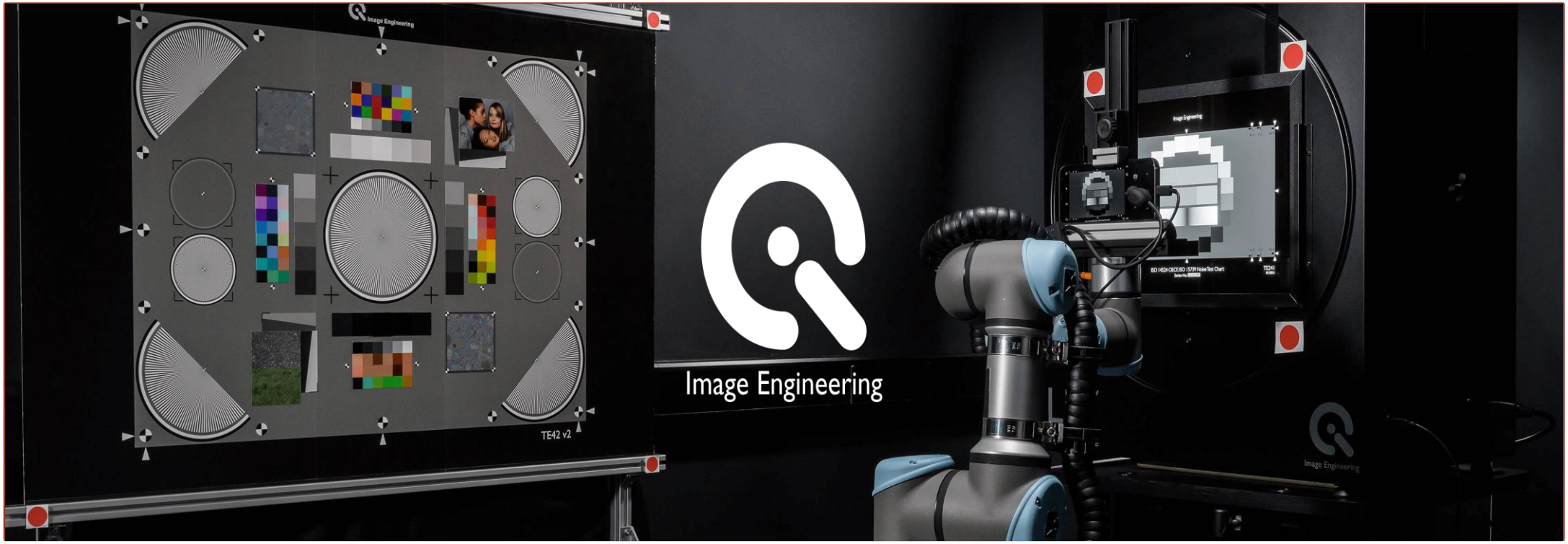

Image Engineering

Member of the Nynomic Group

原产于德国的图像测试解决方案

Image Quality Test Solutions

中国子公司——深圳艾宜光电设备有限公司

台灣用戶請洽商：**登華資訊有限公司** (台灣地區授權代理商)　**sales@dhd.com.tw**　www.dhd.com.tw

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History

1995 Dietmar Wüller先生创办 Image Engineering 公司

1997 Image Engineering作为世界上第一个独立的测试实验室开始对数码相机进行测试

1997 加入德国工业标准组织以及国际标准化组织，积极参与支持摄影和数字成像工作组的工作

2005 首款分析软件上市: IE-Analyzer V2.0 – 图像分析基于 ISO标准

2006 收购行业著名的图卡制造商——Esser Test Charts.产品选择的有效扩展使得现在可以通过Image Engineering公司获得相机完美测试和校准所需的全部方案，包括软件、设备、图卡等等。

2011 公司名称更改为Image Engineering GmbH & Co. KG. 公司所有者为 Dietmar Wüller 跟Uwe Artmann.

2013 研发的IQ-LED技术在行业引起轰动，也成为了其他几款革命性产品的基础。

2019 为了更好的服务大中华区客户，Image Engineering中国子公司——深圳艾宜光电设备有限公司在深圳成立

2021 Image Engineering正式加入Nynomic集团，作为Nynomic战略目标极其重要的一环，他们可以为我司提供更多的资源，以更快、更高水平地实现我们的目标。

Image Engineering 今日概况

我司的主营业务是提供图像质量评估整体解决方案，包括各类符合ISO标准或其他通用标准的测试图卡、专业图像分析软件、影像实验室标准光源以及其他测量必备设备，以帮助客户更充分的评估摄像头系统的图像性能。

摄像头图像质量评估我司可涉及的行业包括: 传统摄影, 手机，汽车、安防、机器视觉、医疗内窥镜、广播以及扫描仪存档等等

- 成立于1995年德国科隆
- 2017将总部迁至德国克彭市（ Kerpen）

- 美国、中国均设有全资子公司，世界其他地区大量的合作商

- 2021年加入Nynomic 集团

德国克彭市总部

产品组合

TEST CHARTS

- 超过250张图像测试图卡
- 多功能综合测试图卡
- 支持客户定制图卡

SOFTWARE

- 专业图像分析软件 (C++)
- 产品控制软件
- API 集成与二次开发

Image Engineering

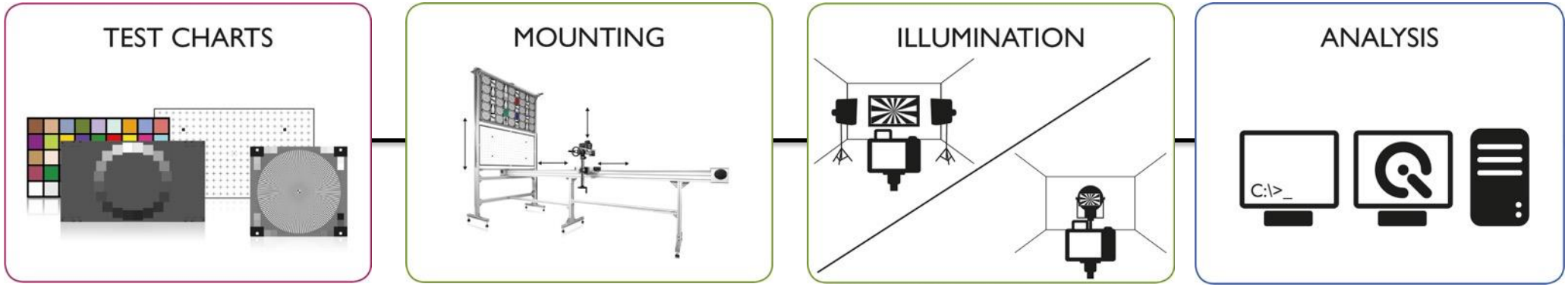
MEASUREMENT DEVICES

- 时序性能评测
- 相机几何标定
- 光学防抖评测
- 高低温环境下的图像质量实时评估

ILLUMINATION DEVICES

- 大图卡立式补光光源
- 高均匀性低照灯箱
- 产线集成光源
- 大广角测试均匀光源

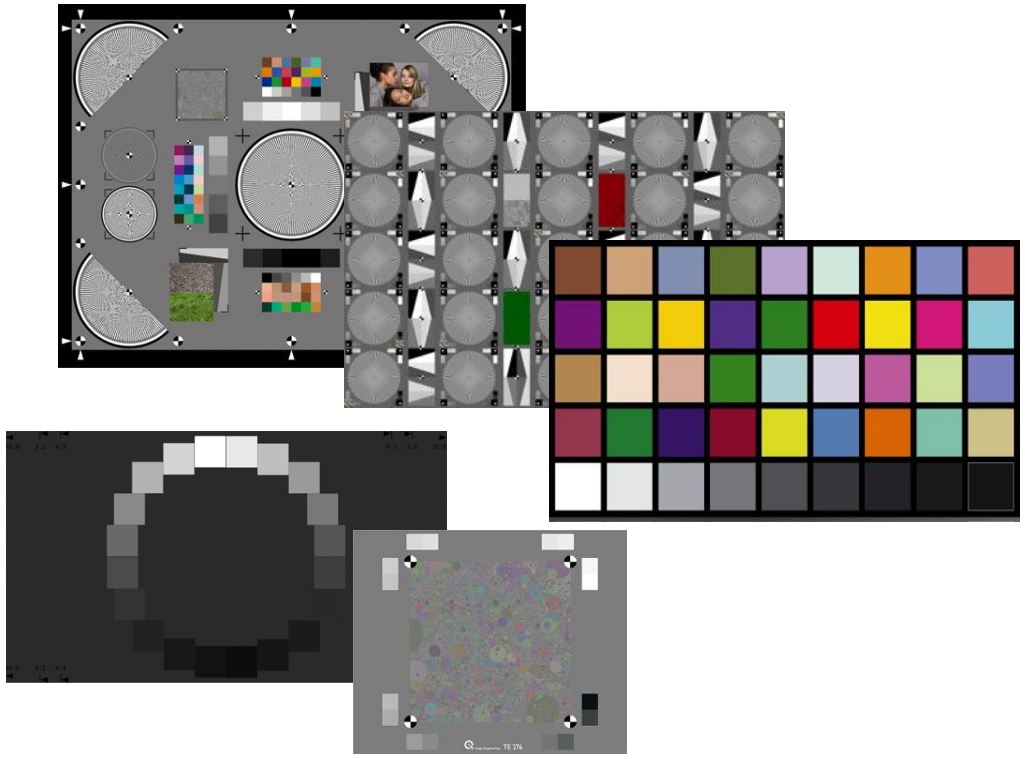
图像质量测试实验室整体解决方案

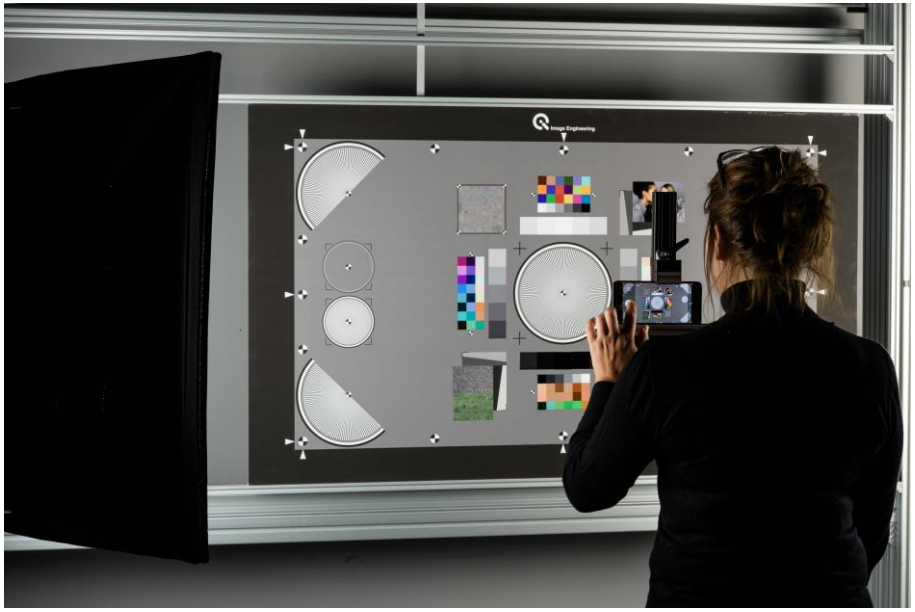


- 测试图卡跟测量设备
- 固定测试图卡、摄像头、照明设备等所需的支架配件
- 配合反射式跟透射式图卡使用的照明设备
- 图像质量分析软件

测试图卡

各类型、各标准的测试图卡我司几乎都可以提供，同时支持客户的定制图卡需求。





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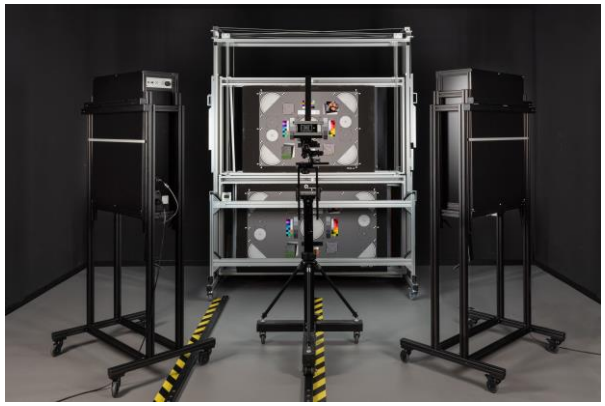
光源设备

作为行业内最先进的光谱可调光源，我司的IQ-LED 光源技术已被应用到我司全系列光源设备上——大图卡的立式补光光源、高均匀性低照灯箱、行业通用的主观实景灯箱、产线的校准集成光源...



iQ-Flatlight 立式补光光源

lightSTUDIO 主观实景灯箱

产线集成校准光源CaI3

Public

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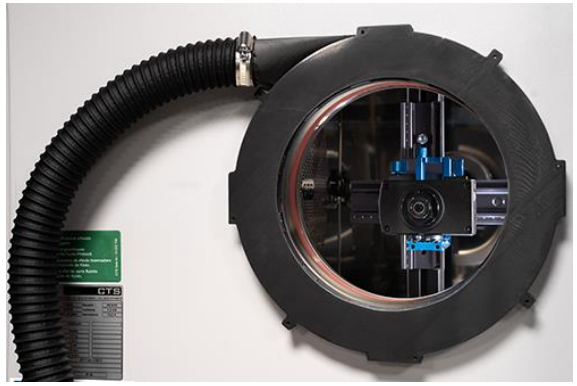
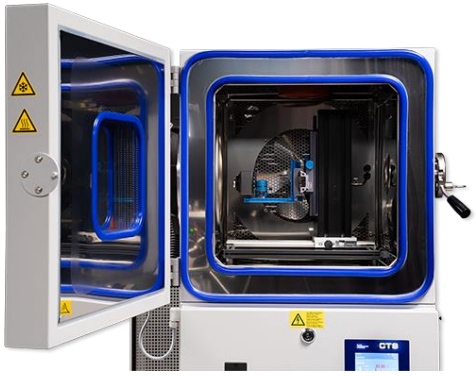
部分测量设备

