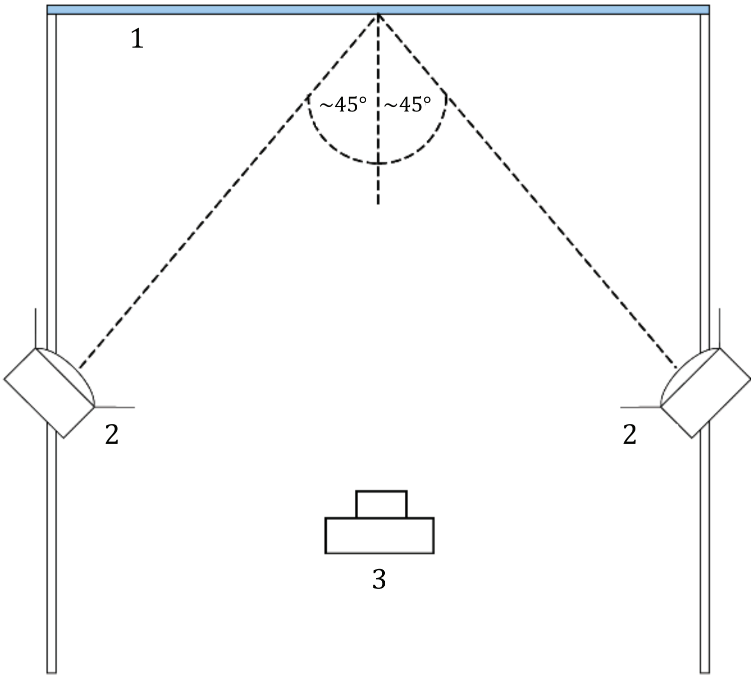
— device to measure the chart height captured in the image;

— mirror (for camera alignment with the target).

5.2 Lighting

Lighting uniformity is recommended to ease the processing of the target but does not influence the phenomenon of distortion. The light sources should be adjusted such that illumination is uniform on the target at ±10 %. Light sources should be baffled to prevent the direct illumination of the camera. The light sources should be located so as to minimize the occurrence of specular reflections off the surface of the target when viewed by the camera under test.

The illumination should be set so that the auto-exposure of the camera gives a suitable result. More precisely, the image should not be clipped in either bright or dark parts of the target. The camera should be positioned so that it casts no shadow on the chart.



Key

1 test target

2 illumination

3 camera

Figure 3 — Lighting system

5.3 Dot chart

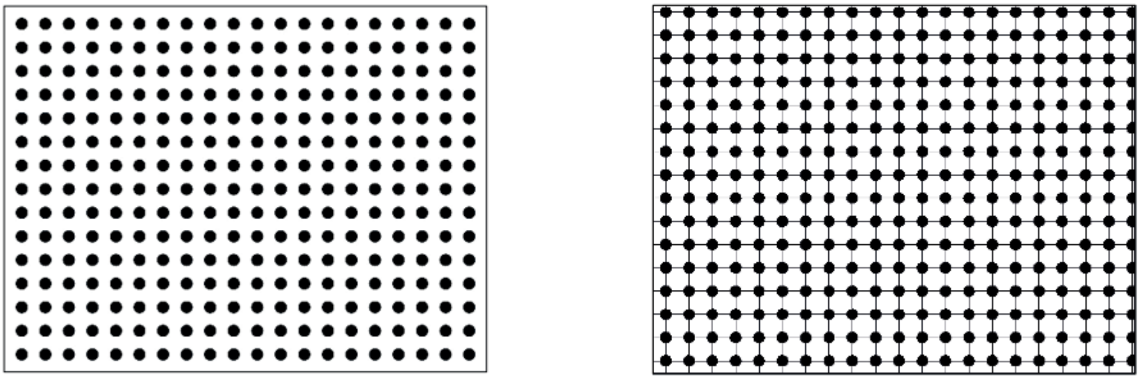
5.3.1 Design and characteristics

The test chart contains black circular dots placed on a perfectly regular square grid on a uniform white background.

The dot centres may be connected by straight black lines with a thickness of approximately 1/10 of the dot diameter as shown in Figure 4 b). That way, it does not affect the dot detection but helps to better align the camera to the chart for example, by eliminating rotation between the chart and camera's image sensor axes. The straight black lines are especially useful if the mirror method described in 5.5.4 is not possible or available.

The chart can be either a reflective test chart, which is front illuminated, or a transparency test chart, which is rear illuminated. The chart contrast level should at least be 40:1 and not be higher than 10 000:1.

The size and the number of dots should depend on the resolution of the camera and the shooting distance. The chart shall be shot compliant with the condition specified in 5.5.3.



a) Simple dot chart **b) Dot chart with connecting lines**

Figure 4 — Dot chart

5.3.2 Requirement for the chart planarity

Non-planarity can be caused by bending of a chart.

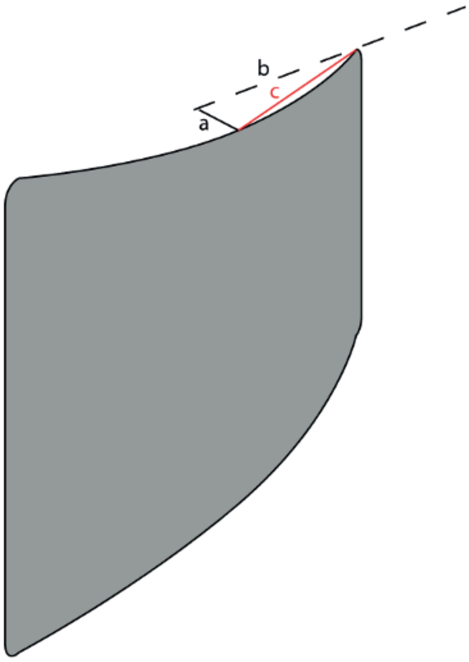
Requirement for the chart planarity is as follows.

Surface deviation which is a height or depth from the reference plane [indicated as bending “a” in Figure 5 a)] shall be less than 1,5 % of the width of the chart.

The required accuracy for a specific measurement sets the requirement for the chart planarity as follows.

For small bending, c is equal to half the width of the chart to which all numbers are normalized. If bending a occurs in a chart, the effective chart width seen by the camera is b. The difference between c and b causes the deviation in % measured due to the bending of the chart and calculated by (1-b/c) × 100.

The standard requirement for local geometric distortion measurement should be a maximum error of 0,045 % due to deviation in planarity of the chart. This equals a maximum deviation in planarity of 3 %. And 3 % of half the width equals to 1,5 % of the full width of the chart.



a) Explanation of the parameters

Deviation in %	a/c	b/c = cos ($\sin^{-1}$ a/c)	Deviation of measured distortion in %
0,5	0,005	0,999 987	0,001 3
1	0,01	0,999 950	0,005 0
2	0,02	0,999 800	0,020 0
3	0,03	0,999 550	0,045 0
4	0,04	0,999 200	0,080 0
5	0,05	0,998 749	0,125 1
6	0,06	0,998 198	0,180 2
8	0,08	0,996 795	0,320 5
9	0,09	0,995 942	0,405 8
10	0,1	0,994 987	0,501 3

b) Table of numerical relation

Figure 5 — Explanation for the chart planarity and its effect on measured value

5.4 Grid chart

5.4.1 Design and characteristics

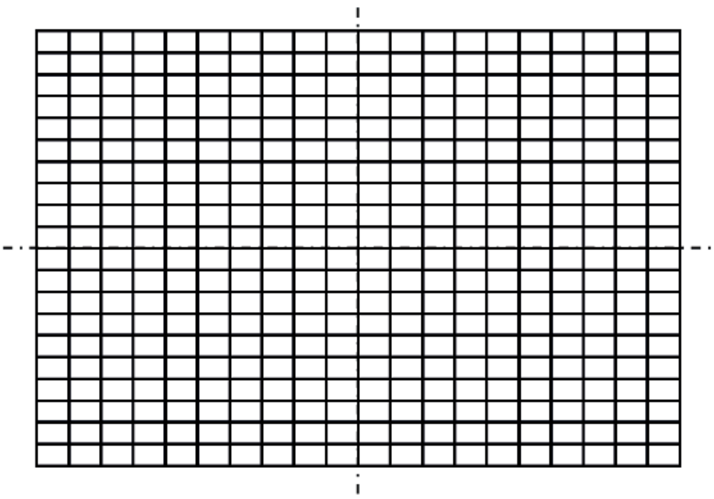


Figure 6 — Line grid pattern chart

The line grid pattern chart shown in Figure 6 is an example of a test chart for line distortion. The horizontal and vertical lines of the grid shall be located between reference lines at no less than 1,0, 0,9, 0,8, 0,7, and 0,6 times the distance between the pairs of reference lines with the tolerance of ±2 %. The pairs of reference lines are the sides of the outermost rectangle.

The chart shall be shot compliant with the condition specified in 5.5.3.

All other aspects regarding size and contrast shall be as described for the dot chart in 5.3.

5.5 Image/camera settings

5.5.1 General

Set the camera at minimal gain to minimize noise (if possible). All special colour modes or tone mode should be deactivated. Quality factors, if available, should be set to their maximum.

5.5.2 Basic settings and influencing factors

The magnification is an important factor in measuring the distortion. The standard shooting distance should be 30 times the focal length equivalent to 35 mm film camera. This means that a chart height of 720 mm fills the complete image. If the chart height differs more than 30 % from this requirement, the chart height captured in the image shall be reported together with the results.

The camera shall be accurately focused on the chart.

Since distortion depends on the wavelength, it also depends on the illuminant and the spectral responses of the sensor. Only the distortion on the green channel shall be reported.

5.5.3 Specific test procedures

5.5.3.1 Local geometric distortion

The chart shall be shot so that

— chart shall fill the field of view,

— number of dots should be no less than 15 dots in height and the related number of dots depending on the image aspect ratio (for 4:3, 20×15 dots; for 3:2, 23×15) to form a regular grid,

— diameter of each dot should be no less than 10 pixels, and

— in case of reporting the single value as ISO local geometric distortion (see 7.2), and when using the method of measuring actual dots, the corner 4 dots in the output image shall be positioned so that the centre of each dot is on a vertex of the frame of the output image with the tolerance of 0 %, −2 % (i.e. the centre of each dot is positioned from 98 % to 100 % at the actual image height).

5.5.3.2 Line geometric distortion

The chart shall be shot so that each reference line pair inscribes the frame of the output image with the tolerance of 0 %, −2 % (i.e. the contact points of the reference line pair and the frame are positioned from 98 % to 100 % at the picture height or at the picture width).

5.5.4 Positioning of the camera

The chart shall be orthogonal to the optical axis. The alignment can be performed by using a mirror set up on the target plane (i.e. parallel to the target plane), as shown in Figure 7.

Pan, tilt, and laterally displace the camera position to the left, right, up, and down until the centre point of the taking lens in the viewfinder image is positioned at the image centre.

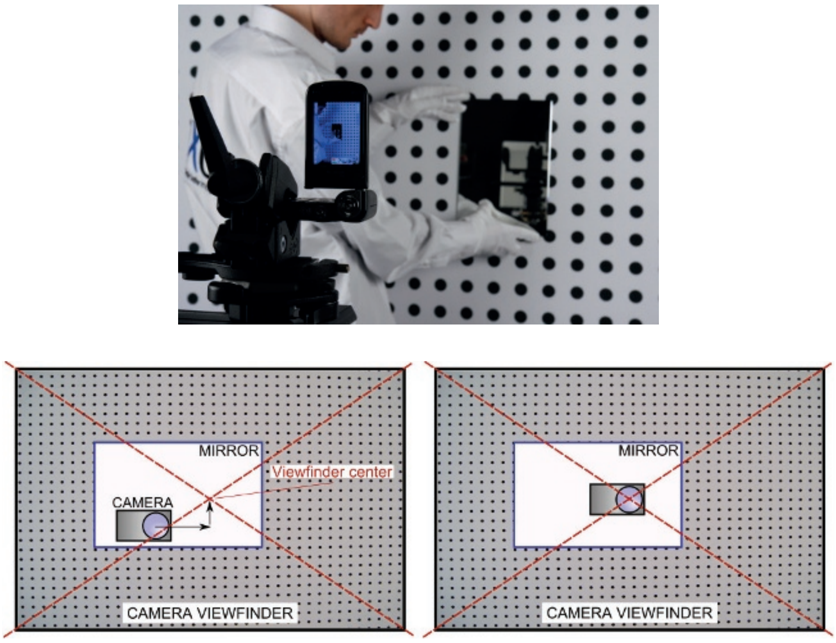


Figure 7 — Alignment of the camera with the target plane using a mirror

If the mirror is not available or the positioning method is not applicable, a manual alignment using the straight lines in the chart shall be performed so that the intersection of the central horizontal and vertical lines of the chart is in the centre of the image. For each horizontal/vertical line, the lines shall be oriented "parallel" to the horizontal/vertical image borders meaning that the line shall be at the same image height for the same distances from the vertical/horizontal centre of the image.

5.5.5 Exposure, white balance, and focus

The exposure shall be set by automatic exposure or set to an exposure level such that the uniform white background becomes 110 to 160 (8-bit digital).

For a colour camera, the white balance shall be in a variable white balance mode or an automatic white balance mode. The camera white balance should be adjusted, if possible, to provide proper white balance for the illumination light source as specified in ISO 14524.

The focusing shall be adjusted in focus by a proper way, for example, a manual-focusing mode or an auto-focusing mode.

6 Determination of geometric distortion

6.1 Local geometric distortion

6.1.1 Numerical definition

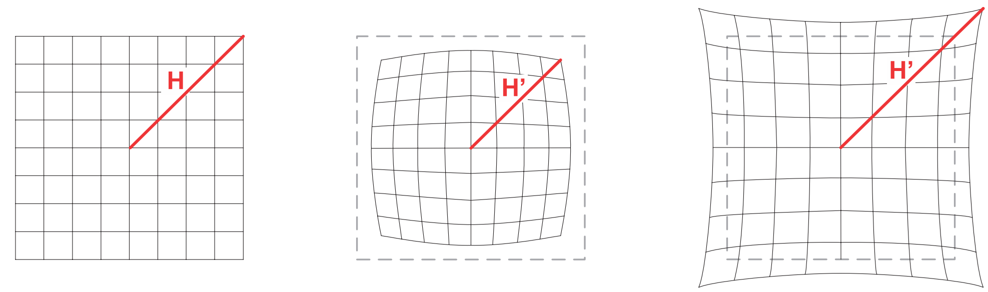
The local geometric distortion D_{local} (in %) is defined as given in Formula (1):

$$D_{local} = (h' - h'_0)/h'_0 \times 100\,\% \qquad (1)$$

where

h' is the distance to the actual dot position from the centre of the image (i.e. actual image height);

h'_0 is the distance to the ideal dot position from the centre of the image (i.e. ideal image height).



a) Undistorted grid

b) Barrel distortion (negative)

c) Pincushion distortion (positive)

Figure 8 — Common types of geometric distortion

The image is assumed to have no distortion at the centre. Therefore, h'_0 can be estimated from the position of a few dots at the centre of the image. Each detected dot provides a value of local geometric distortion, D_{local}. If the distortion is rotationally perfectly symmetrical, D_{local} is then plotted as a single-valued function of the distance to the image centre.