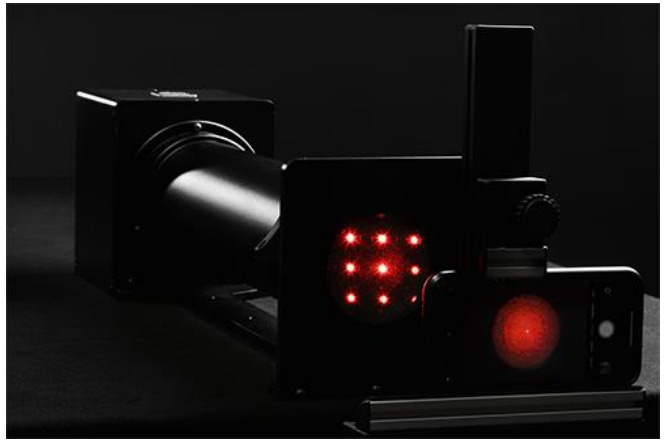
各类测试方案满足客户不同方面的需求

LED-Panel 时序测试仪





高低温环境下的图像质量评估
iQ-Climate Chamber



GEOCAL相机几何标定

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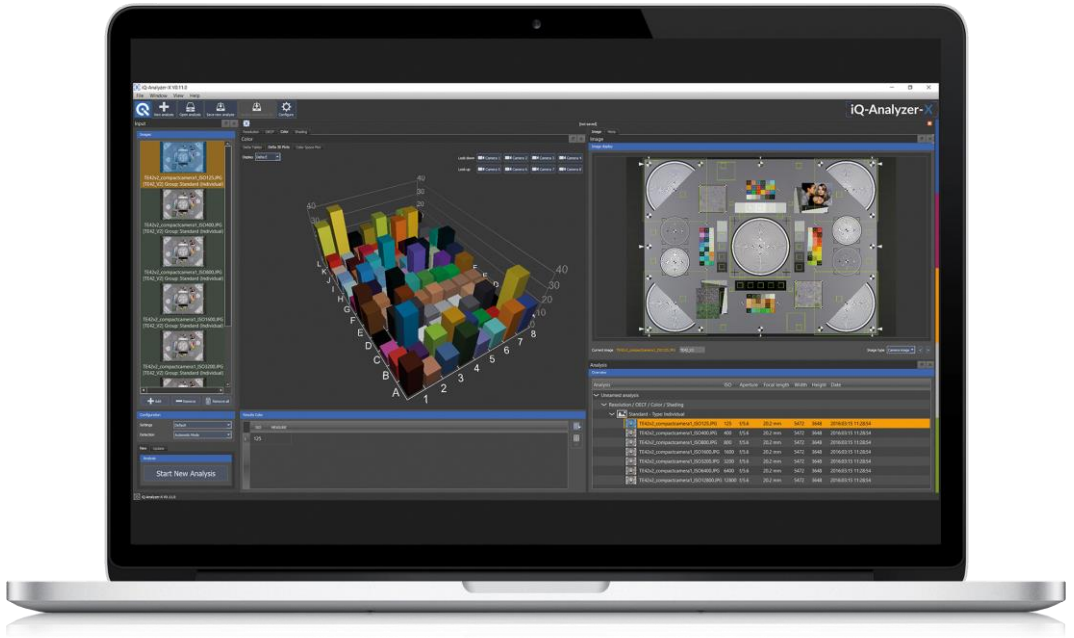
2021年我们开发了新一代专业图像质量分析软件

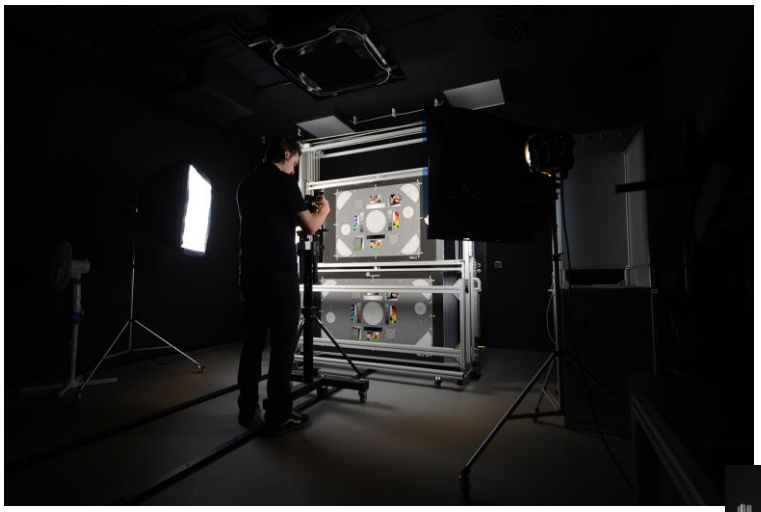
- 完全基于 C++ 语言编写
- 灵活的用户界面
- 快速分析结果
- 多功能数据库
- 图卡自动检测
- 自定义测试模板
- 分析软件参考数据



Other Services

TEST LAB

全球最大影像实验室之一

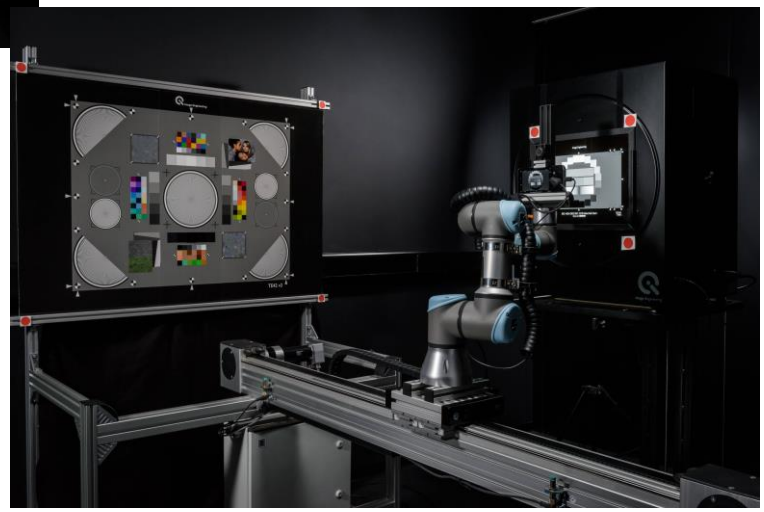


CONSULTING

与客户共同开发产品以及现场的
实验室建设咨询

TRAINING

可提供图像质量与测试相关的专业培训



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着眼于全球范围内的图像质量评估

Image Engineering 公司目前拥有三个直销点——德国本部、中国子公司与美国分公司。全球其他区域内也有40多个合作经销商，我们期待着与行业专家们共同提高摄像头的图像质量。

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leon.xiao@image-engineering.com

合作标杆客户

部分客户: 涵盖摄影、手机、汽车、安防、广播等大量行业

And many more…

合作标杆客户

部分客户: 涵盖摄影、手机、汽车、安防、广播等大量行业

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And many more…

高低温箱环境测试图像质量

汽车、手机、安防行业等，越来越关注产品摄像头在不同温度条件下的图像质量，尤其是ADAS摄像头可能会遇到温度波动带来的性能问题。

iQ-Climate Chamber

可为相机性能测试创建不同的温度场景，也是目前市场上唯一一款可以在温度受控环境下同时测试相机图像质量的设备

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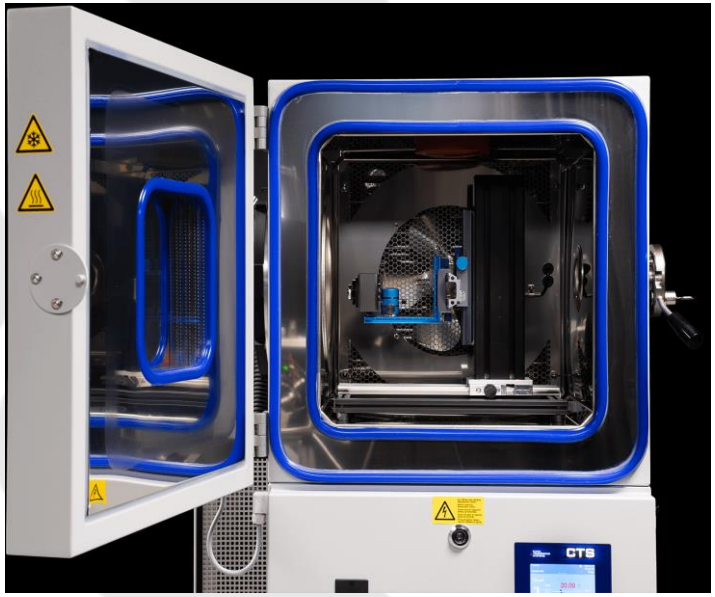
高低温箱环境测试图像质量

ADAS相机经常会遇到温度波动的性能问题。因此，这些系统必须经过严格的极端温度环境测试，才能安全地供消费者使用。

主要特点

- 可调温度范围 -30~150℃
- 温度稳定性 +/- 0.3° K
- 调温速度5℃/min
- 内置摄像头夹具
- 可通过设备直接创建测试环境与序列
- 带滚轮可移动，方便对准图卡进行实时拍摄测试



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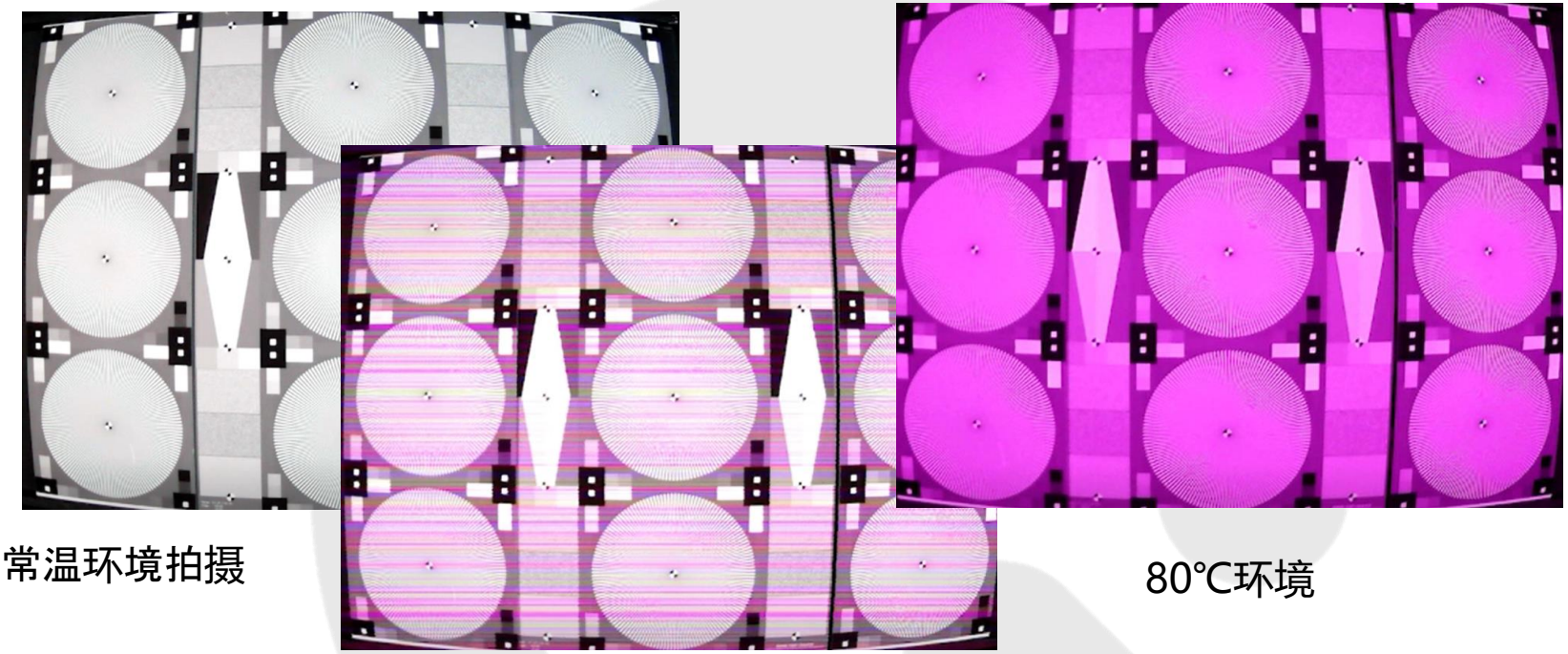
高低温箱环境测试图像质量



常温环境拍摄

45°C环境

80°C环境

在高低温环境下直接测量图像质量

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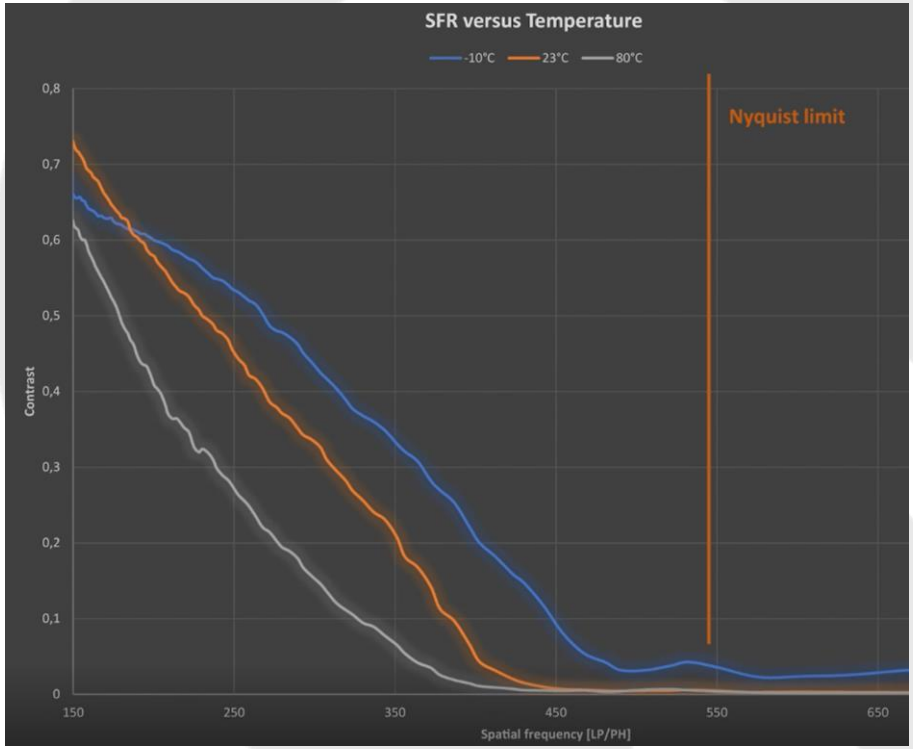
高低温箱环境测试图像质量

目前几乎所有的极端环境测试方法，都依赖于在实际的室外的自然环境中进行测试，但这些天气条件都是不可控制的。iQ-Climate Chamber, 从标准实验室的角度，提供了温度可控的重复性测量环境，实时的测量镜头的性能。



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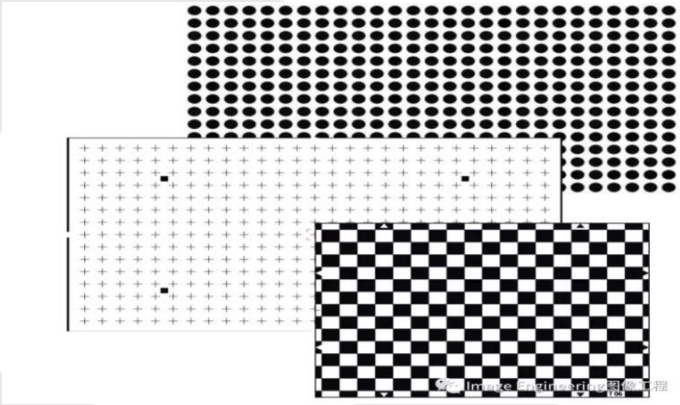
相机标定测试

在影像行业有许多测试图卡和软件可以确定相机的几何标定、失真。

在汽车应用中，基于所测量的摄像机的几何特性来计算到物体的距离。

使用增距镜的确是一种常用的解决距离限制的方案。但是使用这些增距镜并不完美。



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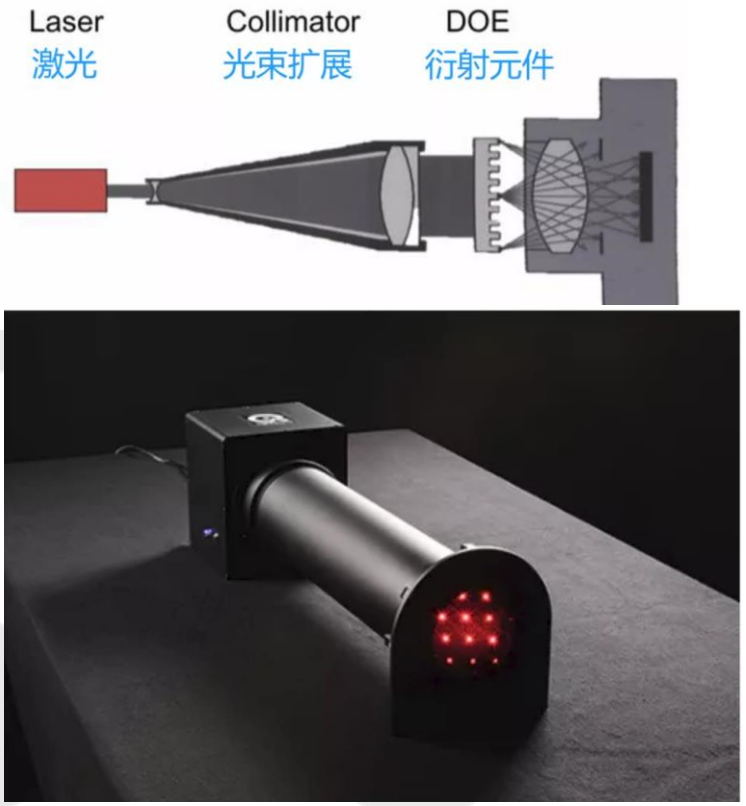
相机标定测试

Geocal——几何校准设备，该解决方案基于衍射光学元件（DOE），该衍射光学元件被由扩展的激光二极管光束产生的平面波照射。来自激光器的光束被放大，光面波落在DOE上。

光束波长为632.8nm，扩束后直径为 75 mm，
支持最大视场角150°，它具有以下特征:

- ✓ 可产生无限远距离的规则光点网格
- ✓ 在一定范围内可调整相机位置
- ✓ 方便调整摄像机旋转角度
- ✓ 不需要使用增距镜
- ✓ 校准大视场角摄像机
- ✓ 立体摄像头调整
- ✓ 非常紧凑的设计



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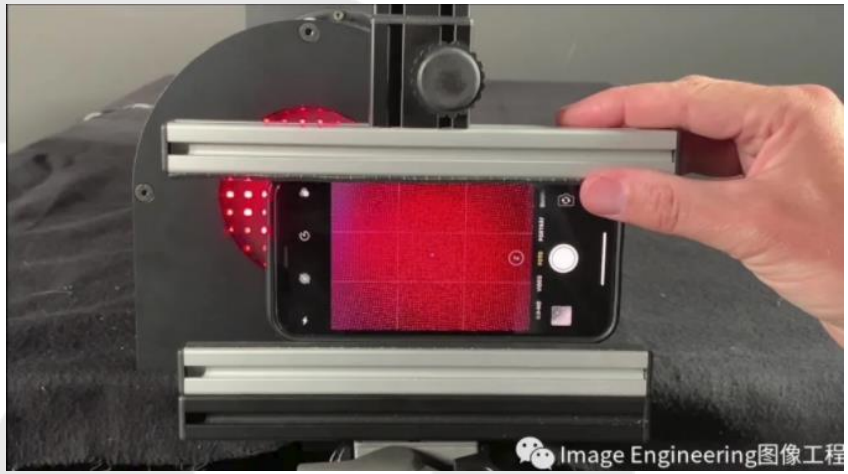
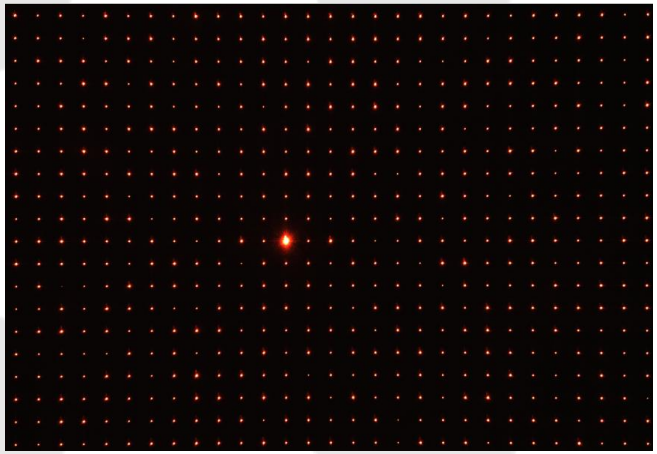
相机标定测试

我们可以计算相机标定所需的所有必要值：

- 内参主点u0、v0
- 焦距f
- 失真系数k1、k2、k3
- 测试设备的倾斜角度α，β
- 外部相机方位ω，φ，κ
- 均方误差值辅助验证畸变





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广角镜头相机标定

Geocal-XL版本

具有更大发光口的Geocal，支持更大角度的镜头进行标定

功能与标准版一样，但发光口直径为 150 mm

支持最大视场角180°，非常适用于车载行业。

XL版与标准版对比

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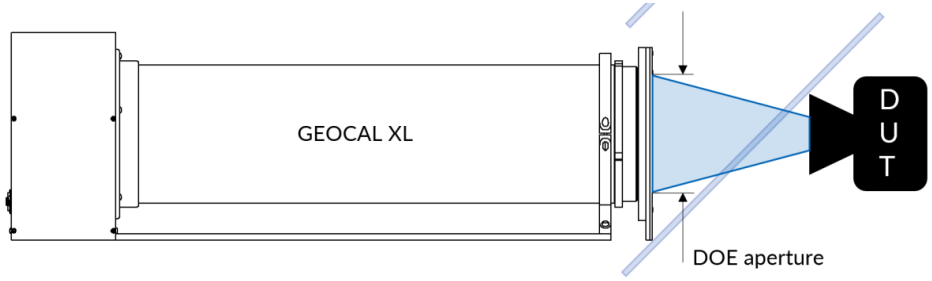
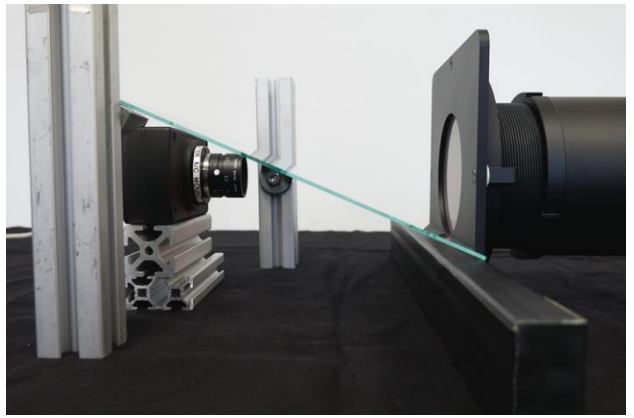
广角镜头相机标定

Geocal-XL版本

对于畸变模型，支持针孔、鱼眼切换分析



XL版本可在发光口与标定设备间
添加“挡风玻璃”



测试样例

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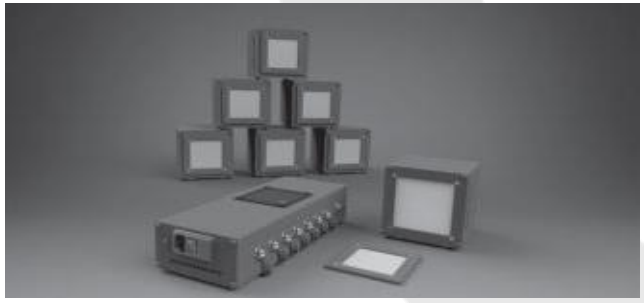
Vega直流光源

- Vega 最适用于高强度测量，如对比度检测概率 （CDP）、调制光缓解概率 （MMP）、噪声和色调曲线测量。这些测量非常适用于汽车级摄像头和其他对精度要求很高的系统。

- Vega 可选择不同用途的组合，包括1个光源的基础集，3个光源的Flicker测试集和包含7个光源的CDP 测试集。每个组合都配有控制器和控制软件。



CDP测试套装

搭配图卡

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Vega直流光源

Vega 是一种直流光源，用于对相机系统进行高精度测量，例如曝光时间极短的镜头测试。

它使用由直流（DC）技术驱动的 LED，使其成为我们开发的最先进和最独特的光源之一。

- 直流驱动的LED技术
- 高稳定性DC直流光源
- 温度稳定
- 高级Flicker编辑功能
- 多种波形可调（正弦波、三角波和方波）
- API控制/程控
- 可自选搭配数量

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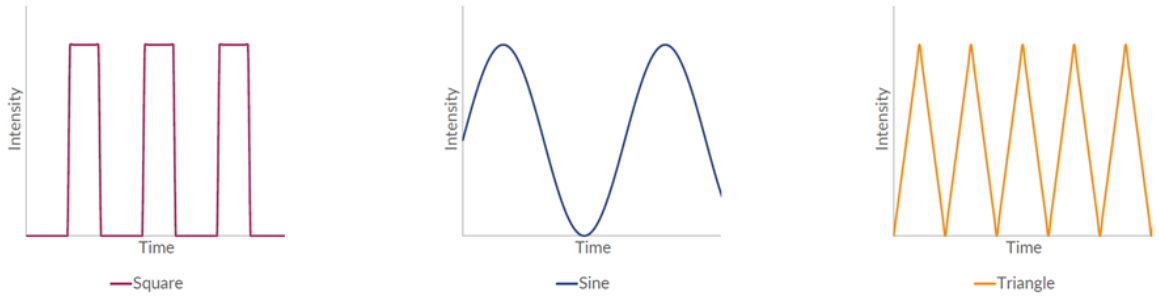
Vega直流光源

与PWM 控制的光源不同，Vega根据电流的电流量调节强度。Vega 提供 1,000,000个等宽步骤用于强度控制。

Vega还具有高级Flicker闪烁调节功能，可从更宽的频率范围生成。我们进一步开发了低频功能，包括正弦波、三角波和方波波形，使我们能够覆盖几乎所有实际生活的Flicker场景。



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iQ-LED –可自定义光谱的光源

iQ-LED在可控的实验室环境中可以创建各种常用的测试光源。这种技术目前更新到第二代（V2）,已经应用到了我们的大多数光源设备上。

iQ-LED V2几乎可以还原、复制任何光源，以确保摄像头更精准的测试跟校准。

- 光谱可调光源
- 20个光谱通道
- 高频PWM模式可达128KHz
- 波长范围为380~820nm
- 可不连接PC直接控制设备
- 可连接多个iQ-LED光源设备
- 通过温度控制保证长期稳定
- 通过温度控制保证短时间高亮度的光谱稳定