6.1.2 Outline of the practical algorithm

The following are the processing steps of the algorithm.

— Extract the dots.

— Determine precisely the position of the centre of the dots.

— Compare the position of the dots with the ideal position.

— Calculate the average grid spacing vector, based on the grid locations adjacent to the central pixel. The use of a vector to represent the grid spacing is necessary to provide robustness against rotation in the grid (a practical issue) (see Figure 9).

— The centre of the image is considered as the (0,0) grid location and all ideal grid positions are calculated on a grid whose positions are integer values (it is not necessary but natural for usual case).

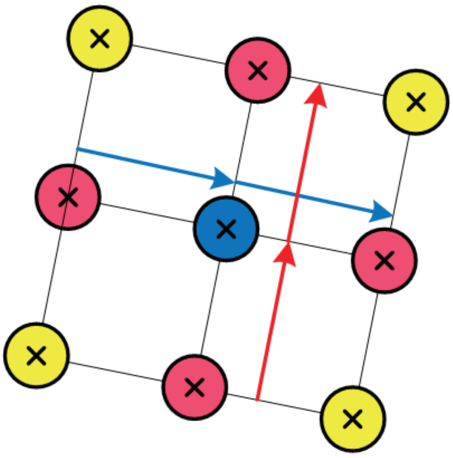
— The geometric distortion for a grid position is the difference between the radial distance of the actual grid position (h’) and radial distance to the ideal grid position (h'_0), divided by the ideal grid position (h'_0).

  If $h' < h'_0$, then distortion is negative. If $h' > h'_0$, then distortion is positive

— The above geometric distortion value is calculated for each valid grid position. This provides a 2D data set for the lens distortion.

— The geometric distortion is plotted as a function of actual radial distance from the centre of the image (i.e. actual image height: h’) for each grid point.

An algorithm for the detection of dots is provided in Annex B. An algorithm for sorting the grid from the dots positions is provided in Annex D.



NOTE The distortion reference spacing is used to generate an “averaged” vector.

Figure 9 — Distortion reference spacing

6.2 Line geometric distortion

6.2.1 Horizontal line distortion

Let the maximum value of the height of the output image of the line grid pattern of each picture height be Ai and the minimum value be Bi, and the number of pixels of the short side of the frame of the output image be V, then horizontal line distortion is numerically defined as follows (see Figure 10).

When the vertical line Ai is located closer to the vertical line through the image centre than Bi, use Formula (2):

$$\text{Dhi} = \left(\text{Bi} - \text{Ai}\right) / 2\text{V} \times 100\,\% \qquad (2)$$

Otherwise, use Formula (3):

$$\text{Dhi} = \left(\text{Ai} - \text{Bi}\right) / 2\text{V} \times 100\,\% \qquad (3)$$

where

i is a suffix representing each picture height;

Ai, Bi, and V shall be represented by the number of pixels of the output image.

NOTE The height means the vertical distance of the regarded line pair of the line grid pattern.

6.2.2 Vertical line distortion

Let the maximum value of the width of the output image of the line grid pattern of each picture width be αi and the minimum value be βi, and the number of pixels of the short side of the frame of the output image be V, then vertical line distortion is numerically defined as follows (see Figure 11).

When the horizontal line αi is located closer to the horizontal line through the image centre than βi, use Formula (4):

$$\text{Dvi} = \left(\beta\text{i} - \alpha\text{i}\right) / 2\text{V} \times 100\,\% \qquad (4)$$

Otherwise, use Formula (5):

$$\text{Dvi} = \left(\alpha\text{i} - \beta\text{i}\right) / 2\text{V} \times 100\,\% \qquad (5)$$

Where

i is a suffix representing each picture width;

αi, βi, and V shall be represented by the number of pixels of the output image.

NOTE The width means the horizontal distance of the regarded line pair of the line grid pattern.

6.2.3 Total line distortion

— Line geometric distortion $D_{line}i$ in each size is defined as Formula (6):

$$D_{line}i = \begin{cases} \left(\text{Dhi}/\left|\text{Dhi}\right|\right) \times \sqrt{\text{Dhi}^2 + \text{Dhi}^2}\ \% & \left(\text{in case: } \left|\text{Dhi}\right| > \left|\text{Dvi}\right|\right) \\ \left(\text{Dvi}/\left|\text{Dvi}\right|\right) \times \sqrt{\text{Dhi}^2 + \text{Dhi}^2}\ \% & \left(\text{in case: } \left|\text{Dhi}\right| \leq \left|\text{Dvi}\right|\right) \end{cases} \qquad (6)$$

— The expression for $D_{line}i$ can be rewritten as Formula (7), where the sign shall either be Dhi or Dvi, whichever has the larger absolute value:

$$\left|D_{line}i\right| = \sqrt{\text{Dhi}^2 + \text{Dvi}^2}\ \% \qquad (7)$$

— Total line geometric distortion, D_{line}, is defined as the maximum $D_{line}i$ value for i in absolute value.

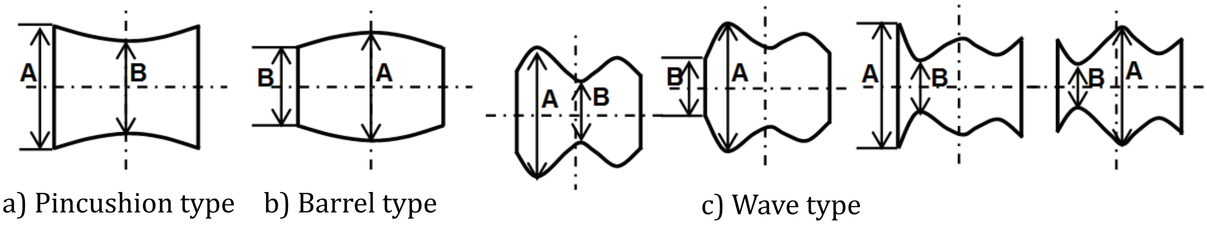


Figure 10 — Schematic drawings for measuring the horizontal line distortion

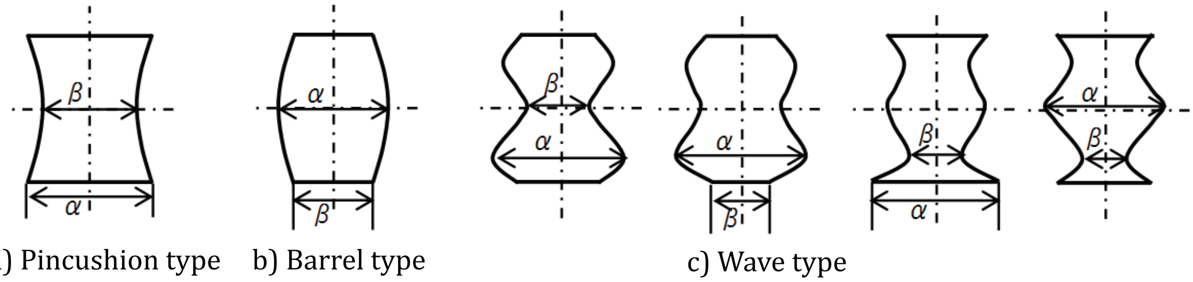


Figure 11 — Schematic drawings for measuring the vertical line distortion

7 Presentation of results

7.1 General

Two metrics of geometric distortion are defined in this International Standard and it is required to note which distortion is reported, "local geometric distortion" or "line geometric distortion".

7.2 Local geometric distortion

The presentation of local geometric distortion should be in the form of curves or tables of "D_{local} versus the actual image height (h')".

If the actual image height is not indicated in relative expression, the absolute value of the maximum image height in the same unit (e.g. in millimetres or in pixels) shall be reported beside.

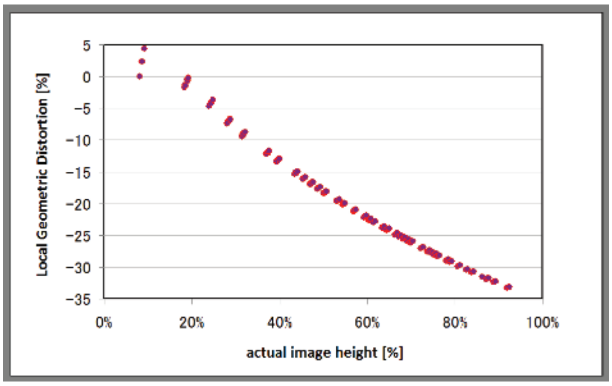
NOTE This value understandably corresponds to 100 % in relative expression then equals to one half of the diagonal of the image area.

Two examples of distortion profiles are shown in Figure 12, for both barrel and pincushion distortion.

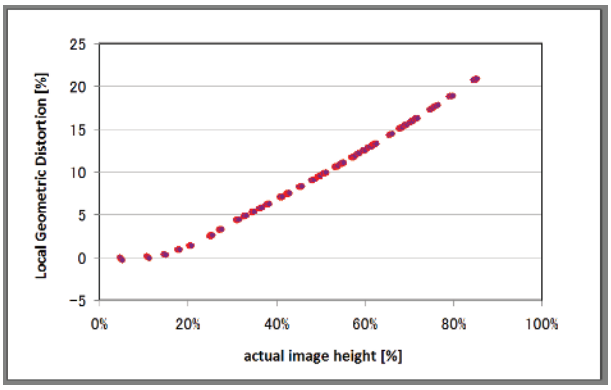
A single value may be reported as ISO local geometric distortion when it is the largest absolute value of an average of the distortion value at the same actual image height in the image field. If the largest local geometric distortion appears to be at the maximum actual image height, the average distortion value shall be determined by one of the following.

— Using an appropriate polynomial fitting of the distortion over actual image height and the value appearing at the maximum actual image height shall be reported, if the profile of distortion (i.e. the shape of the curve) is known and the accuracy of the fitting is expected less than or equal to 2 %.

— Measuring the dots at the maximum actual image height (i.e. the corner dots) positioned in accordance with 5.5.3, the actual measured values shall be used.



a) Example of barrel



b) Example of pincushion

Figure 12 — Examples of the presentation of local geometric distortion in the form of curves

7.3 Line geometric distortion

The presentation of line geometric distortion shall be a D_{line} value.

EXAMPLE Examples are listed below.

— ISO line geometric distortion +2,5 %

— Geometric distortion -2,0 % (ISO line geometric distortion).

Annex A
(informative)

Illustrative example and validation

There are generated simulated dot chart images with known levels of geometric distortion applied.

— 22 images in total

— Negative and positive geometric distortions in the 0 % - 16 % range

— 10 % negative and 10 % positive wave geometric distortion

— Image size 1 600 × 1 200 (image height = 1 000 pixels)

Simulated Geometric Distortion **Measured Geometric Distortion**

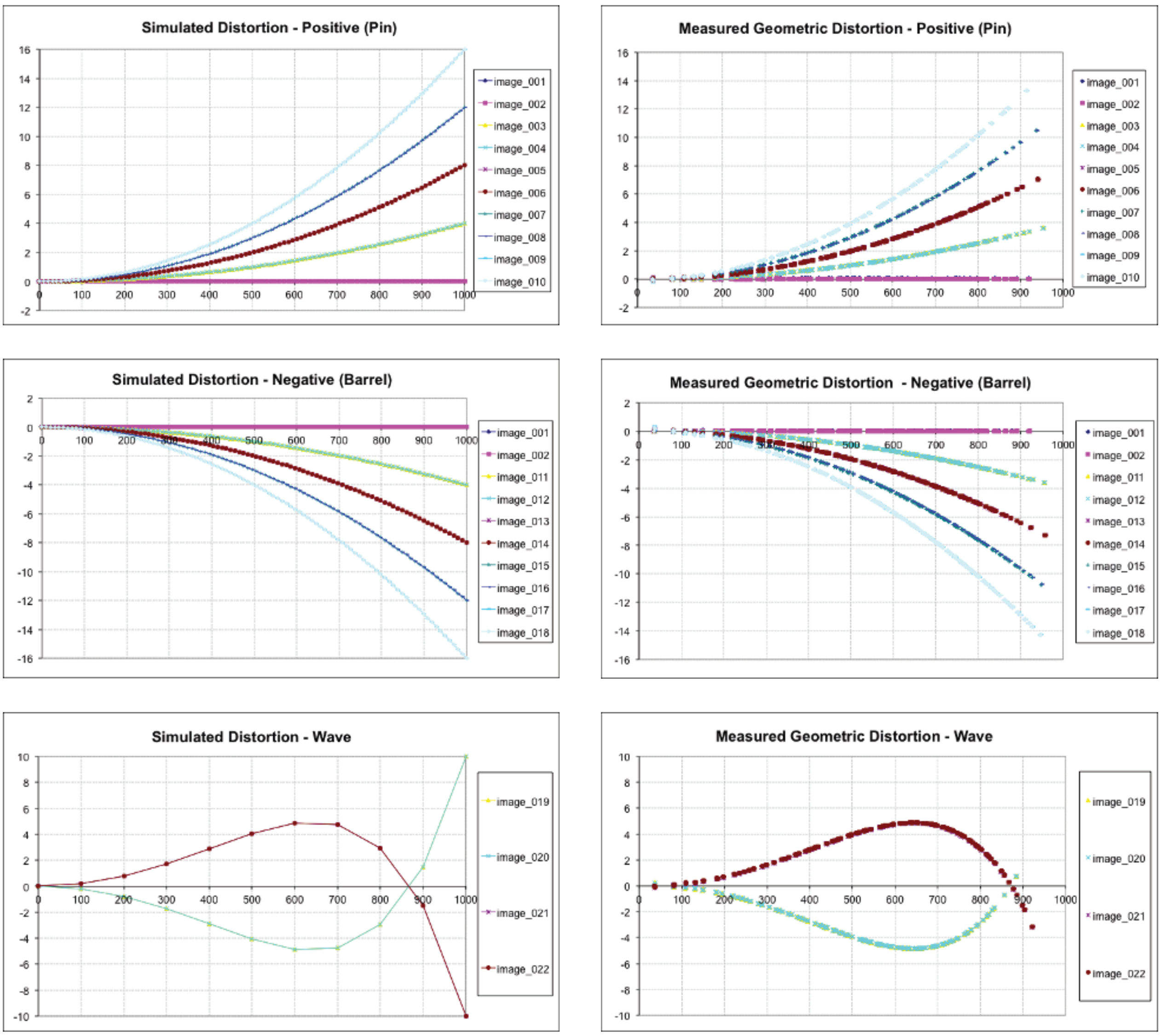


Figure A.1 — Reference images: simulated vs. measured geometric distortion values (X-Axis in per mille of image diagonal and Y-Axis in %)

For all graphs, the x-axis is actual image height in per mille, i.e. the position in the image field (1 000 is 100 % of the diagonal), and the y-axis represents the amount of distortion in %.