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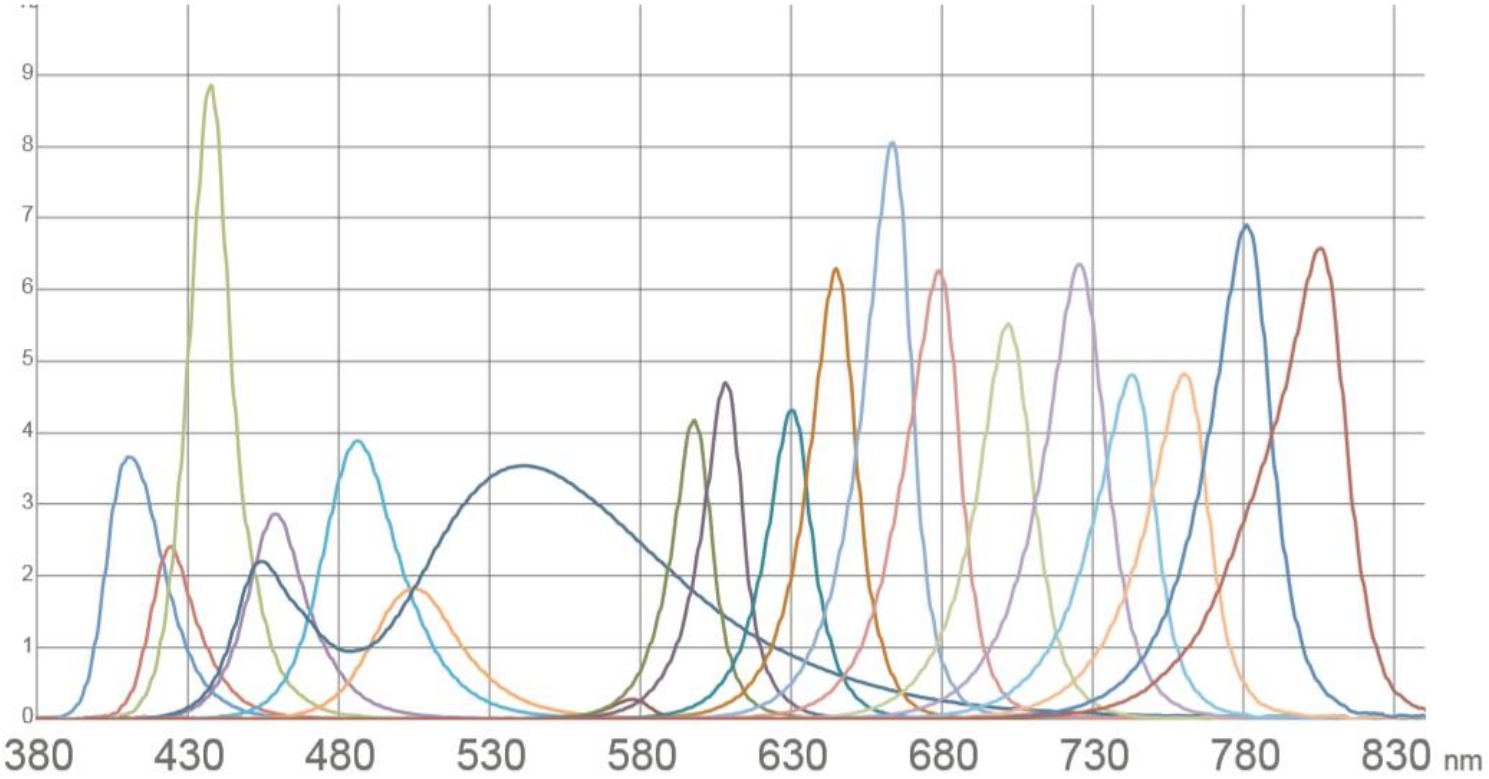
iQ-LED多通道混光技术

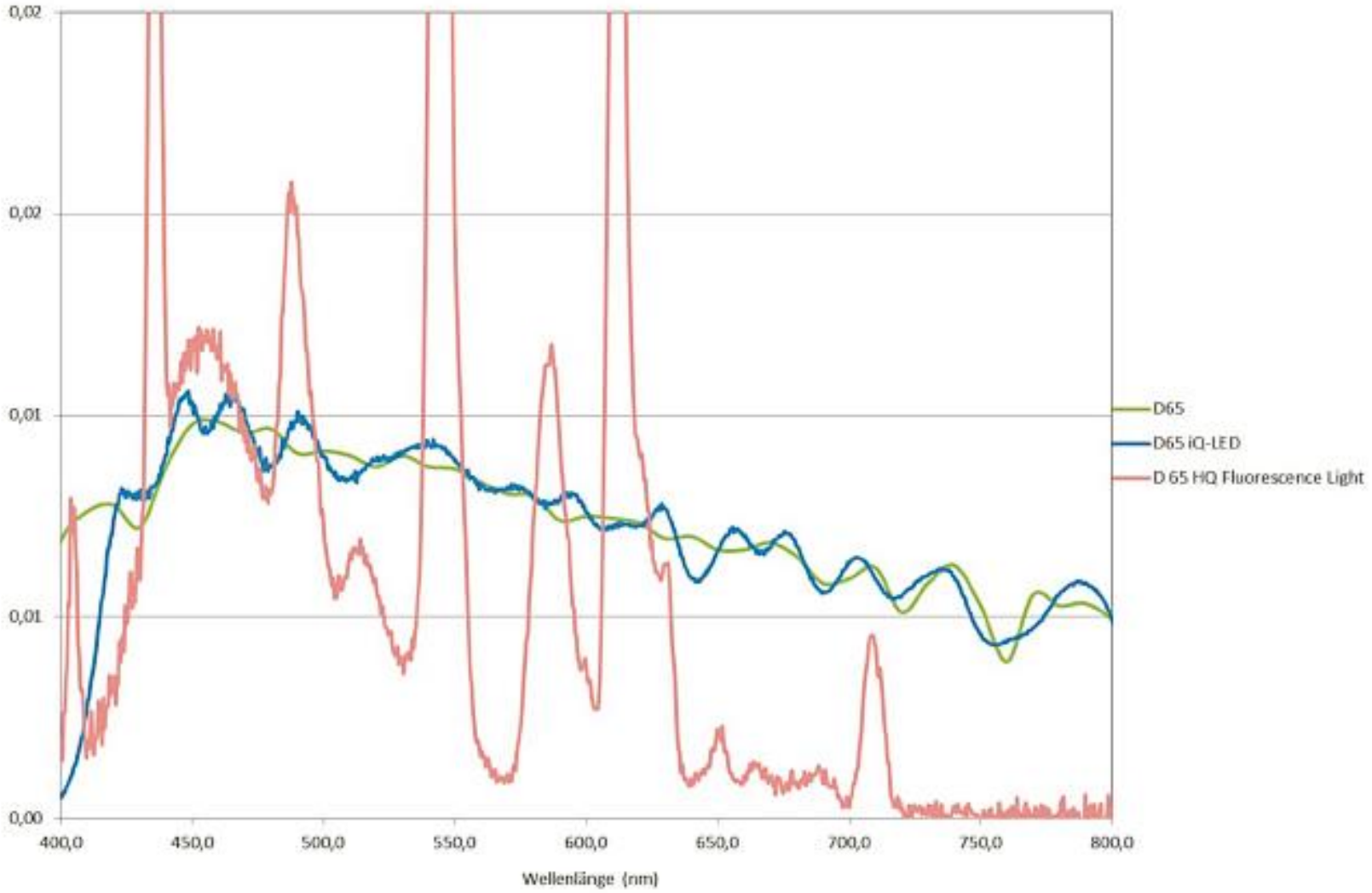
- iQ-LED技术使用NIST可溯源校准光谱仪和iQ-LED控制软件来校准并正确生成光谱。一旦正确校准，光源就可以存储在设备上，无需PC即可使用。单台设备上最多可存储44个光源和一个序列。
- iQ-LED 技术*可通过光学混合来自多个LED 的光谱生成自定义的连续光谱。标准模块是由10*10 cm板上的41个高功率 SMD LED产生的 20个不同通道组成。



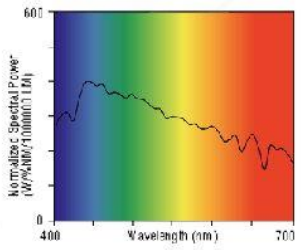
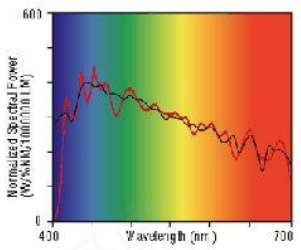
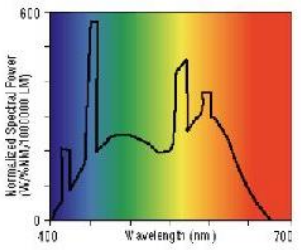
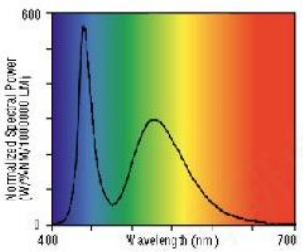
20 individual spectral channels

iQ-LED光源完美模拟目标光源

D65 – created by Fluorescent light tubes and the iQ-LED technology

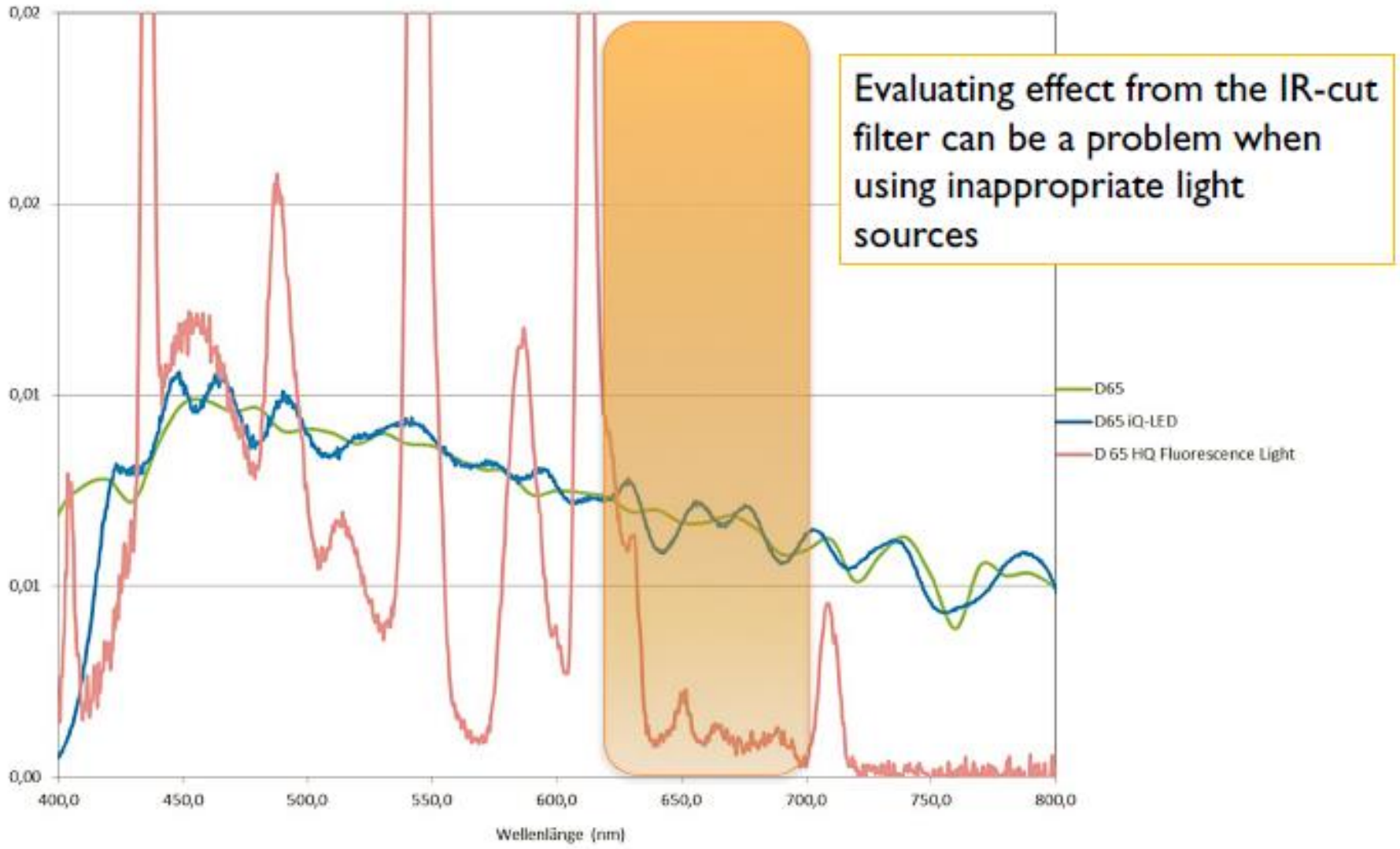


- 各种光源的光谱以及效果对比图

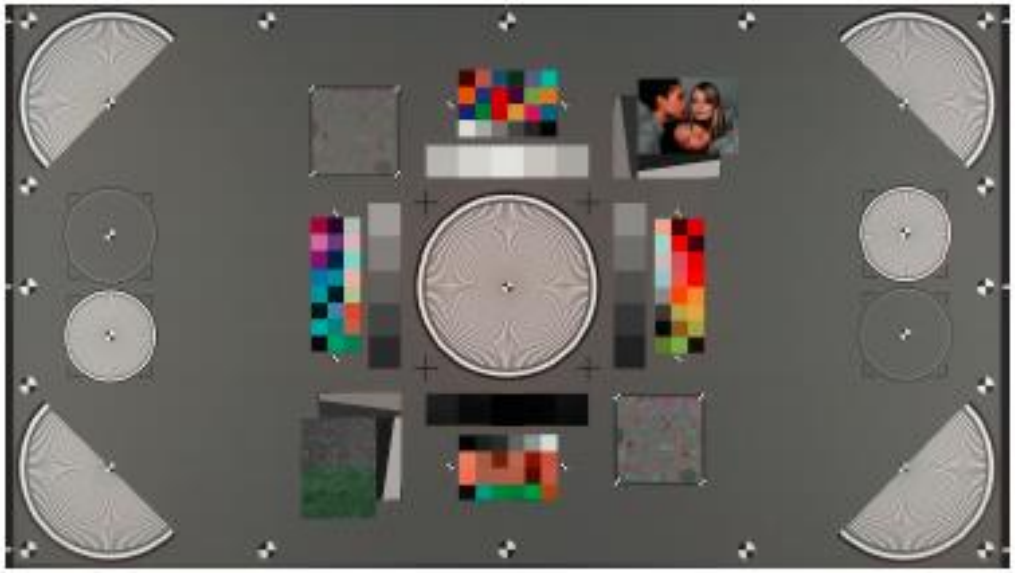
光源	日光	iQ-LED	普通灯管	普通LED
6500K 光谱				
成像参考				