There is good correlation between the level and shape of the simulated distortion and the measured geometric distortion in the region of the image height that the measured points exist. However, the maximum image height for measured values depends on the position of the farthest dot from the centre. Care needs to be taken about the effects on actual measurements.

Annex B
(informative)

Extracting the dots from the target

B.1 Overview

This International Standard only uses the green channel to determine the geometric distortion. Because there is difference of the dot positions for the three colour channels, which is evaluated as lateral chromatic displacement.

NOTE This Annex describes about not only single channel but three colour channels. Readers are able to use any partial information of this Annex as necessary.

The dot-finding method consists of two distinct phases.

The first phase uses the Green channel information to determine the region of interest for each dot. Separating the dot finding into two steps allows each dot to be pre-processed individually prior to determining the centre of mass. The following Clause describes the main ingredients of the algorithms and then gives the related MATLAB code lines. The complete code is available from the following URL:

www.iso.org/17850

The following are several issues that a robust centre-finding method should manage:

— lens distortion (up to 15 %);

— lens shading (radial roll off in image intensity) (up to 40 %);

— ±10 % lighting illumination non-uniformity;

— different intensities of the red, green, and blue channels;

— noise.

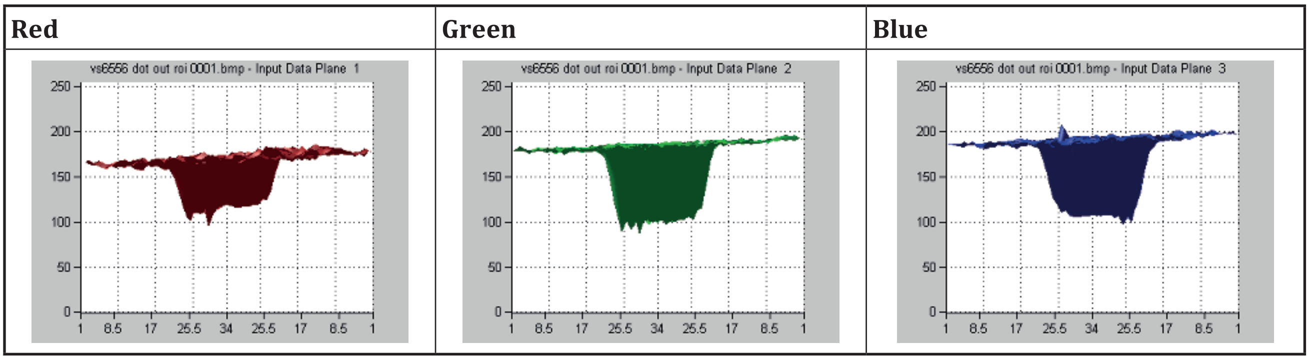


Figure B.1 — What a dot really looks like

The simplest approach to finding the dots is to binarize the image using an appropriately chosen threshold value. The presence of lens shading and colour channel imbalance complicates matters.

As Figure B.1 shows, the dots will have a variable depth and a variable tilt depending on where on the lens shading profile the dot is. The presence of diffraction-based infrared filters in mobile phone camera modules results in the uncorrected red channel data having faster colour shading roll off than the other colour channels.

Management of the variable dot tilt and depths leads to an approach that individually pre-processes each dot on each colour plane to correct the tilts and normalize the depths.

B.2 Finding dot regions of interest

B.2.1 Binarization threshold

As the green channel is typically the channel with the lowest noise and the highest resolution, it is used to find the region of interest (ROI) of each dot. To find the region of interest for each dot, the image is binarized.

The effects of lens shading mean that the threshold for binarization cannot be based on the whole image. The solution to this is to calculate the threshold for an 8 × 8 grid of region of interests, each 1/8 of the image in size.

The threshold used for the binarization is then the minimum of the thresholds for all of the regions of interest.

This implementation uses Otsu's method (MATLAB graythresh function) to calculate the thresholds.

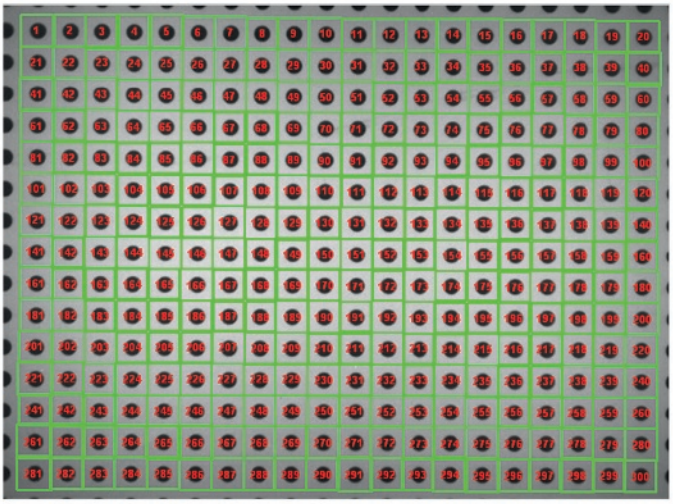


Figure B.2 — Region of interest for each dot

B.2.2 Finding ROIs

The above threshold is used to binarize the green colour plane.

```
bw = im2bw(double(input)/double(max_code), threshold);
```

The max code is used to normalize the input data to ensure that both 8-bit and 10-bit are correctly handled by MATLAB's binarization function.

Invert to make black dots white for the subsequent processing.

```
bw = ~bw;
```


Use MATLAB’s image processing functions to fill in any small gaps.

```
se = strel(‘disk’,2);
bw = imclose(bw,se);
```

Then fill any holes, so that region props can be used to estimate the area enclosed by each of the boundaries.

```
bw = imfill(bw,’holes’);
```

The next step is to find the area, centroid, and bounding box for each object (dot) in the binarized green plane data.

```
[B,L] = bwboundaries(bw,’noholes’);
stats = regionprops(L,’Area’,’Centroid’,’BoundingBox’);
```

The three sets of checks below use the above information to filter out any unwanted objects.

The first check is on the roundness of the object. The ratio of the bounding box area to the area of the shape is used as a measure of roundness. For a circle, the value should ideally be 4/3,14 = 1,27. The range of acceptance is 1,05 to 2,00. This wide range is necessary as geometric distortion will convert the dots in the chart into ellipses.

```
dot_check(area_ratio < 1.05) = 0;
dot_check(area_ratio > 2.00) = 0;
```

Typically, there should be about 300 dots of similar diameter in the image; thus, the median diameter of all the objects will represent the desired dot size. The assumption is that the 300 dots will be the most common objects in the binarized image.

For the median calculation, only use dot sizes greater than the specified minimum allowed dot size (default: 5 pixels).

```
dotSizeList = dot_size(dot_check > 0);
dotSizeList = sort(dotSizeList(dotSizeList > MinDotSize));
```

Find the median index of the list of dot sizes, clipping if necessary.

```
dot_count = length(dotSizeList);
median_index = uint16(dot_count / 2);
if median_index < 1, median_index = 1; end
```

Find the median dot size value.

```
if dot_count > 0
       MedianDotDiameter = dotSizeList(median_index);
else
       MedianDotDiameter = MinDotSize;
end
if MedianDotDiameter < MinDotSize
       Config.MedianDotDiameter = MinDotSize;
end
```

Build the dot size check limits on the median dot size value.

```
MinDotDiameter = MedianDotDiameter / 2;
if MinDotDiameter < MinDotSize
       MinDotDiameter = MinDotSize
end
MaxDotDiameter = MedianDotDiameter * 2;
```

The diameter check looks to see if the diameter of an object is within −50 % and +100 % of the median.

```
dot_check(dot_size < MinDotDiameter) = 0;
dot_check(dot_size > MaxDotDiameter) = 0;
```

For each object, a region of interest that is 1,9 times the width and 1,9 times the height of the object is generated.

The final check is to reject any region of interest that touches the edge of the image.

```
dot_check(roi_x_ll < = 1) = 0;
dot_check(roi_y_ll < = 1) = 0;
dot_check(roi_x_ur > = image_width) = 0;
dot_check(roi_y_ur > = image_height) = 0;
```

Only objects that pass all of the above checks are considered to be valid dots.

B.2.3 Dot region of interest processing

The shape/profile of the dot is dependent on the following factors:

— noise;

— lens shading;

— channel sharpness;

— spatial resolution;

— matrix values.

For each ROI on each colour plane, the ROI data are processed as follows.

B.2.4 Dot pre-processing

The first step is to generate two masks, one for the background and a second for the dot. These masks are used to remove the unwanted regions of the ROI.

The Otsu's gray threshold function is used to determine the binarization threshold.

```
threshold = graythresh(input(:,:,plane));
```

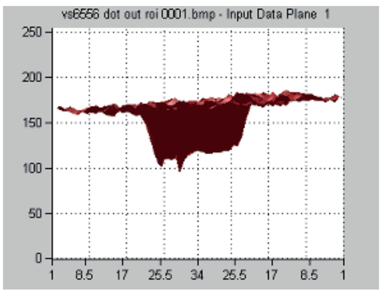
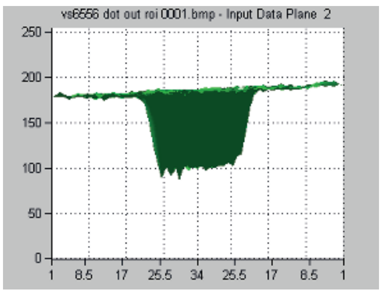
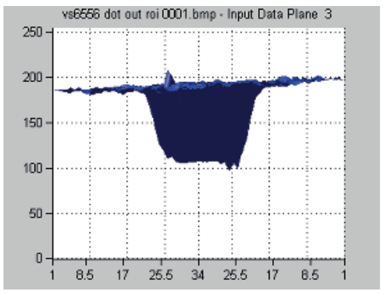
<table>
<tr><th>Red</th><th>Green</th><th>Blue</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Threshold = 0.573 (146.0)</td><td>Threshold = 0.569 (15.0)</td><td>Threshold = 0.600 (153.0)</td></tr>
</table>

Figure B.3 — Unprocessed ROI dot data

Generate a binary mask using the above threshold.

```
image_plane = input(:,:,plane);
mask = im2bw(image_plane, threshold);
```

Define a disk filter (radius 3 pixels); this is then used to erode the masks for the background and dot to remove the edge transition data.

```
se = strel('disk',3);
bg_mask = imerode(mask, se);
dot_mask = imerode(~mask, se);
```

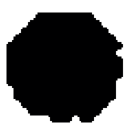
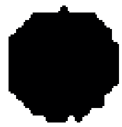
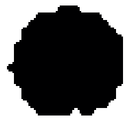
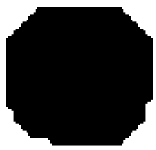
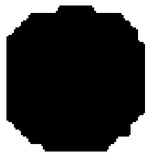
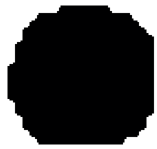
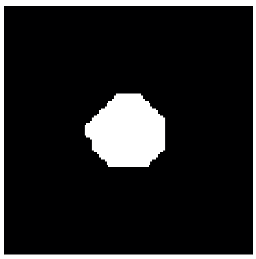
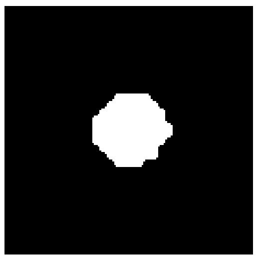
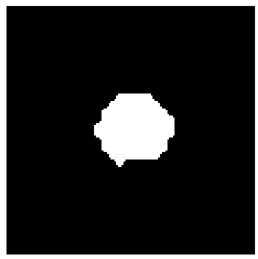
	Red	**Green**	**Blue**
Thresholded Binary ROI			
Background ROI Mask			
Dot ROI Mask			

Figure B.4 — Thresholded ROI data

If lens shading is present, then the profile of the dot can be tilted.

The effects of lens shading are removed by using the white data (background) to calculate a best-fit linear plane ($z = ax + by + c$).

The ROI is normalized and has tilt removed at the same time by dividing by the best-fit plane.

As there typically is a 20 × 15 array of dot in the image and lens shading is a low frequency variation, the assumption is made that the lens shading for one dot can be approximated by a linear plane.

Use a background mask to make any non-background pixels zero.

```
image_plane = image_plane .* uint8(bg_mask);
```

Build a set of simultaneous equations for MATLAB to solve to get the best-fit linear plane.

However, first the 2-D arrays have to be converted into 1-D arrays.

```
image_size = image_height*image_width;
tmp_i = reshape(image_plane, image_size, 1);
tmp_x = reshape(xi, image_size, 1);
tmp_y = reshape(yi, image_size, 1);
```

Only use valid data (>0). Get an index list of valid data.

```
indices = tmp_i > 0;
x1 = tmp_x(indices);
x2 = tmp_y(indices);
y = tmp_i(indices);
```

Build a set of simultaneous equations.

```
X = [ones(size(x1)) x1 x2];
```

Solve simulation equations – least squares fit.

```
a = X\double(y);
```

Rebuild best-fit image plane 2-D array.

```
best_fit = [ones(size(tmp_x)) tmp_x tmp_y]*a;
best_fit = reshape(best_fit, image_height, image_width);
```

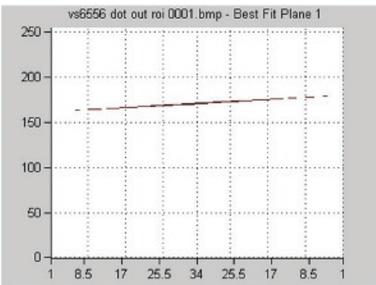
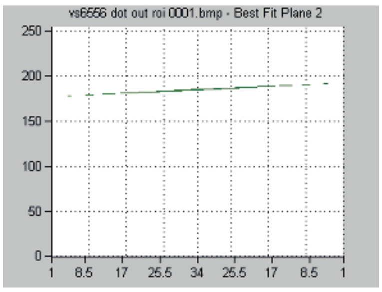
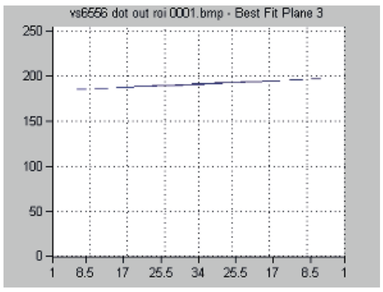
Red	**Green**	**Blue**
		
z = 169.414 + 0.310x -0.249y	z= 185.362 + 0.208x -0.259y	= 191.624 + 0.188x -0.243y

Figure B.5 — Best-fit dot tilts

Correct lens shading and normalize image data.

```
corrected = double(input(:,:,plane)) ./ best_fit;
```

After correcting the lens shading, the average background level will be 1,0.

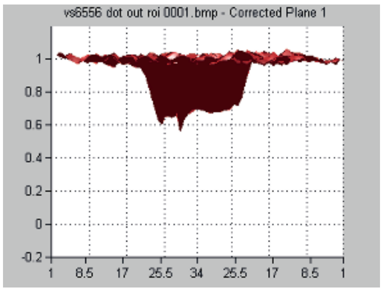
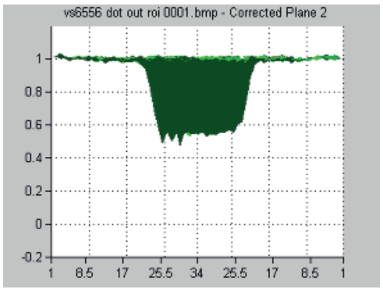
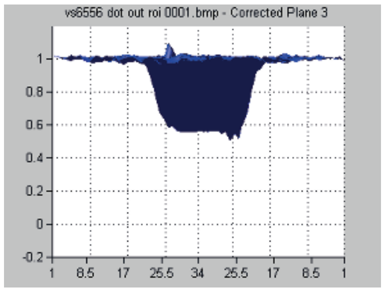
Red	**Green**	**Blue**
		

Figure B.6 — Dot data after tilt removal

The next step is to stretch the dot so that the average dot value is zero.

The average dot value is the mean of the pixels selected by the dot mask:

```
black = double(sum(sum(corrected.*dot_mask))) /
                    double(sum(sum(dot_mask)));
```

Determine re-scale factor:

```
rescale_factor = 1.0 / (1.0 - black);
```

Re-scale image data:

```
rescaled = 1.0-(corrected - black)*rescale_factor;
```

Invert dot:

```
rescaled = 1.0 - rescaled;
```

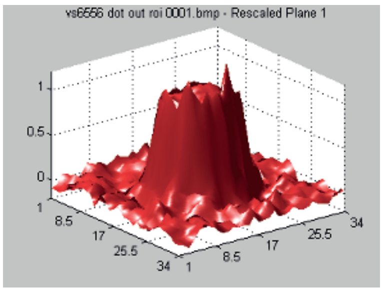
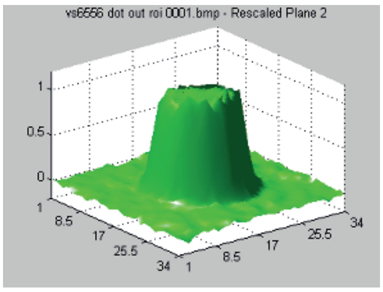
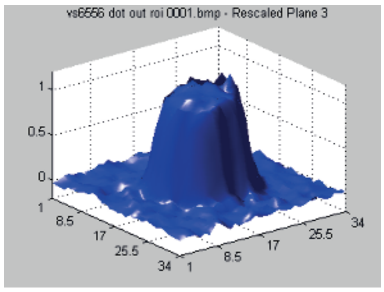
Red	**Green**	**Blue**
		

Figure B.7 — Dot data after inversion and re-scale

As the objective is to measure the lateral colour shift in the image, any contributions due to either the background or non-uniformity in the blackest region of the dot need to be removed. The aim is to isolate the white-to-black transition ring around the dot.

This is performed using the background and dot binary masks.

The background mask is used to force all of the pixels outside the dot to 0,0, and the dot mask is used to force the central dot pixels to 1,0.

Define a smaller disk for eroding the image mask to generate the background mask, smaller as needed to ensure that the background is removed. The larger erosion earlier was necessary to ensure that the black-to-white transition was completely removed for finding the best-fit plane.

```
se = strel('disk',2);
bg_mask = imerode(mask, se);
clipped = rescaled;
clipped(bg_mask > 0) = 0.0;
clipped(dot_mask > 0) = 1.0;
```

The next step is to clip image data to ensure that it lies in the [0,0:1,0] range.

```
clipped(clipped > 1.0) = 1.0;
clipped(clipped < 0.0) = 0.0;
```

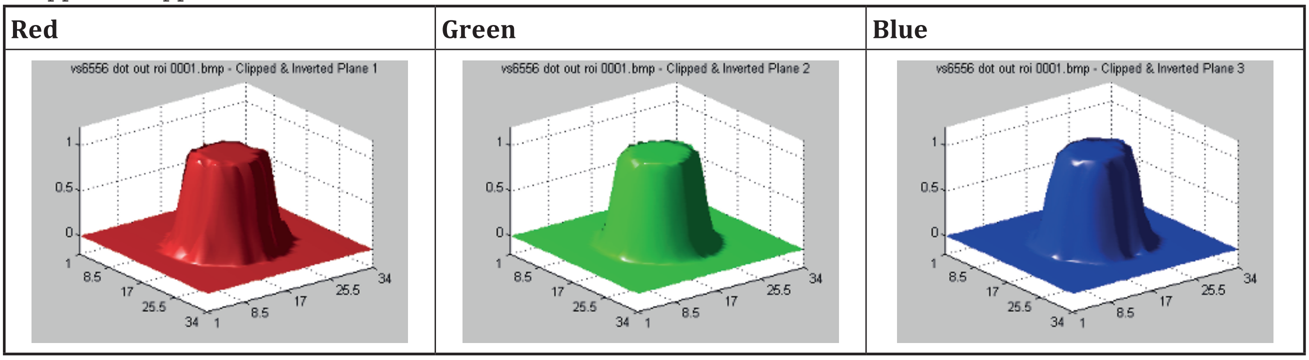


Figure B.8 — Dot data after background removal and clipping

B.2.5 Dot centre of mass

Calculate the centre of mass:

```
area = sum(sum(double(clipped)));
centre(1) = sum(sum(double(clipped).*xi))/area;
centre(2) = sum(sum(double(clipped).*yi))/area;
```

xi and yi are arrays containing the x and y coordinates, respectively.

Annex C
(informative)

Dot centre validation

C.1 Dot centre validation

Two sets of reference images were used to validate the accuracy of finding the dot centres. Three laboratories implemented the algorithm independently and this Annex shows the results and demonstrates the accuracy that can be achieved.

— AMD reference images – synthetic with different levels of blur but with zero lateral colour aberration.

— Lab A's, Lab B's, and Lab C's real-world reference images from three camera phones.

C.2 AMD reference images

Blur = 5, Dot = 45 pixels   Blur = 10, Dot = 45 pixels

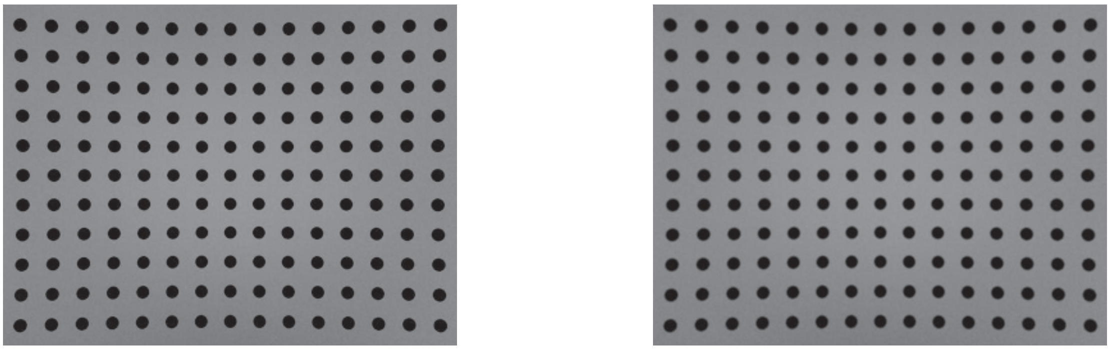


Figure C.1 — AMD reference images

The AMD images have known centre information prior to the application of noise, Gaussian blur, and distortion. The intention of these images is to test robustness of the centre-finding algorithm with respect to different levels of noise/blur noise.

The dot size in the AMD image is 45 pixels. The Gaussian Blur was applied using the "Lens blur" function in Adobe Photoshop. Figure C.2 and Figure C.3 show the distributions of the distance between the original centre and centre extracted by the proposed centre-finding method for each colour channel for the Blur 5 image.

The mean centre distance error increases from 0,073 pixel to 0,093 pixel from the Blur 5 to Blur 10 images.

The maximum error distance between centres is in the 0,2 to 0,3 pixel range, with the blue colour channel centres giving the worst-case values.

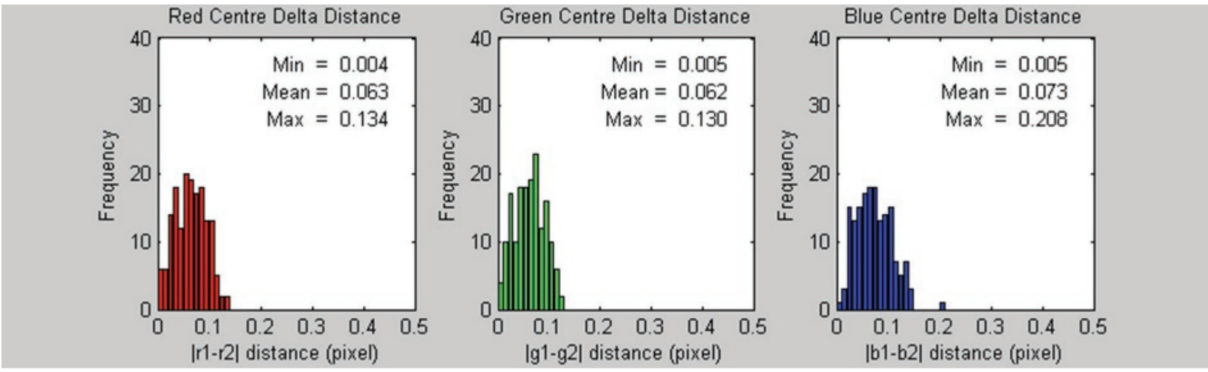


Figure C.2 — Distance between Lab B's centres vs. reference centres for AMD Blur 5 image

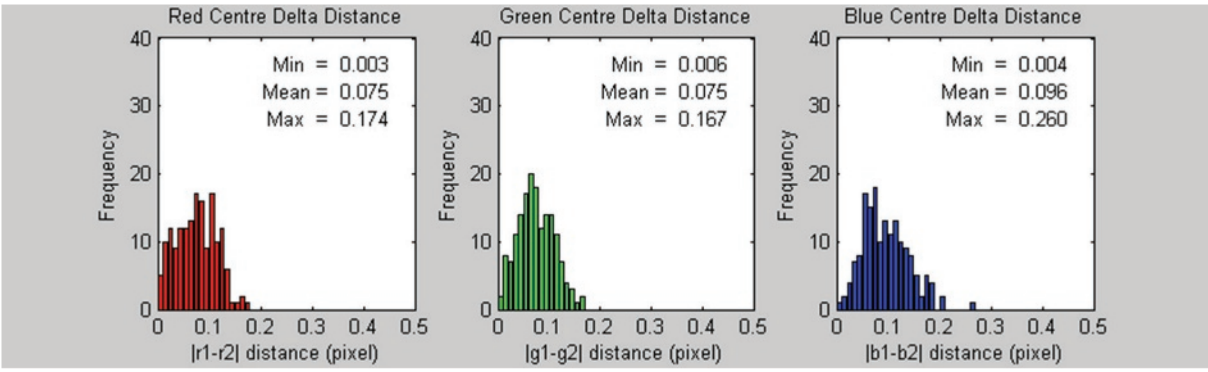


Figure C.3 — Distance between Lab B's centres vs. reference centres for AMD Blur 10 image

C.3 Lab A's reference images

DxO Laboratories supplied the following three JPEG reference images captured from three commercial camera phones:

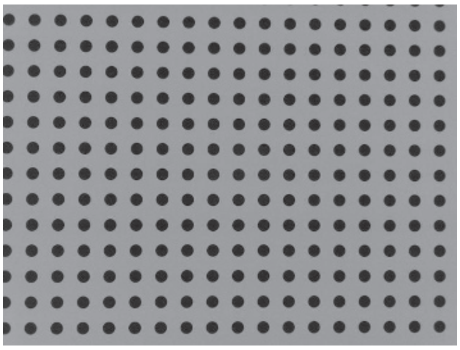
— Camera phone 1: Dot size: 41 pixels.;

— Camera phone 2: Dot size: 18 pixels;

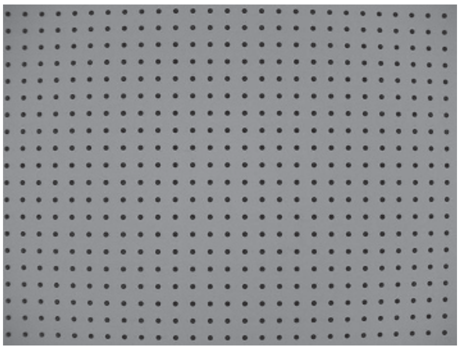
— Camera phone 3: Dot size: 26 pixels.

Along with the above images, DxO Laboratories also supplied the dot centre information extracted by the DxO Laboratories dot-finding implementation. The reference centres were used as part of a three-way correlation among the DxO Laboratories, Vista Point Technologies and STMicroelectronics dot-finding implementations.

Camera phone 1, Dot size = 41 pixels



Camera phone 2, Dot size = 18 pixels



Camera phone 3, Dot size = 26 pixels

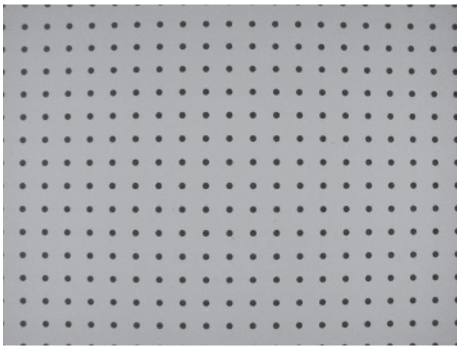


Figure C.4 — Lab A's reference images

Figure C.5 to Figure C.10 show the correlation among the three different dot-finding implementations.