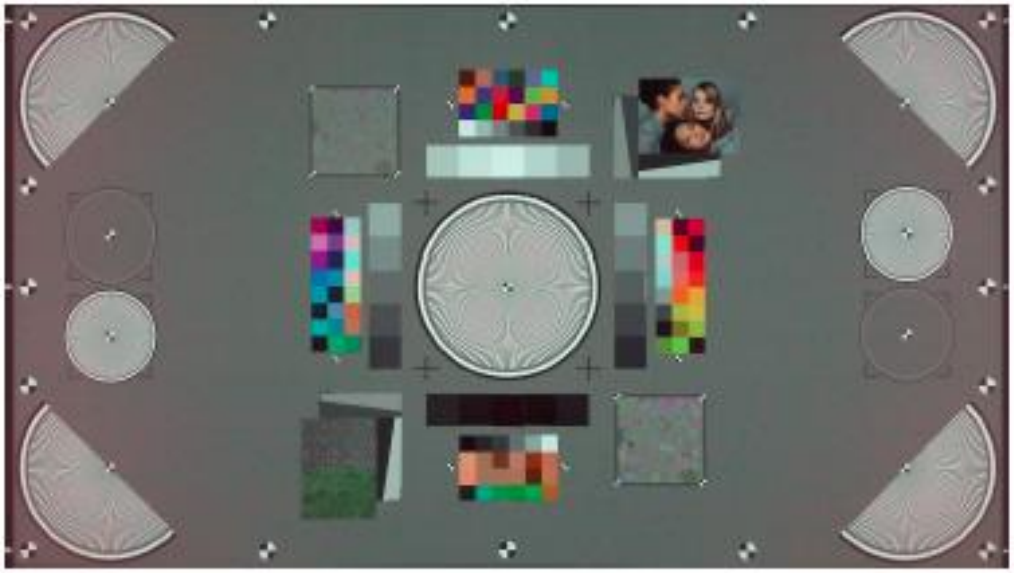
近红外光谱的重要性NIR effect

D65 – created by Fluorescent light tubes and the iQ-LED technology



Importance of light spectrum

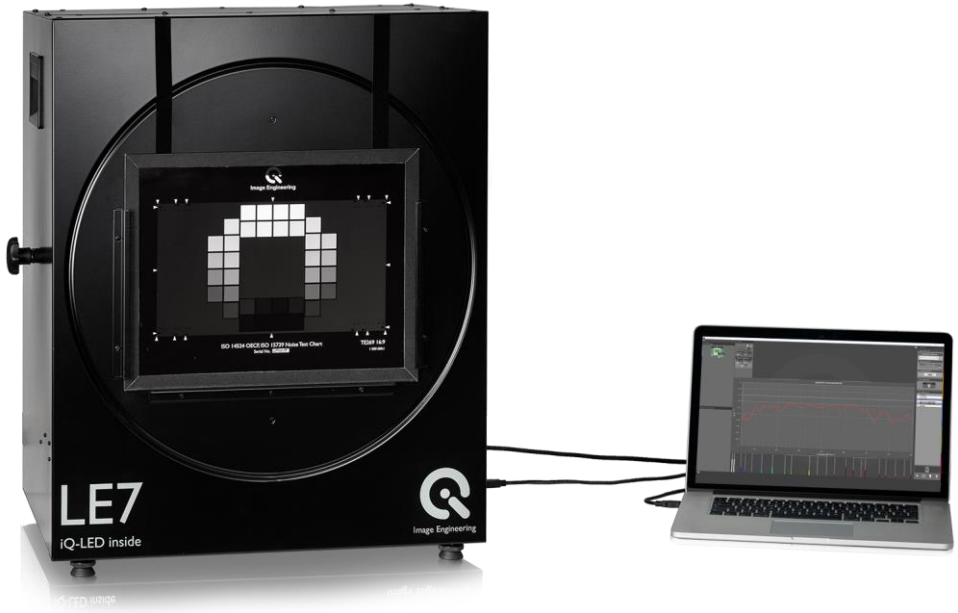




Example: Colorshading visible and not visible – both were light sources with 5500K CCT, but based on flourescent and the other including IR

同样5500K色温的光源，左侧无近红外光源无法测试出Color Shading的问题。
右侧iQ-LED光源可以测试出Color Shading问题。
结论：摄像头测试光源光谱需要覆盖400nm-820nm

基于IQ-LED技术所研发的光源设备



配合光源:IQ-Flatlight——行业内最先进的测试光源（VCX测试指定测试光源）

iQ-Flatlight采用了iQ-LED技术, 使用10个iQ-LED来重现用于测试图卡或场景照明的几乎所有光源。这种集多种功能于一身 的光源大大扩展了光学实验室的测试能力。

主要特点

- 包含 iQ-LED 光源所有功能（光谱可调、色温从1900-18000K完美模拟，照度可调、不连接PC直接使用光源，最多可储存44个光源跟1个序列等）
- 用于相机测试的光谱可调光源
- 用于 VCX 测试指定光源
- 大图卡补光均匀性> 90% (样本参考设置)
- 手动可调的荧光灯选项

LE 7 透射式图卡测试专用灯箱：

采用IQ-LED技术，具有高亮度、高均匀性，配合透射式图卡可有效提高相机图像质量测

主要特点

- 包含iQ-LED光源的所有功能
- 在图卡范围内均匀度>97%
- 可提供2x、4x iQ-LED模块
- IR版本提供可见光和近红外波段光谱

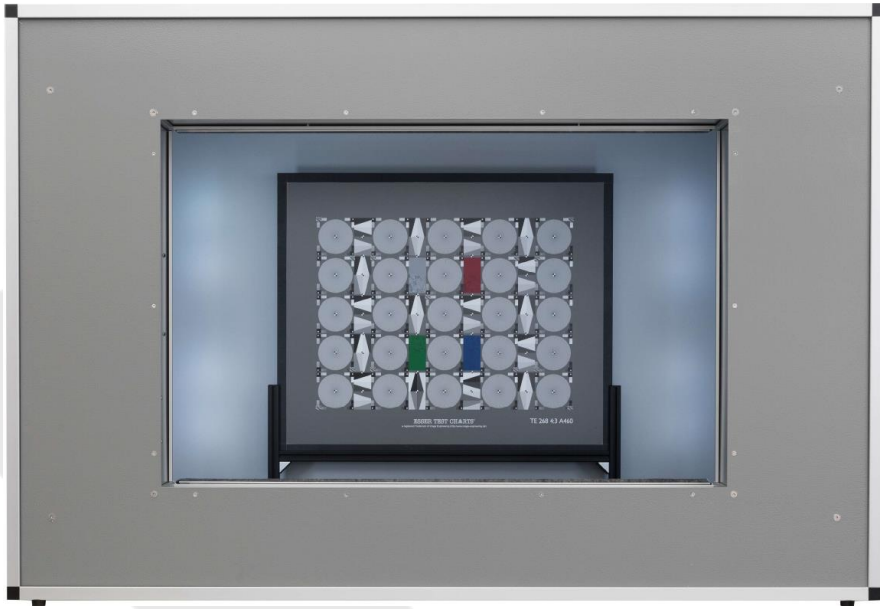
此外，LE7 还有红外版本 LE7-IR供选择，
它使用两个普通的 iQ-LED 模块和四个 iQ-LED IR 模块。每个 IR 模块有11个额外的光谱通道， 并将光谱范围扩展至380-1050 nm。

用于反射式测试图卡的高均匀性灯箱

iQ-Chart Box采用紧凑型设计，内置8个iQ-LED灯头和4根荧光灯管，用于照亮A460及以下尺寸的反射测试图卡。 每组光源都对称固定，以确保始终均匀照明测试图卡。

主要特点

- 包含iQ-LED光源的所有功能
- 均匀度> 95%（图表尺寸A460）
- 用于尺寸A460和A280大小反射测试图卡
- 荧光灯光源可选
- 专为空间有限的实验室而设计



专为小型实验室设计，占据空间小，灵活方便

Subjective Testing

主观评测利器——实景灯箱

主观实景测试

许多图像质量都可以通过测试图卡得到最好的测试。不过也有一些比如白平衡，可以用真实场景更好地分 析。lightSTUDIO包含各种颜色和纹理的多个测试对象，用于准确的视觉分析。

主要特点：

两种光源组合供选择：IQ-LED 光源与荧光 灯管、卤素灯组合光源相同的内部实景道具，便于不同地点实验室 之间的比较

可选移动模块，用于测量运动伪影

可选HDR模块，用于评估高对比度场景

可用PC软件控制所有灯箱组件

通过lightSTUDIO内部的实景道具评估主观图像质量

1. 分辨率
2. 纹理细节
3. 锐化
4. 近红外灵敏度
5. 灯光细节
6. 阴影细节
7. 摩尔纹
8. 畸变
9. 人体皮肤再现
10. 色彩还原
11. 常见的自然已知的颜色
12. 低对比度细节

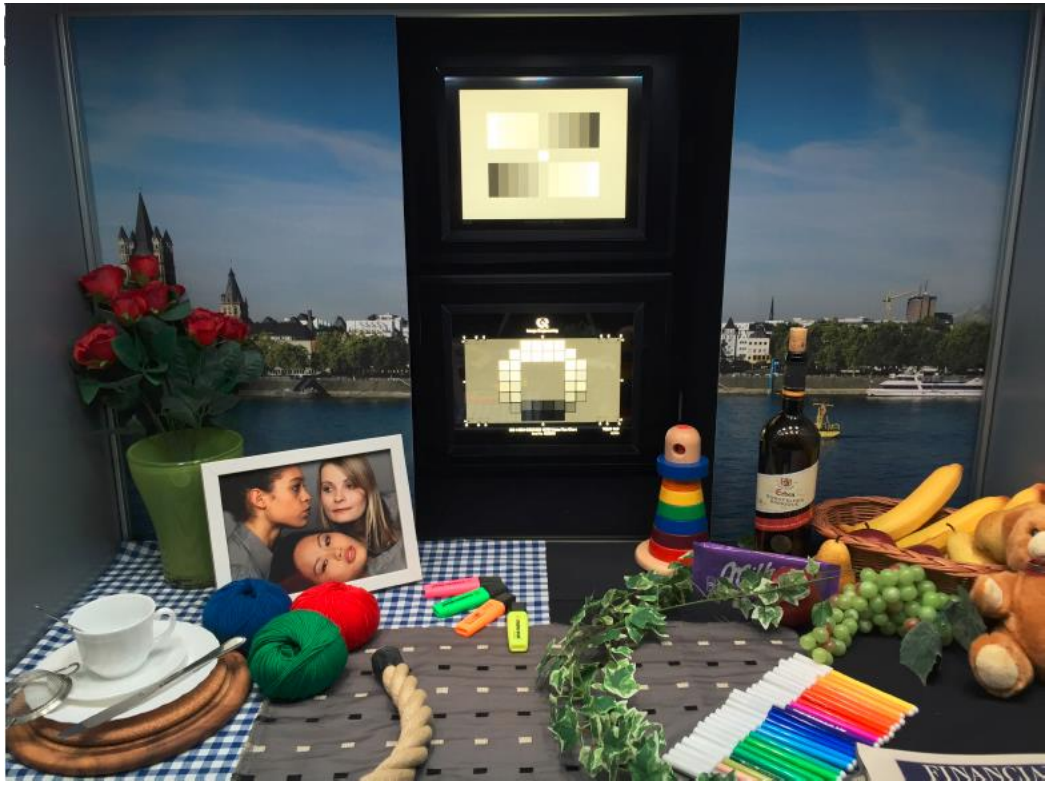
HDR版本实景灯箱

模拟室内室外场景

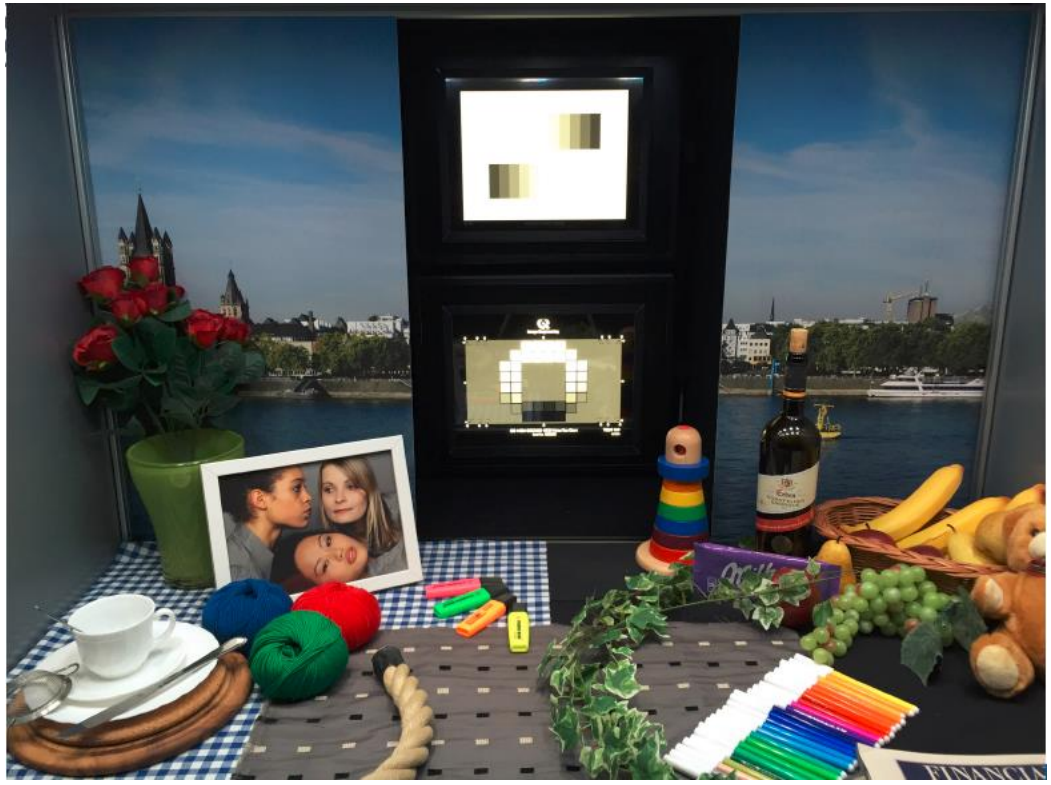
2个可单独调光的LG4灯箱，支持插入透射式图卡

HDR版本实景灯箱

HDR on

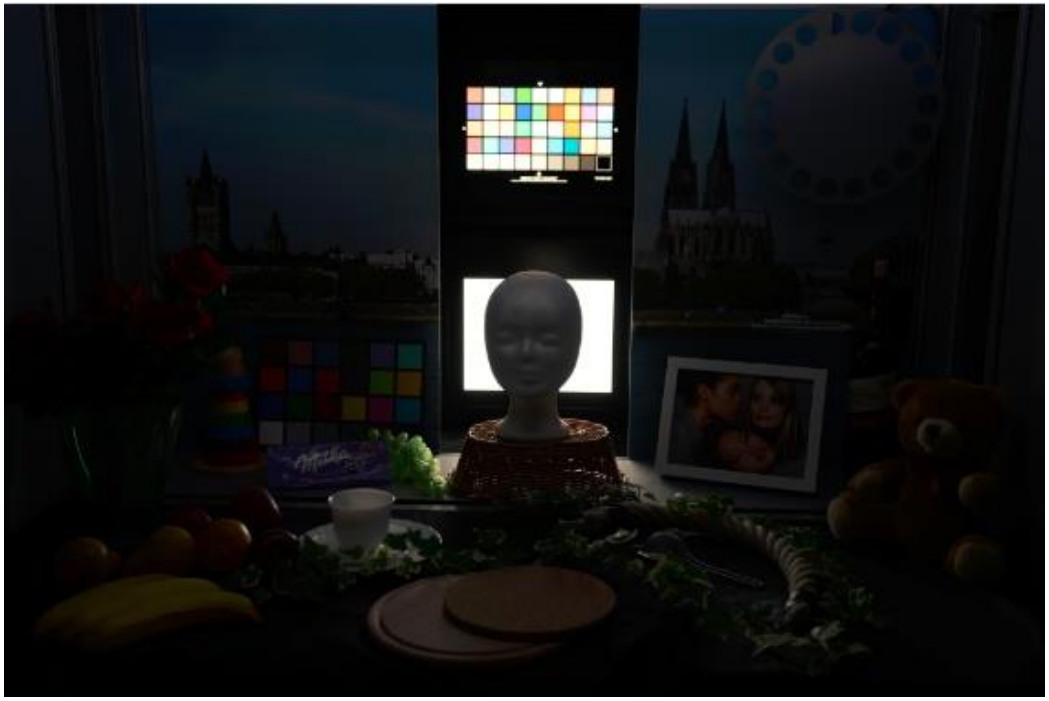


HDR off



HDR版本实景灯箱

逆光场景的评估

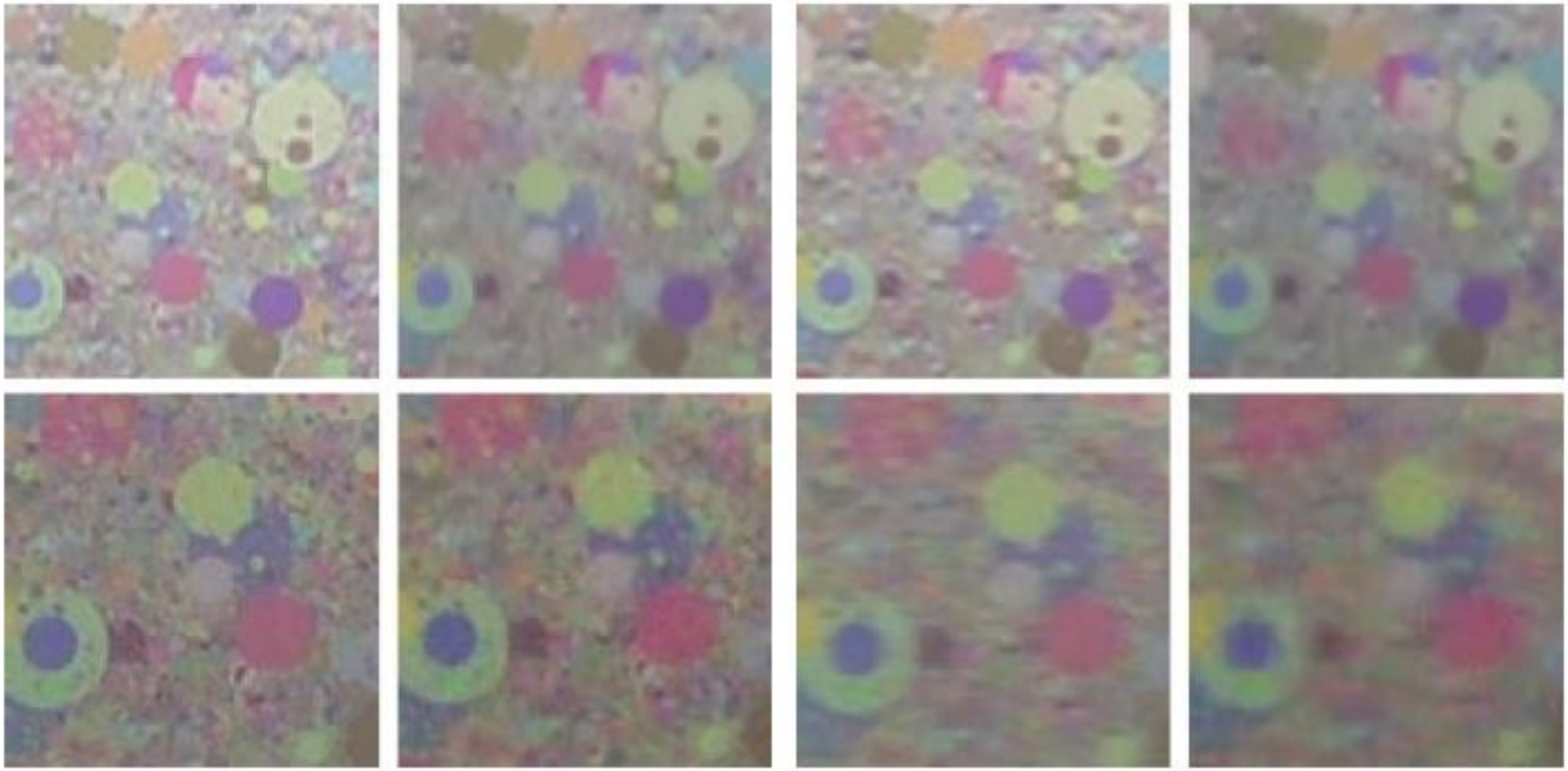


Moving版本实景灯箱

lightSTUDIO with moving targets

- Two moving targets horizontal and rotating.
- The speed of the motion is adjustable up to 3 m/s.
- Measurement of image quality on moving objects
- Evaluation for ghosting and other artifacts

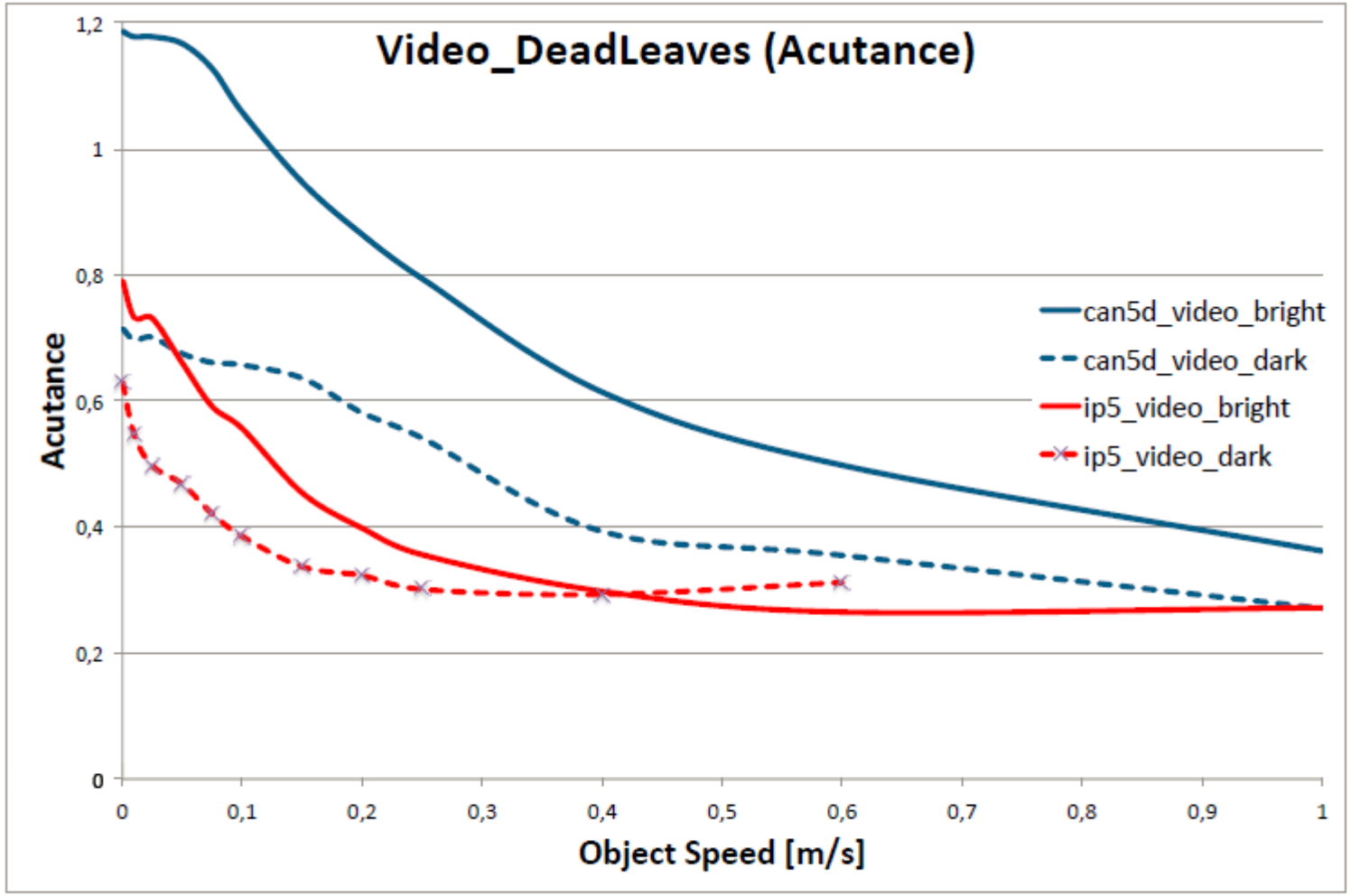
lightSTUDIO-M 版本内置移动模块，其中的移动框架默认搭配一张枯叶图卡，配合实景灯箱进行不同功能的测试。这些功能在测试照片和视频中的运动伪影 和模糊时非常有用。



(a) No object movement　　(b) Object moved with 0.2 m/s

放大视频帧的情况下的枯叶图表现。
上图：佳能5D MKIII，下图：苹果iPhone5，左：亮，右：暗

Object Speed vs.Acutance



Object speed vs. Acutance (Dead Leaves)

Automated solution using the lightSTDIO

车载摄像头动态范围测试

- 一款具有超高亮度又带有Flicker测试功能的灵活透射式灯箱
- 通过用超过150000勒克斯的光照亮高动态范围的测试目标，以了解相机设计的差异。同时LG3还 可以模拟Flicker的光源，使其成为图像质量测试实验室最强大和最灵活的灯箱之一。

主要特点

- 超高亮光源：最高可至15万勒克斯
- 闪烁频率跟占空比均可调
- 步径可微调
- 有效扩大测试范围 相对照度稳定性＞98%

LG3可与我们的高动态范围测试图卡（如TE269C）同步工作。 因为具有如此高动态范围的目标 需要强大的照明，以便为被测相机生成逼真的信号。闪烁的光源（例如脉宽调制驱动的LED）是相机在许多应用的问题。 LG3可以在您的测试实验室中生成这些光源，以评估相机处理这些光线 情况的能力。

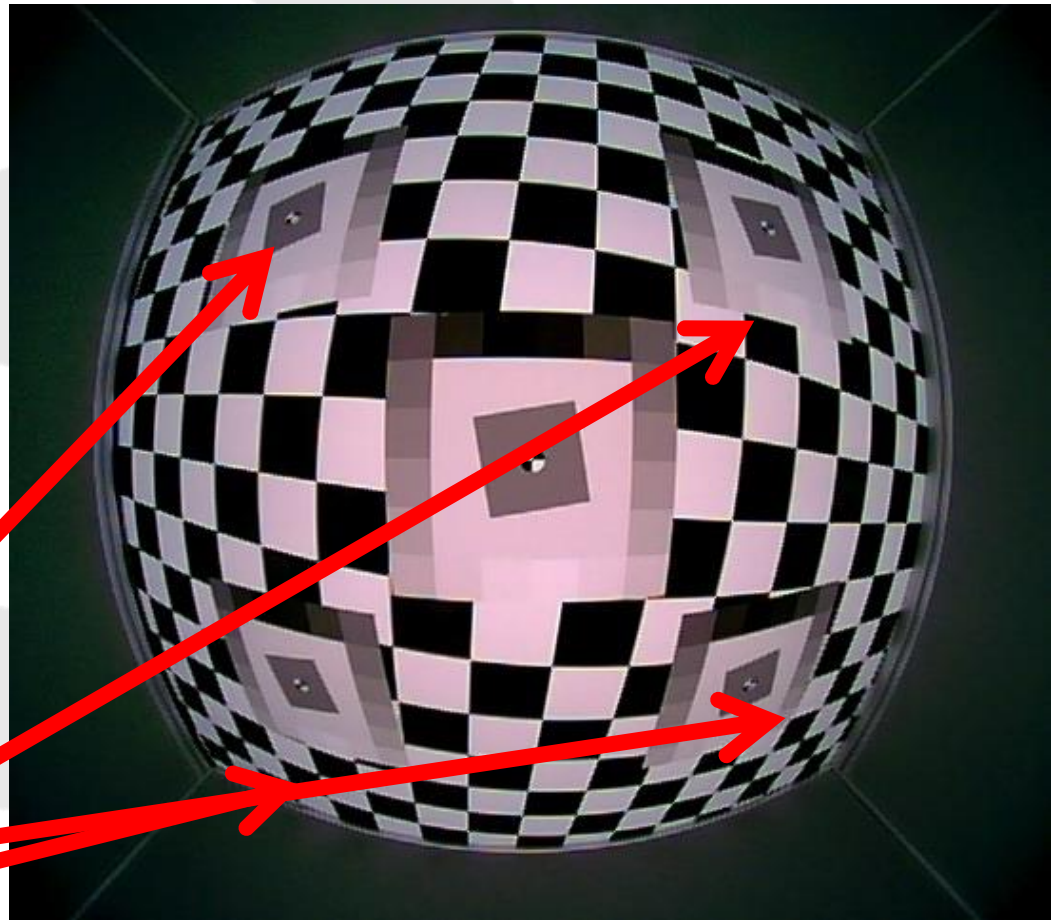
LG3 配合 OECF 测试图卡 TE269C

可以使用LG3重新创建各种光频率

基本信息	LG3
概述	光源具有多种广范围的强度以及特殊的Flicker模式
Light source	432 LEDs
色温	approx. 5000 K +/- 5%
亮度范围	Low mode: < 10 to > 6500 lx Normal mode: < 100 to > 65000 lx High mode: > 150,000 lx
均匀性	> 95% for active chart area**, 280.0 x 157.5 mm > 95% for full output window**, 290.0 x 220.0 mm > 95% (70 mm diameter circle)** approx. 90% at very low intensity (intensity < 1%)
亮度调节方式	2种模式下大约1000个步径，可在控制器上选择照度 32 kHz PWM

大视场 + 分辨率测量 FOV-BOX

使用平面视场目标



角落是问题所在...