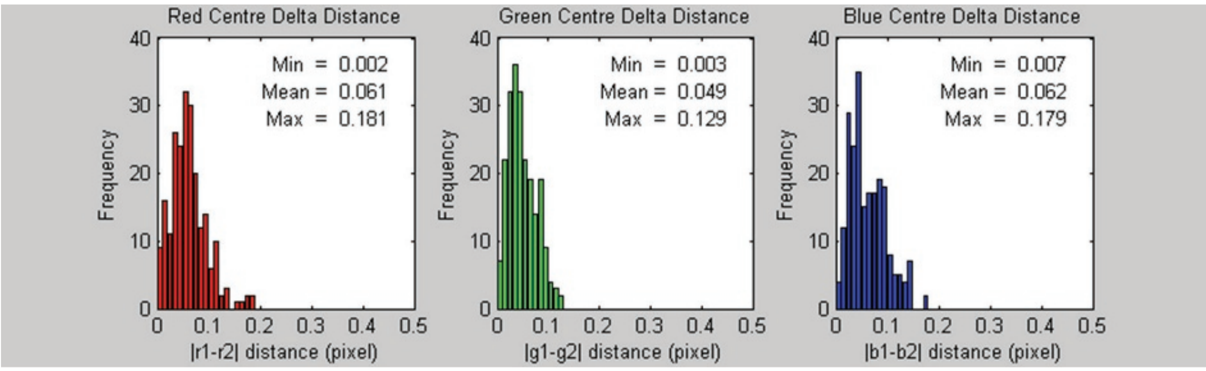


Figure C.5 — Distance between Lab A's centres vs. Lab B's centres for the camera phone 1 image

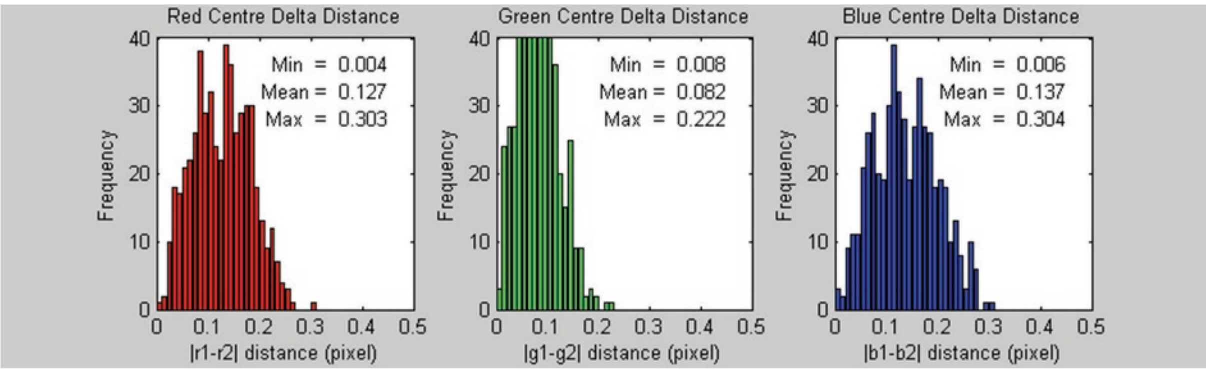


Figure C.6 — Distance between Lab A's centres vs. Lab B's centres for the camera phone 2 image

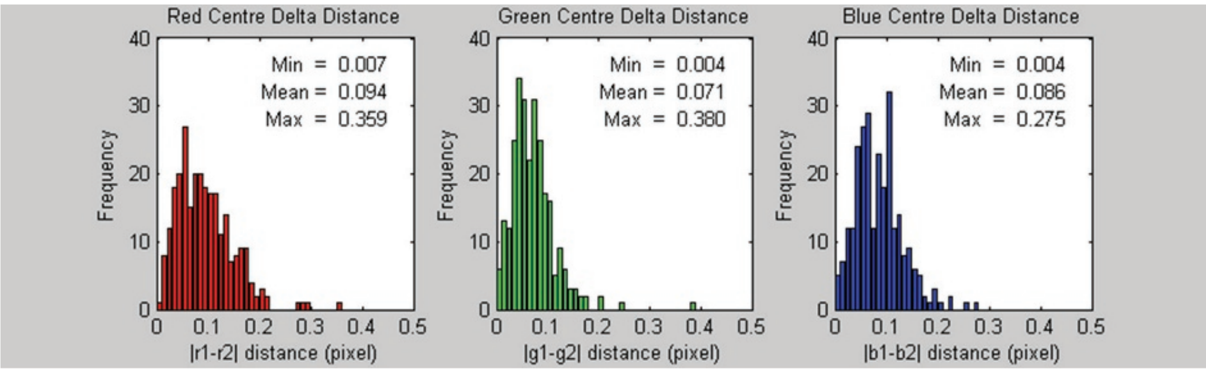


Figure C.7 — Distance between Lab A's centres vs. Lab B's centres for the camera phone 3 image

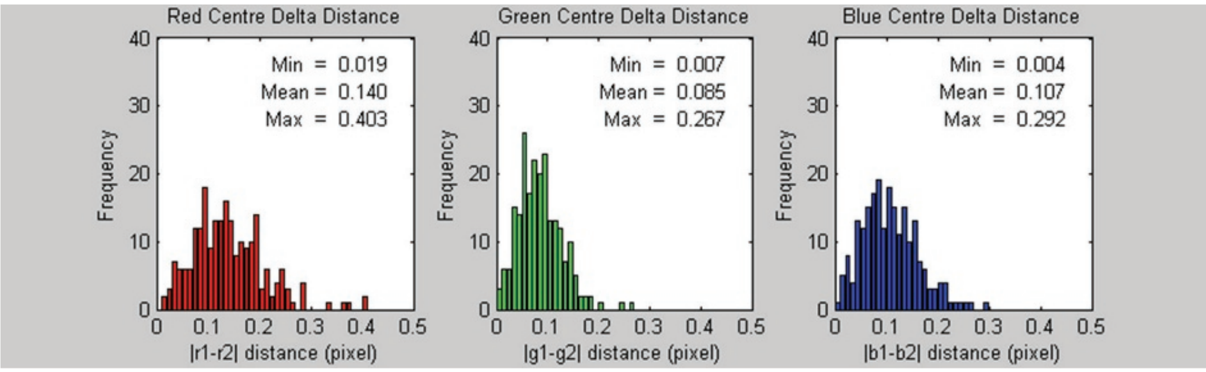


Figure C.8 — Distance between Lab C's centres vs. Lab B's centres for the camera phone 1 image

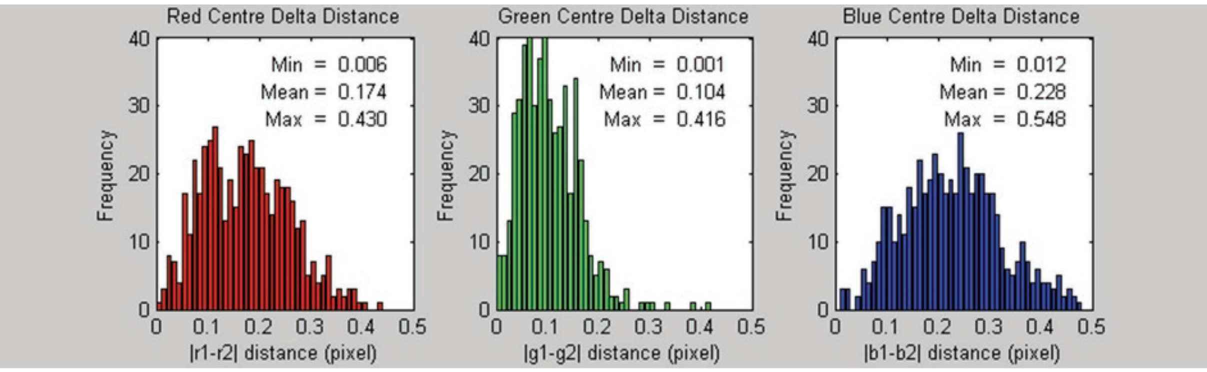


Figure C.9 — Distance between Lab C's centres vs. Lab B's for the camera phone 2 image

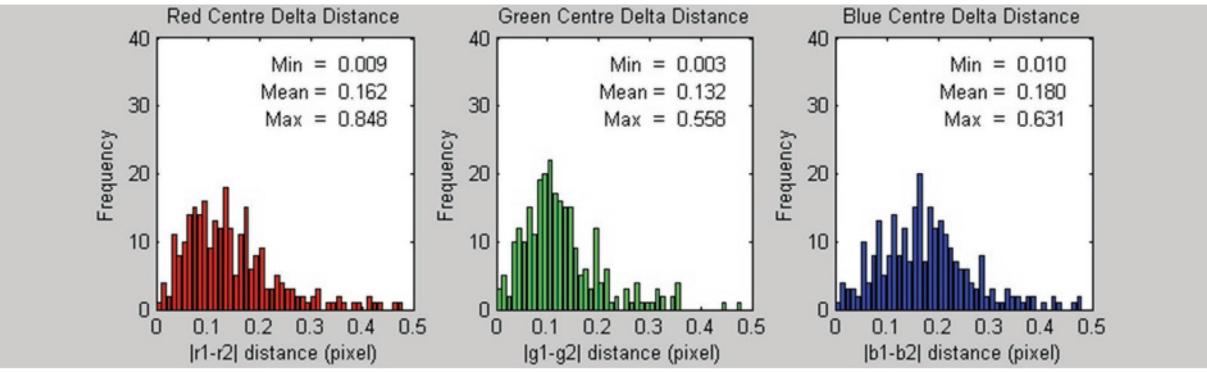


Figure C.10 — Distance between Lab C's centres vs. Lab B's centres for the camera phone 3 image

In summary, the inter lab implementations differed by less than 0,23 pixels for the set of reference images.

The correlation is the strongest for the camera phone 1 image, which has the largest dot size by almost a factor of two.

Annex D
(informative)

Grid sort

D.1 Overview

This Annex describes the procedure to follow to match the distorted (actual recorded) grid from the image shot by the camera with the original (ideal) grid target.

The following are the main steps.

— Use the green plane dot centre data.

— Find the dot closest to the centre of the image.

— Find the dot spacing at the centre of the image. The assumption/ground truth is that there is no distortion at the centre of the image.

— Use the centre dot spacing to predict the size of the grid. Over-size the grid by 50 % to ensure that there is sufficient space. Create an empty grid based on the oversized value.

— Populate the empty grid with the location of the centre dot.

— From the centre dot, scan left and then scan right to find the dots (along the horizontal axis X-X). Use previous dot x spacing to predict the next dot location.

— From the centre dot, scan up and then scan down to find the dots (along the vertical axis Y-Y). Use previous dot y spacing to predict the next dot location.

— From each grid point on the horizontal axis (X-X), dot scan up and then scan down to find the dots. Use nearest horizontal neighbour dot y spacing to predict the next dot location.

The order in which the grid positions are built up is very important and effectively, the population of the grid with the corresponding dot locations grows out from the centre of the image, where there should be no distortion.

D.2 Initialization

D.2.1 Finding the closest dot

The core routine finds which dot is nearest the predicted centre.

The Euclidean distance between the predicted centre and all of the dot centres is calculated. The routine returns which dot is the nearest (the minimum distance) and the distance to that dot.

In MATLAB function *GD_grid_find_nearest_match* is implemented via the following two lines:

```
radius = sqrt((x - xi).^2 + (y - yi).^2);
[min_value m_index] = min(radius);
```

where (x,y) is the list of dot centres and (xi, yi) is the predicted centre location.

If the distance between the match and prediction is less than a threshold (say the current dot spacing/2), the match is considered to be valid. This allows the case of missing dots to be correctly managed without generating false matches.

The match tolerance allows a few degrees of rotation in the grid to be handled.

D.2.2 Finding the centre dot

Use the green plane dot centre data for the grid sort.

First, find the dot location nearest the centre of the image. This dot is stored in the centre of the grid.

```
[c_error c_index] =
GD_grid_find_nearest_match(x,y,image_width/2,image_height/2);
```

D.2.3 Finding the central dot spacing

Proceed in small steps (decrement of 8 pixels) from the centre dot location until the next dot is found.

The distance between the two dots defines the initial value for estimating both the central dot spacing and the size of the grid that should be created.

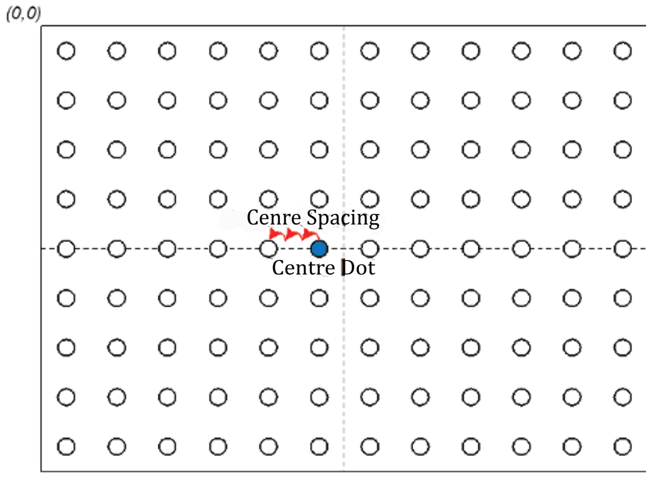


Figure D.1 — Grid sort – step 1

The assumption is that there is zero distortion in the centre of the image, thus the dot spacing in the centre of the image can be assumed to be the reference case to predict the geometric distortion value.

D.3 Grid creation

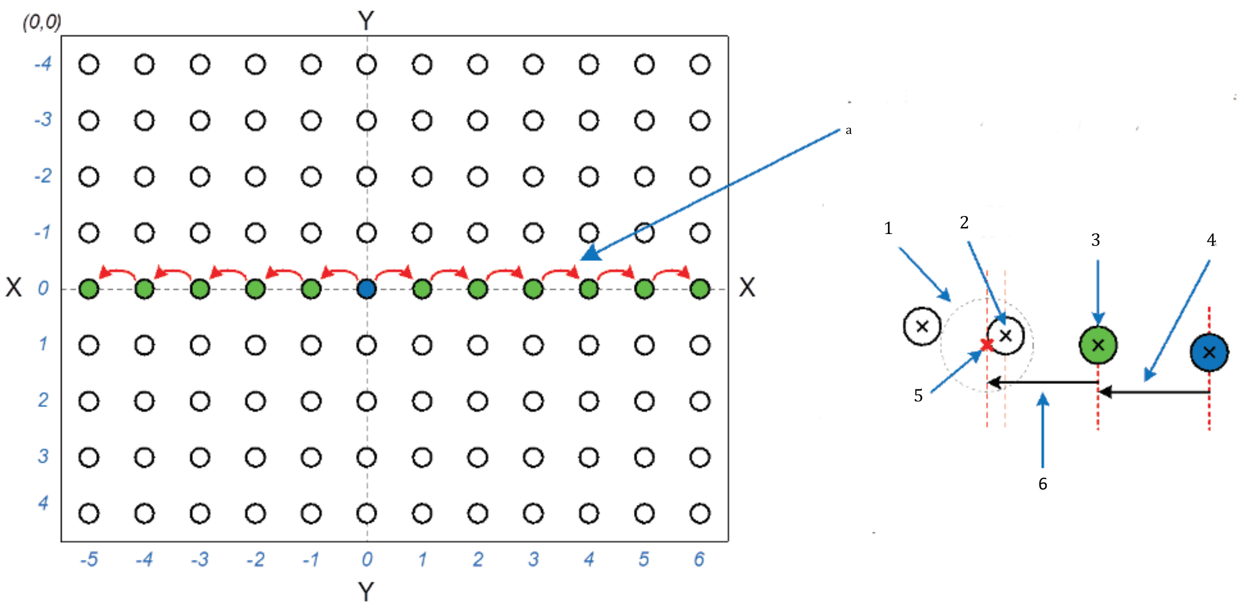
The image size is divided by the above central dot spacing. The resulting grid size is oversized by 50 % to handle the negative distortion case where the dot spacing reduces as radial distance from the centre of the image increases.