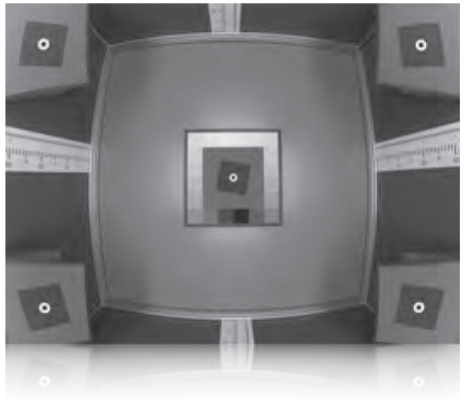
广角镜头分辨率测试专用灯箱——FOV BOX

FOV BOX

用于测量近距离监控条件下广角摄像头分辨率

测量广角摄像头要求一个特殊的方案。FOV　BOX是一个用于分辨率领域图像质量测量的灵活工具。因为测试图卡的位置可调，图像的测试模式畸变就会最小化，斜边的分析方法也适用。畸变以及分辨率这两项重要的因素，可以用分析软件进行自动分析。

Interior with measurement scales



IQ广角镜头测试灯箱	
原理	广角镜头测试箱
光源	8个18W的荧光灯管，色温5000K
伸出臂的行程	75 cm / 15 cm
旋转范围	Pitch: +/- 15° Yaw: +/- 170° (通过程控实现机械可调)
旋转幅度	+/- 10°（可手动）

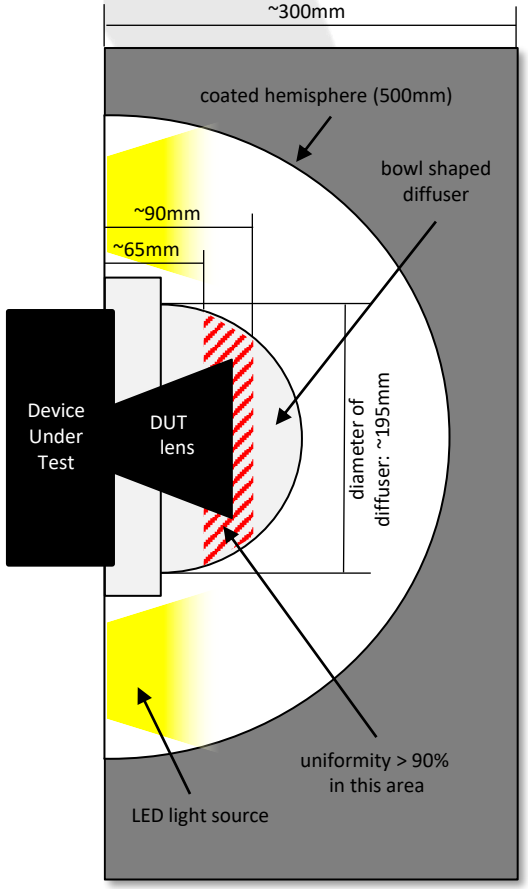
主要特点:

- 用于测量鱼眼镜头 最大视场角180°
- 测试图卡定位灵活
- 照度可调节
- 带有镜头准确定位系统

车载摄像头测试广角测试光源

超广角镜头校准光源——Cal 3XL

CAL 3-XL 是基于iQ-LED技术，具有196 mm圆形开口，可实现均匀照明的积分球光源，是广角镜头校准跟测试的理想选择。由于设备自身的尺寸，CAL3-XL使用四个iQ-LED灯头，而不是普通积分球CAL3使用的一个。四个iQ-LED灯头才能确保在更宽开口条件下的照度均匀性。



大广角 —均匀性测试和校准　　Cal 3光源

CAL3是一个直径0.3米, 基于iQ-LED技术, 38毫米凹形弯曲开口的积分球光源。

与平面校准光源 (CAL1) 相反的弯曲开口更适合
射板材质的球形开口确保了照度的均匀性

主要特点

- 包含所有iQ-LED光源特有的功能
- 均匀性＞95%
- 最高可支持180度可视角摄像头测试
- 紧凑型设计
- 可用于产线集成

车载摄像头测试

使用我们的 CAL 系列光源，您可以做如下测试：

检测缺陷像素
分析亮度和色彩均匀性 （ISO 17957）
校准曝光 （ISO 12232）
调整和验证白平衡
确定系统的增益、OECF 和线性度
测量光谱灵敏度以计算颜色校正矩阵

Image Engineering 积极参与 IEEE P2020标准的制定

IEEE P2020 Automotive Imaging Whitepaper

The IEEE P2020 Working Group[1]

[1]https://standards.ieee.org/develop/project/2020.html

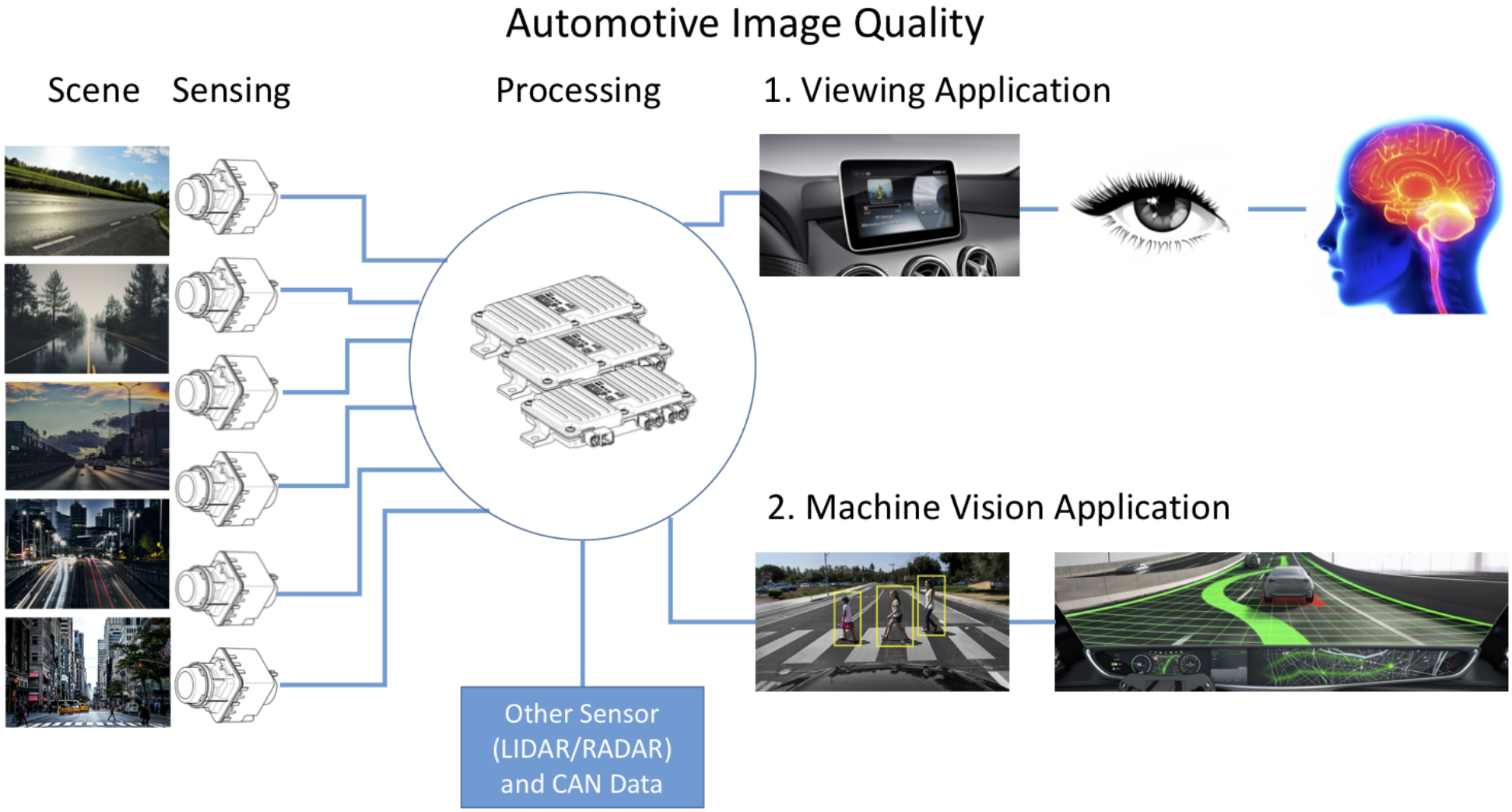
Abstract

The IEEE-SA P2020 working group on automotive imaging standards was established in order to address the considerable ambiguity in measurement of automotive vision systems, both human and computer vision based. This whitepaper lays out the goals, achievements, rationale and plans.

Index Terms

automotive imaging, image analysis, standards, autonomous driving, image quality, KPIs, IQA, video quality

Image Engineering 积极参与 IEEE P2020标准的制定



Example

Project 1: Flicker

如何测量和描述Flicker？

Project 1: Flicker

How to measure and describe Flicker?

摄像机如何动态响应不断变化的场景对比度？

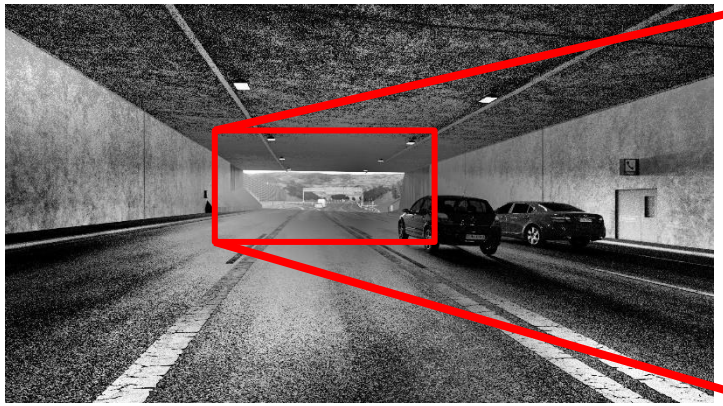
正在讨论的新指标：CDP —— 对比度检测概率

眩光 (照在脏污挡风玻璃上的阳光)

无眩光 (进入隧道)