The content of the grid is initialized to zero to indicate that grid position is not populated. As the grid sort progresses, grid positions are populated with the locations of the associated dot centre.

At the end of the search, the grid positions with matching dot centre locations have non-zero values.

D.3.1 Pass 1: populating the x-axis and y-axis dot location

From the centre dot location, in turn four sweeps are performed to the left, to the right, above, and below the centre dot location to find the dots matching the grid locations on the x and y axes.



Key

1 match tolerance

2 best match

3 previous dot

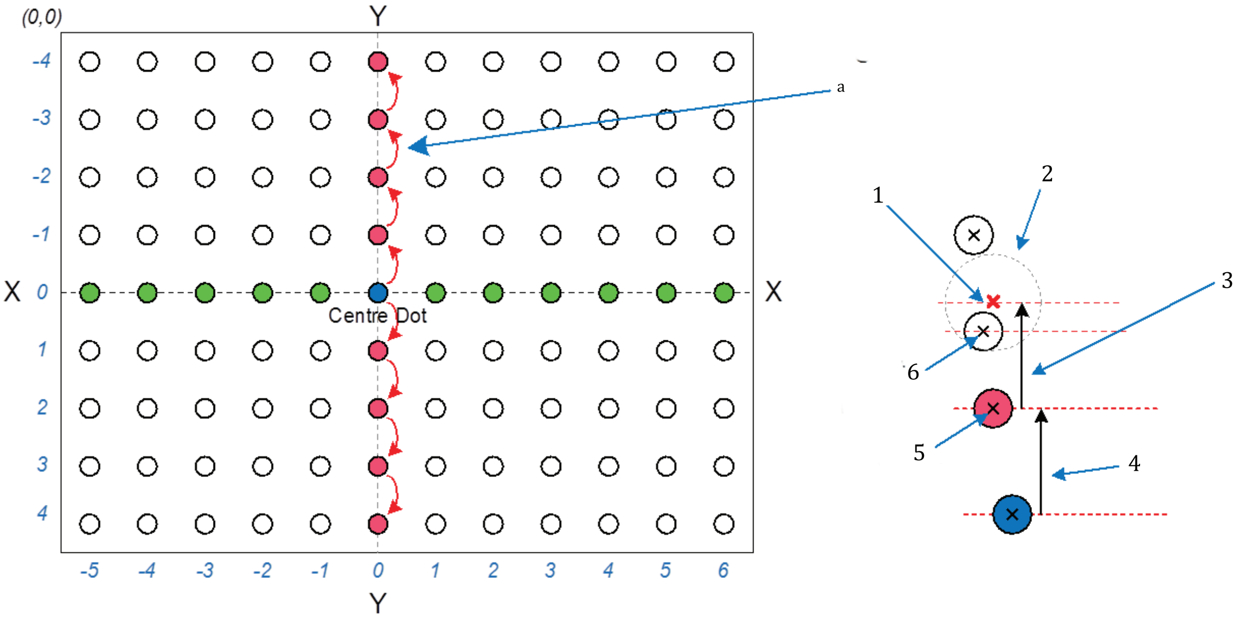
4 previous dot x spacing

5 prediction

6 prediction based on previous dot x spacing and previous dot position

a Use the previous dot positions and spacing to predict the location of the next dot.

Figure D.2 — Grid sort – step 2 (x-axis)



Key

1 prediction

2 match tolerance

3 prediction based on previous dot y spacing and previous dot position

4 previous dot y spacing

5 previous dot

6 best match

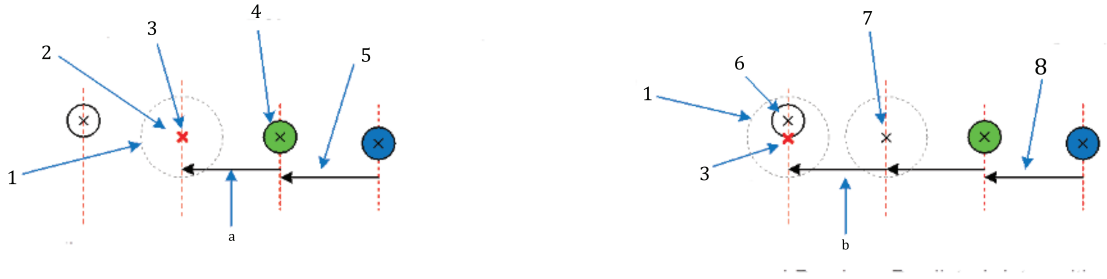
a Use the previous dot positions and spacing to predict the location of the next dot.

Figure D.3 — Grid sort – step 3 (y-axis)

In the horizontal direction (x-axis), the horizontal dot spacing between the previous two dots is used to predict the current grid point relative to the previous dot location. If the closest dot to the predicted grid position is within required tolerance (current horizontal dot spacing/2), then a match has been found for that grid position and that grid position is populated with the coordinates of the matching dot location.

For the grid positions next to the centre dot, the initial dot spacing value is used for the prediction.

If the closest dot lies outside the required tolerance, then there is no match and the coordinates for that grid position will be set to (0, 0), i.e. a missing grid point.



Key

1	match tolerance	6	best match
2	no best match	7	previous prediction
3	prediction	8	last valid dot x spacing
4	previous dot	a	Prediction based on previous dot x spacing and previous dot position.
5	previous dot x spacing	b	Prediction based on last valid dot x spacing and previous predicted dot position.

Figure D.4 — Pass 1: handling missing grid points

Missing grid points usually result from a failure to find a dot in the original image or in complete lines/columns in the grid due to distortion at the edges of the image. If the previous match failed (i.e. it is an empty value), then the previous predicted grid position and the last valid dot x spacing value are used to predict the next grid/dot position.

The sweep in the vertical direction is similar except that the vertical spacing between the dots is used for the prediction.

The distortion can lead to significant local differences between the vertical and horizontal dot spacing; for robust grid sorting/fitting, the vertical and horizontal dot spacing should be tracked separately.

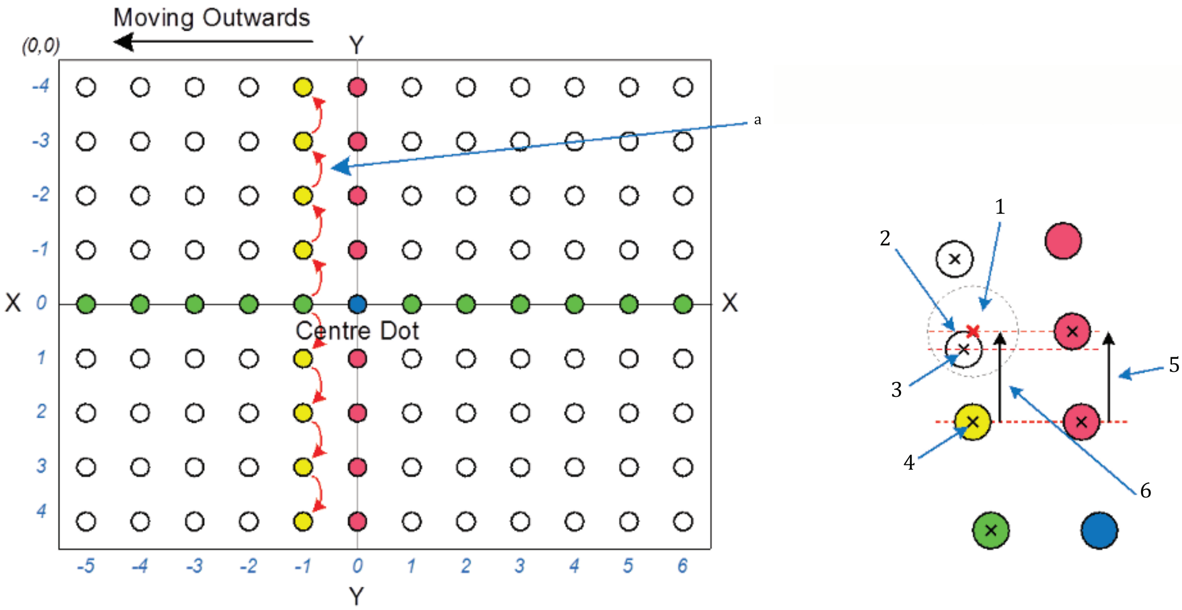
D.3.2 Pass 2: populating the rest of the grid

The second pass populates the grid positions in each quadrant.

Moving out leftwards from the central grid position, select one x grid position on the x-axis at a time.

For each selected x grid position, step through each y grid position, first moving up from the centre, and then secondly downward from the centre.

The prediction for each grid position is based on the vertical spacing of the neighbouring grid position in the same row nearest to the centre plus the previous grid/dot position in that column.



Key

1 match tolerance

2 prediction

3 best match

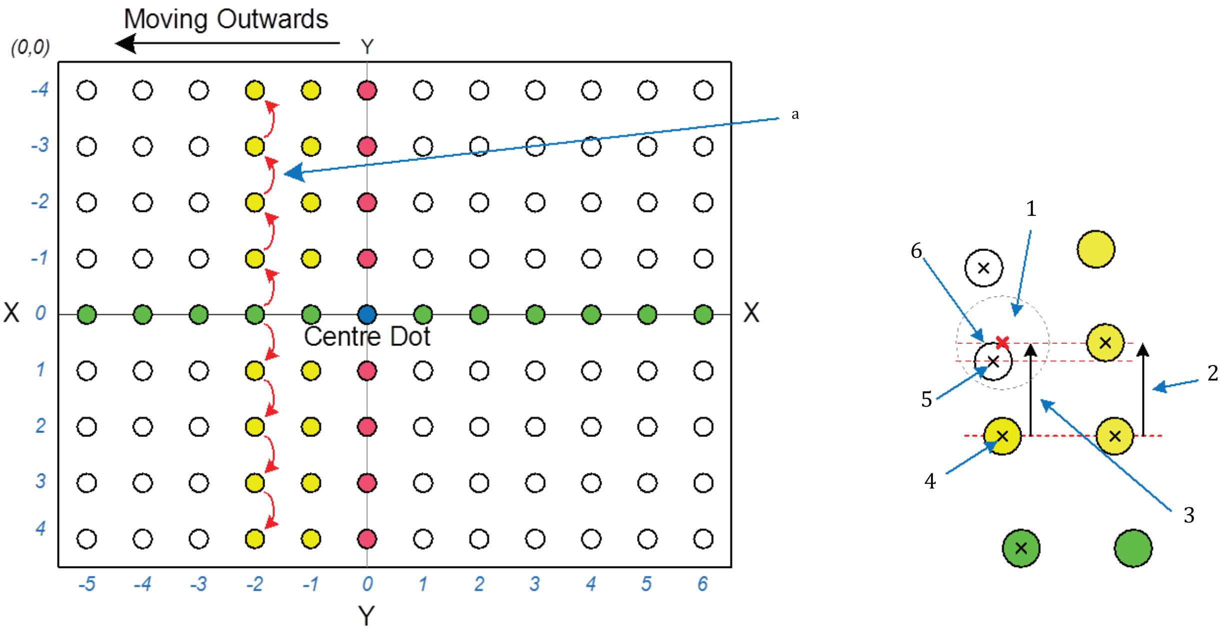
4 previous dot

5 neighbouring dot y spacing

6 prediction based on dot y spacing for neighbour in the same row nearest the centre

[a] Use previous dot positions and dot y spacing of neighbouring dot in the same grid row to predict the location of the next dot.

Figure D.5 — Grid sort – step 4



Key

1 match tolerance

2 neighbouring dot y spacing

3 prediction based on the dot y spacing for neighbour in the same row nearest the centre

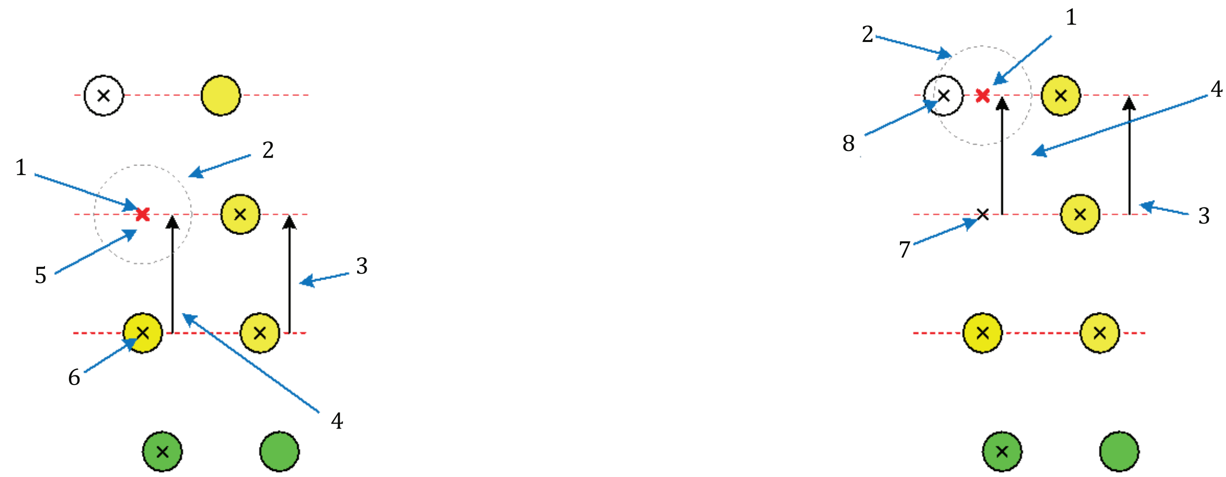
4 previous dot

5 best match

6 prediction

[a] Use the previous dot positions and dot y spacing of neighbouring dot in the same grid row to predict the location of the next dot.

Figure D.6 — Grid sort – step 5



Key

1 prediction

2 match tolerance

3 neighbouring dot y spacing

4 prediction based on dot y spacing for neighbour in the same row nearest the centre

5 no best match

6 previous dot

7 previous prediction

8 best match

Figure D.7 — Pass 2: handling missing grid points

If the previous match failed (i.e. it is an empty value), then the previous predicted grid position and vertical spacing of the neighbouring grid position in the same row nearest to the centre are used to predict the next grid/dot position.

If the neighbouring grid position in the same row nearest to the centre is empty, the last valid dot y spacing is used for the prediction.

Repeat the above, moving out rightwards from the central grid position.

Key

1 match tolerance

2 prediction

3 best match

4 previous dot

5 prediction based on dot y spacing for neighbour in the same row nearest the centre

6 neighbouring dot y spacing

a Use the previous dot positions and dot y spacing of neighbouring dot in the same grid row to predict the location of the next dot.

Figure D.8 — Grid Sort – step 6

Key

1 match tolerance

2 prediction

3 best match

4 previous dot

5 prediction based on dot y spacing for neighbour in the same row nearest the centre

6 neighbouring dot y spacing

a Use the previous dot positions and dot y spacing of neighbouring dot in the same grid row to predict the location of the next dot.

Figure D.9 — Grid sort – step 7

Figure D.10 illustrates fitted grids.

15 % TV Negative Wave Distortion 15 % TV Positive Wave Distortion

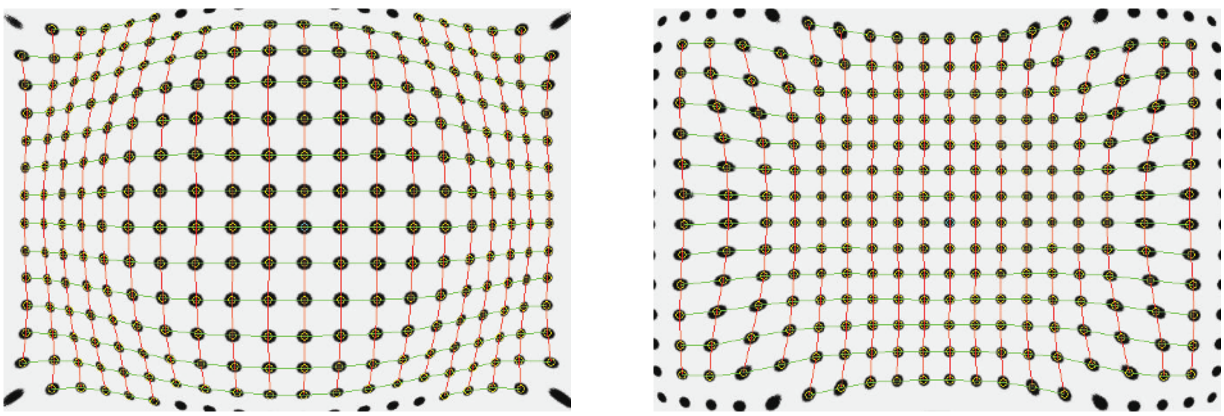


Figure D.10 — Example fitted grids

Annex E
(informative)

Example of subjective evaluation

This Annex is one example of subjective evaluation with relation to geometric distortion of the image. For different conditions, for example, different distortion profiles, the results can vary. In addition, the difference of magnification at the image centre might affect the subjective comparison among different types of distortion, e.g. barrel and pincushion.

Six high-quality pictorial images were used for the subjective testing. The scenes were selected to represent a range of sensitivity to the effects of geometric distortion. For each of the four types of distortion studied (barrel, pincushion, positive wave, and negative wave), five levels of distortion were applied to each of the six images. With the original images included to represent the zero level, the subjective evaluation had (6 scenes) × (4 distortion types) × (6 distortion levels) = 144 separate images.

Figure E.1 — Six test scenes used for the subjective evaluation

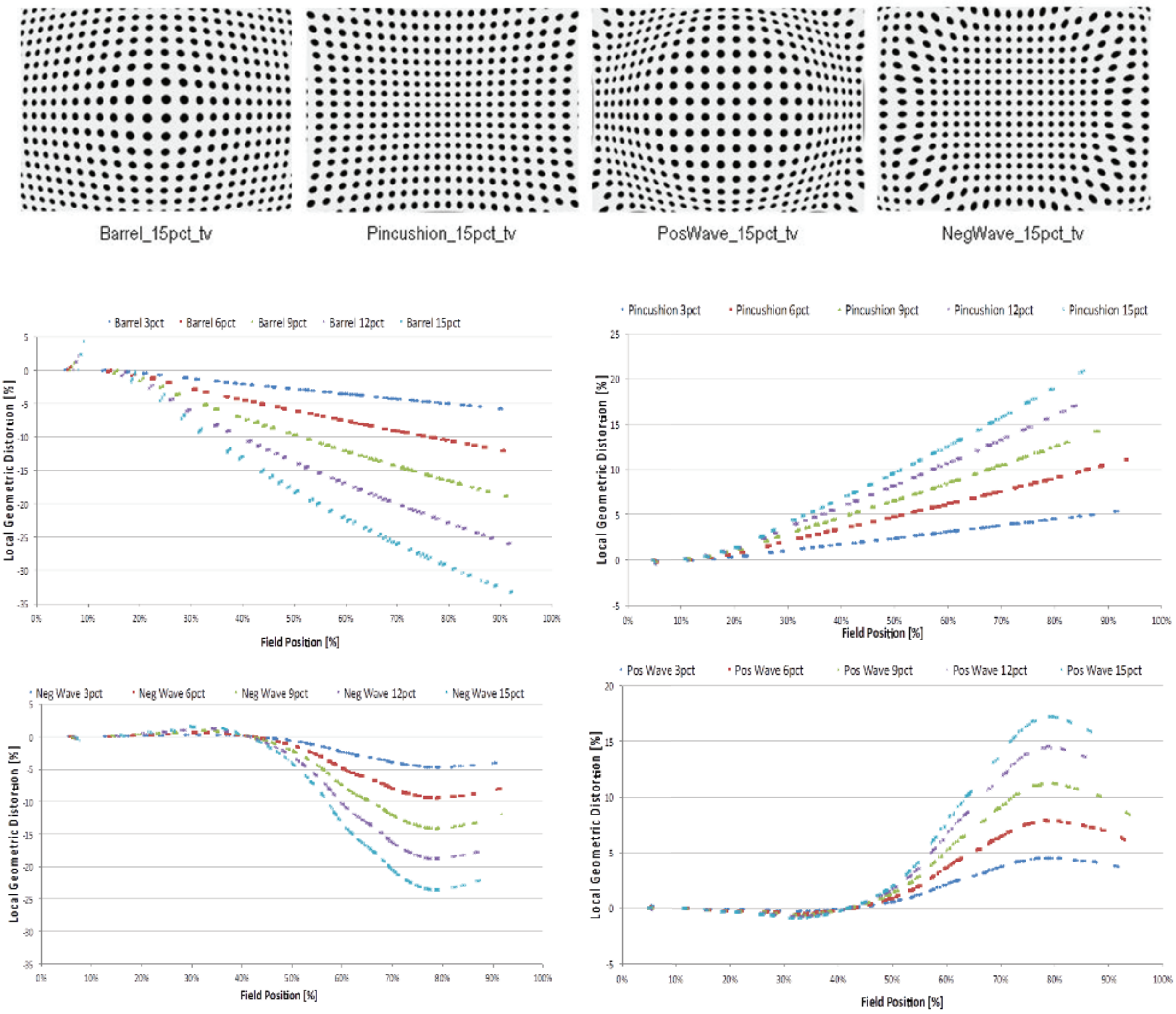


Figure E.2 — Effects of four types of local distortion shown on a regular dot pattern and their distortion functions that were used for the subjective evaluation

The functions of distortion (concrete distortion profiles) used for this analysis are created by a simulating software to represent typical distortions of cell phone camera modules provided by an engineer of a worldwide-known cell phone maker.

For the graphs in Figure E.2, the x-axis is actual image height and the y-axis represents the distortion value. The max image height for measured values depends on the position of the farthest dot from the centre. The graphs show the evaluated dots locations for fully visible lines and columns of dots.

Subjective evaluation of the GD test images was conducted using the softcopy ruler method described in ISO 20462-3.

Their results were combined by a weighted average proportional to the number of observers used at each location. The analysis showed that there was a significant effect due to scene content and also due to distortion type.

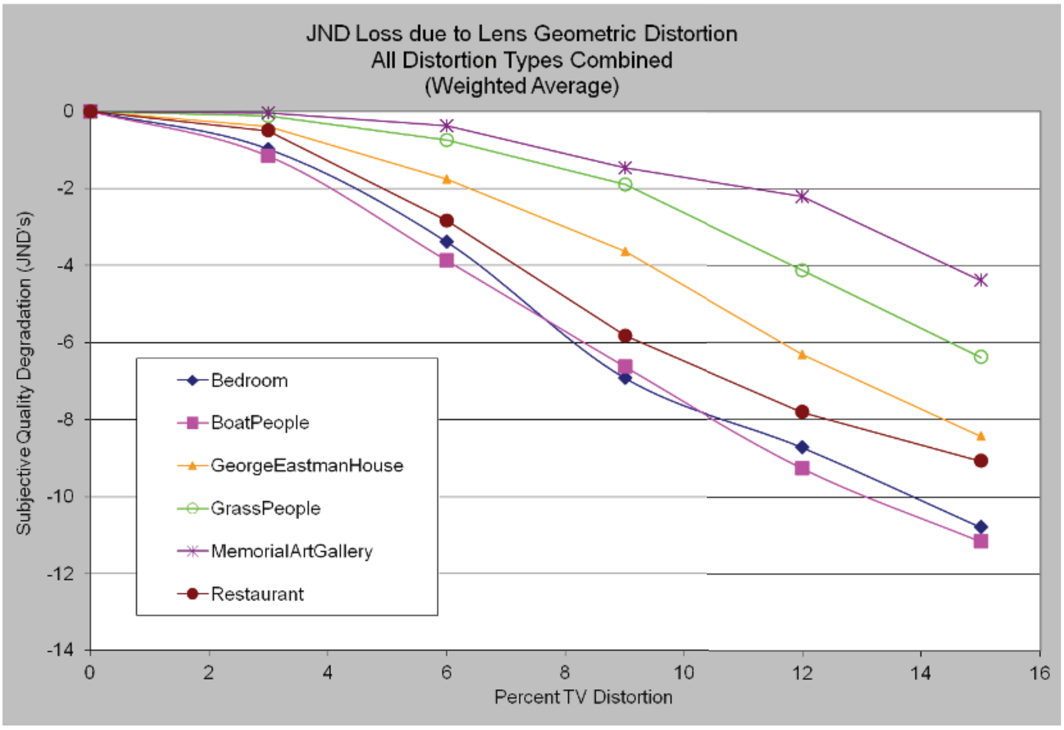


Figure E.3 — Subjective quality loss due to all types of geometric distortions is dependent on scene content

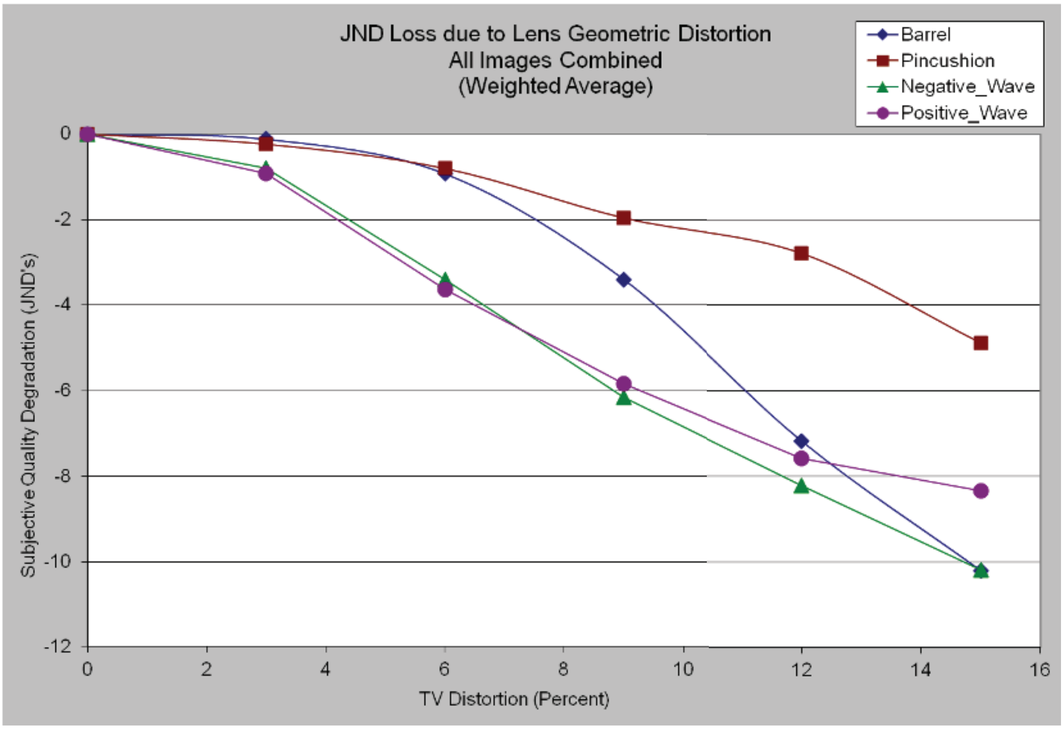


Figure E.4 — Subjective quality loss for different scene content is dependent on distortion type

The type of distortion found to be least objectionable was pincushion and the scene found to be least affected by all types of distortion was the Memorial Art Gallery.

Figure E.5 — Test scene (gallery) and distortion type (pincushion) found to be least objectionable

The type of distortion found to be most objectionable was negative wave and the scene found to be most affected by all types of distortion was Boat-people.

Figure E.6 — Test scene (Boat-people) and distortion type (negative wave) found to be most objectionable

At the start of the subjective testing, the amount of distortion applied to the test scenes was measured in terms of percent TV distortion (as defined in IEC 61146-1 because this test was performed prior to the existence of this standard), as shown in Figure E.3 and Figure E.4. Subsequently, the local geometric distortion was measured (see 6.1) and the data were re-plotted. Table E.1 shows the measured values of local geometric distortion for each distortion type and level.

Table E.1 — Local geometric distortion values corresponding to TV distortion for the four distortion types tested

TV Distortion	Local geometric distortion			
Percent	Barrel	Pincushion	NegWave	PosWave
0 %	0,00	0,00	0,00	0,00
3 %	−5,77	5,31	−4,72	4,49

Table E.1 *(continued)*

TV Distortion	Local geometric distortion			
Percent	Barrel	Pincushion	NegWave	PosWave
6 %	−12,10	11,10	−9,43	7,87
9 %	−18,88	14,25	−14,13	11,20
12 %	−26,04	17,00	−18,90	14,52
15 %	−33,32	20,86	−23,66	17,21

When the measured values of local geometric distortion are used, the distortion plot in Figure E.4 becomes the plot shown in Figure E.7. Note that as barrel and negative wave distortion are defined, they appear as negative quantities.

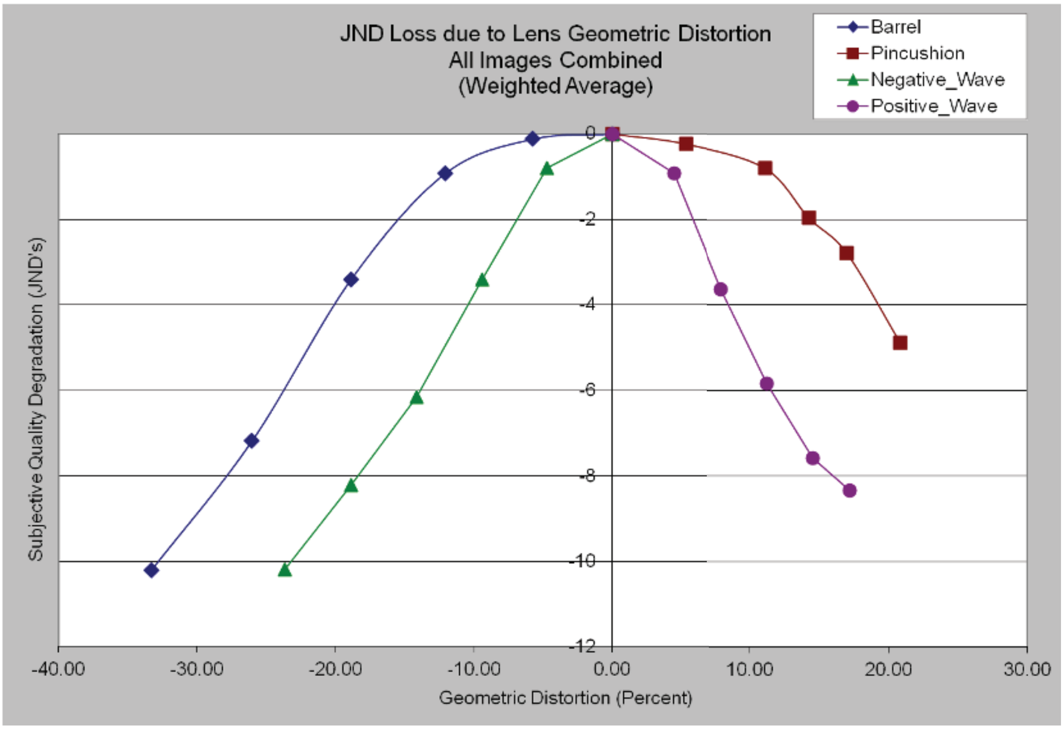
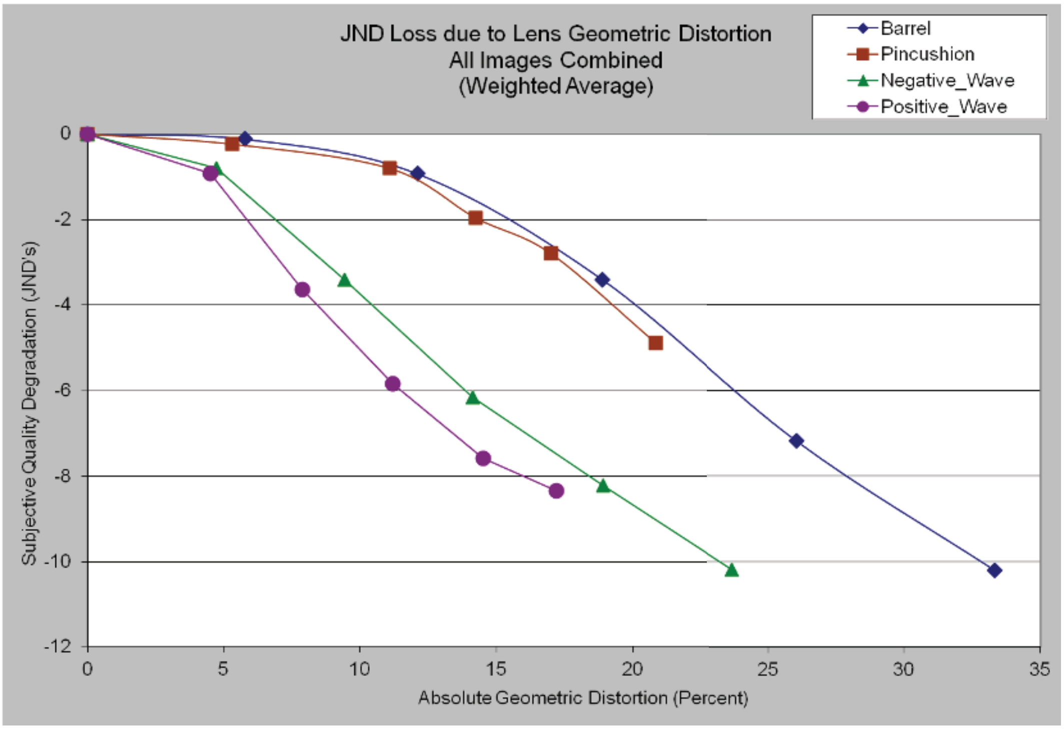


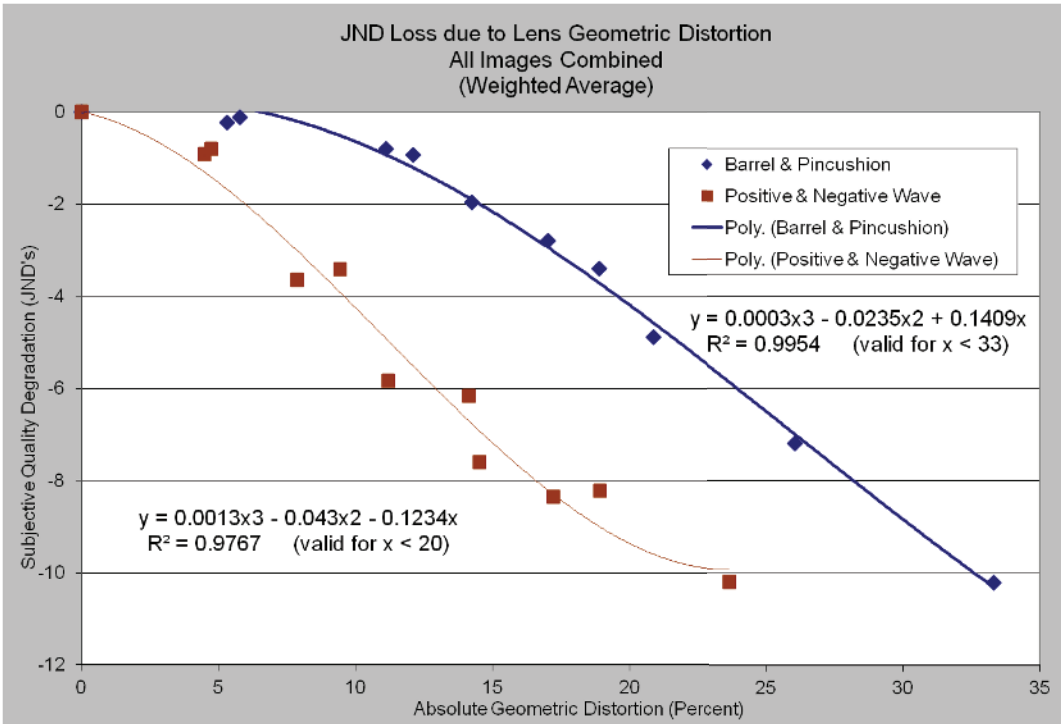
Figure E.7 — Quality loss versus local geometric distortion for different distortion types

At first glance, it appears that a separate formula will be needed for each distortion type to characterize the relationship with subjective quality loss; however, by using the absolute value of geometric distortion, a different picture emerges. As shown in Figure E.8, the curves for barrel and pincushion are very close, well within the uncertainty in the subjective measurement and the same applies to the two wave distortion curves.



NOTE For each pair of curves, the two are not statistically different and can be represented by a single formula.

Figure E.8 — Subjective quality loss as a function of four different distortion types on an absolute scale



NOTE The upper curve represents both barrel and pincushion distortion, while the lower curve represents both positive and negative wave distortion.

Figure E.9 — Subjective quality loss as a function of absolute geometric distortion

The results shown thus far have been calculated by averaging the data from the six different pictorial scenes. The working group was sensitive to the fact that certain image content was negatively affected by the effects of geometric distortion to a significantly greater extent than the average scene and the group decided to provide information on the most extreme case as well. The worst case turned out to be the Boat-people scene with negative wave distortion. To see visually how that image appears with large amounts of negative wave distortion, see Figure E.6. The fitted formula for the worst case is shown in Figure E.10.

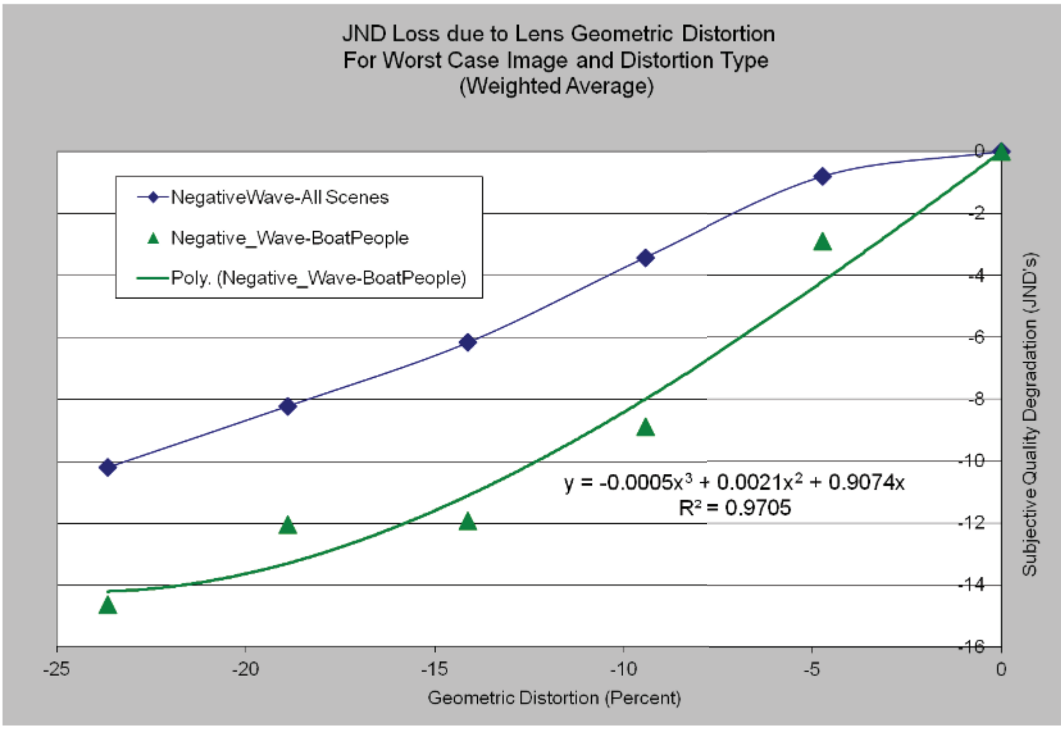
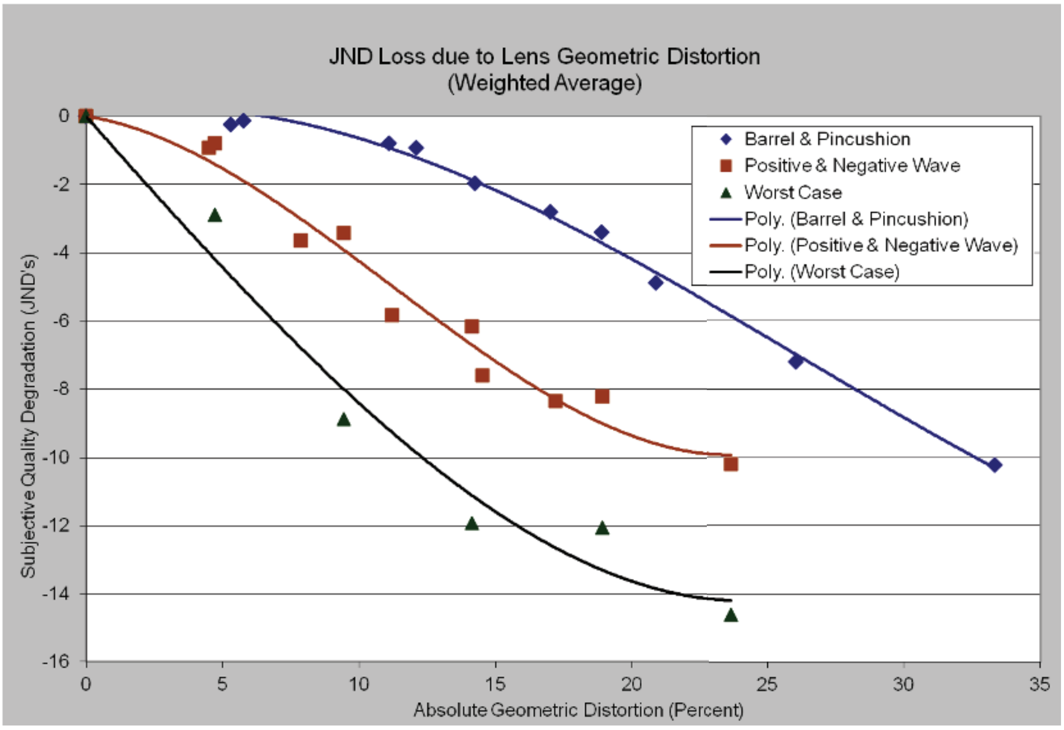


Figure E.10 — Worst-case image and distortion type

Finally, the average and worst cases are plotted together on an absolute distortion scale in Figure E.11.



NOTE The formulae for the curves are shown in Figure E.9 and Figure E.10.

Figure E.11 — Loss of subjective image quality due to distortion for barrel or pincushion, positive or negative wave, and the worst case tested, the Boat-people scene with negative wave distortion

Bibliography

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[2] ISO 20462-3, *Photography — Psychophysical experimental methods for estimating image quality — Part 3: Quality ruler method*

[3] I3A, Camera Phone Image Quality (CPIQ) — Phase 2, Lens Geometric Distortion (LGD) (now administered under IEEE P1858, http://standards.ieee.org/develop/wg/CPIQ.html)

[4] CIPA DCG-002-Translation-2012 with Corrigendum Specification Guideline for Digital Cameras (Revised Version)

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