Detection Probabilities

Examples for object loss due to fog or exposure / tone mapping



HDR色调渲染 - 中等强度的对比度损失

- ADAS摄像头测试方案——DTS 综合测试仪

ADAS摄像头综合测试仪

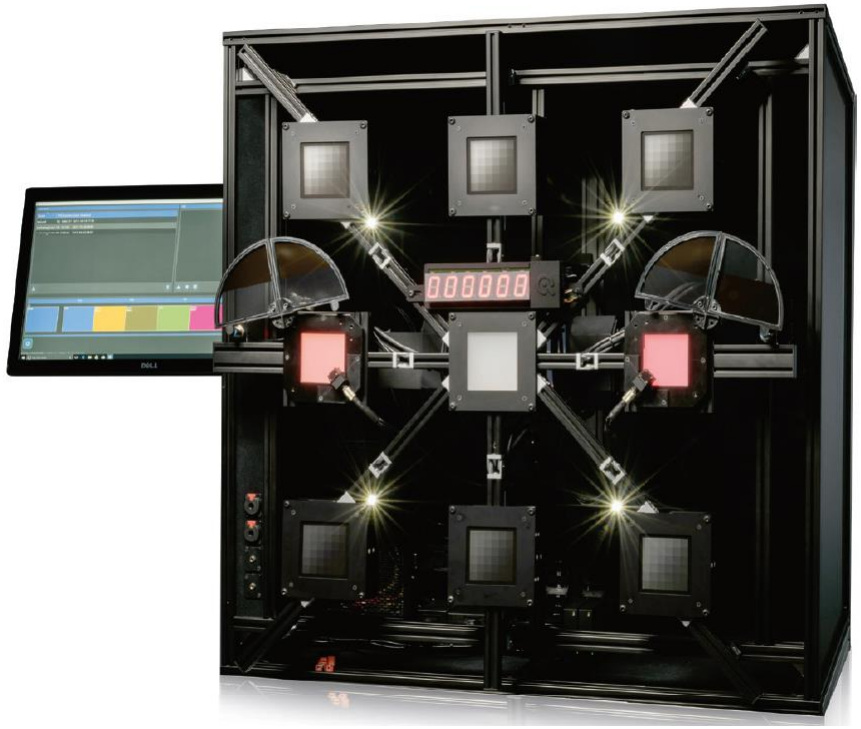
- Dynamic Test Stand – DTS

测试ADAS 摄像头系统的性能和有效性

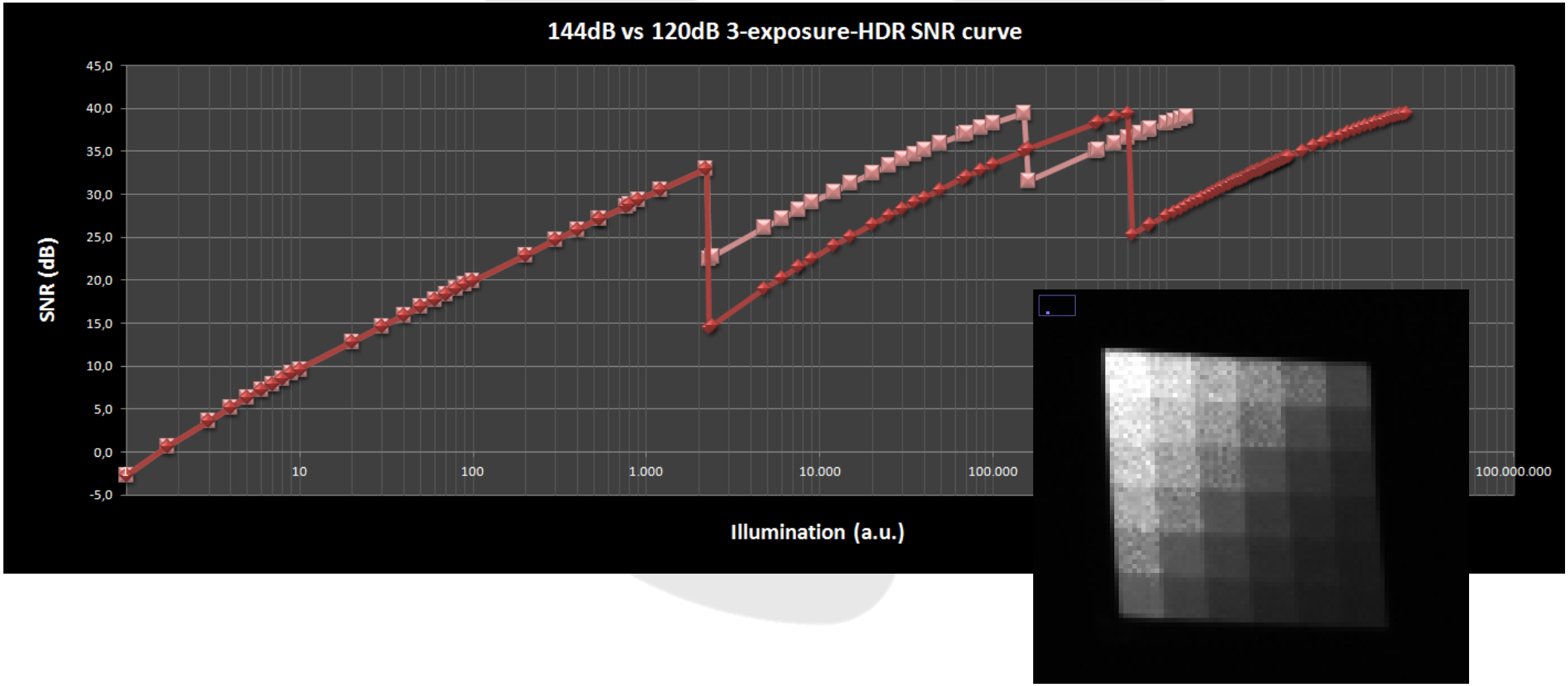
- DTS采用对比度检测概率(CDP)以及其他方式来测试车载摄像头在其视野范围内识别和探测物体的能力。DTS始终与IEEE-P2020 *工作组的目标保持一致。

主要特点

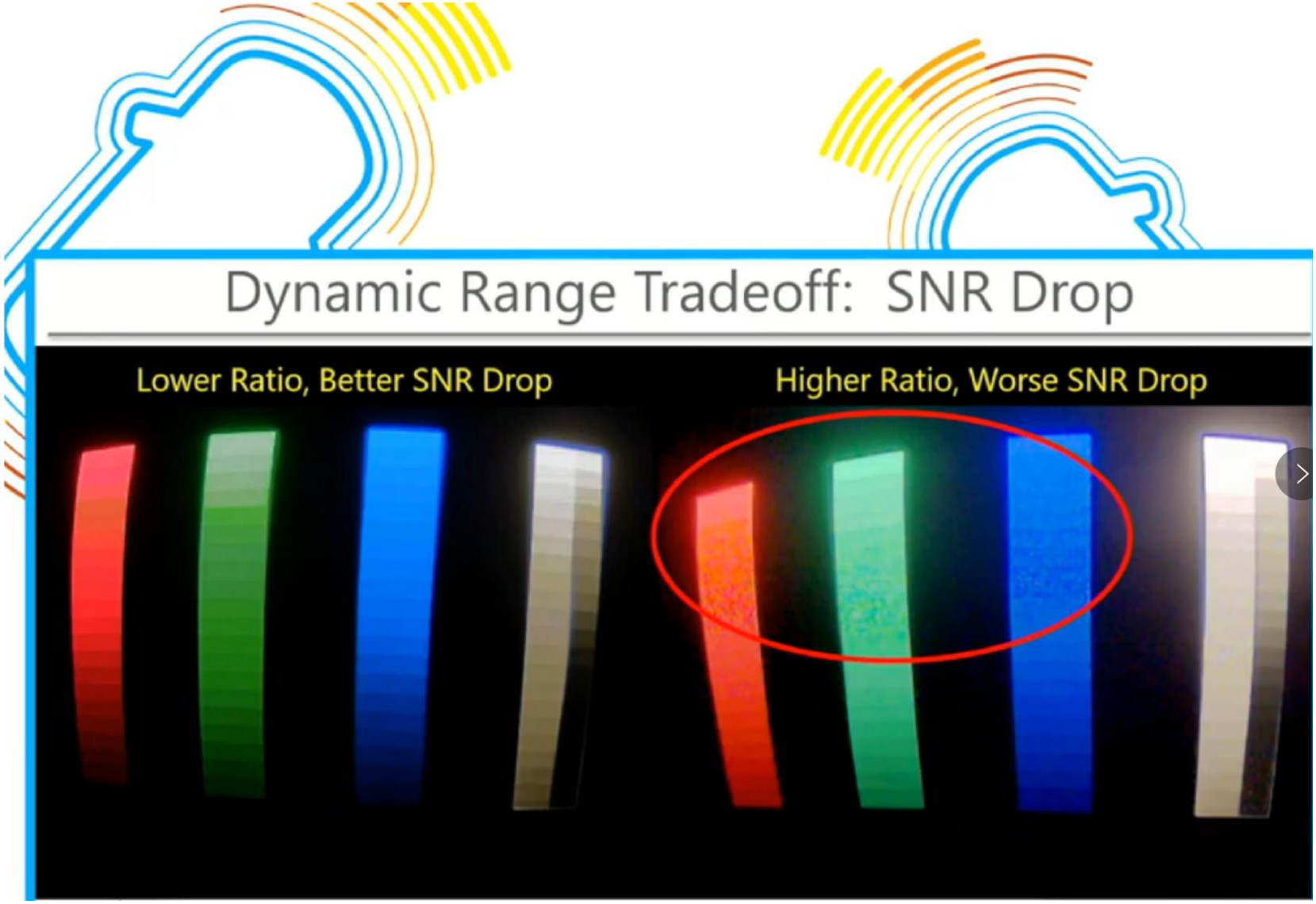
- 对比度检测概率 (CDP)
- 色彩辨析概率 (CSP)
- 调制光减弱概率 (MMP)
- 运动伪影 (Blurring)
- 畸变补偿



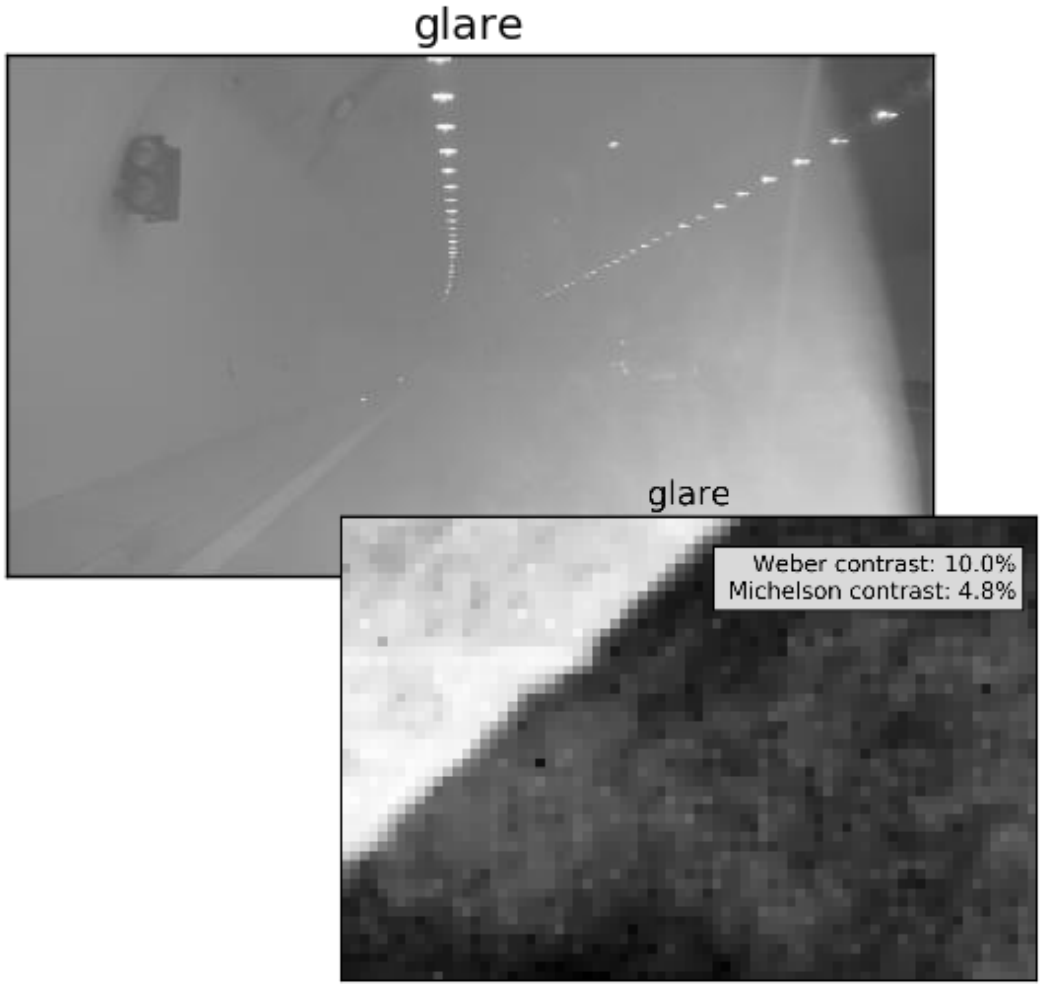
Multi-Exposure HDR – SNR Drop

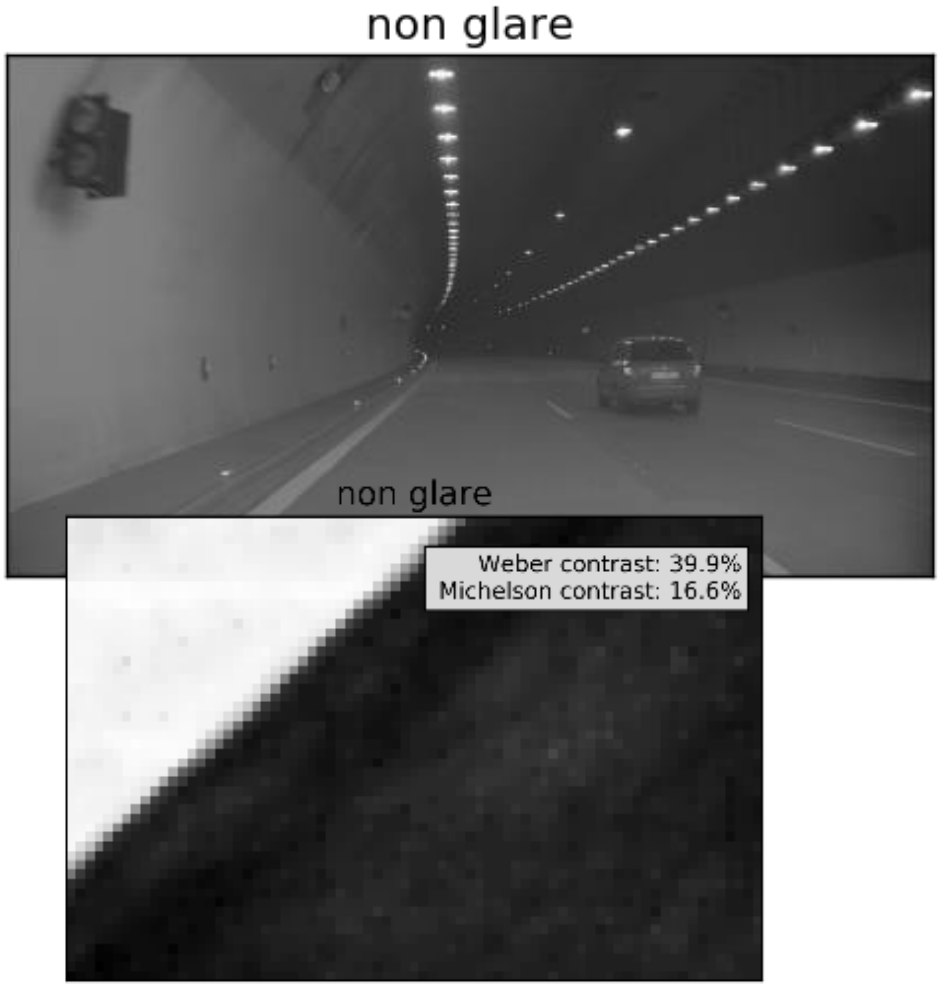


SNR DROP

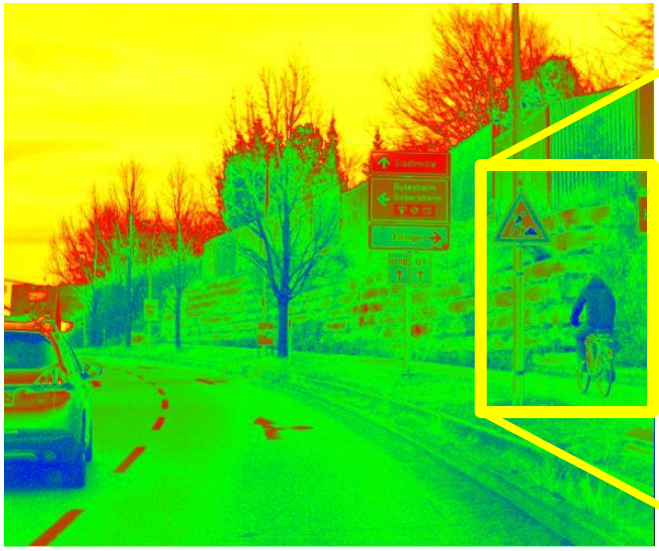

Dynamic Range Tradeoff: SNR Drop
Lower Ratio, Better SNR Drop
Higher Ratio, Worse SNR Drop

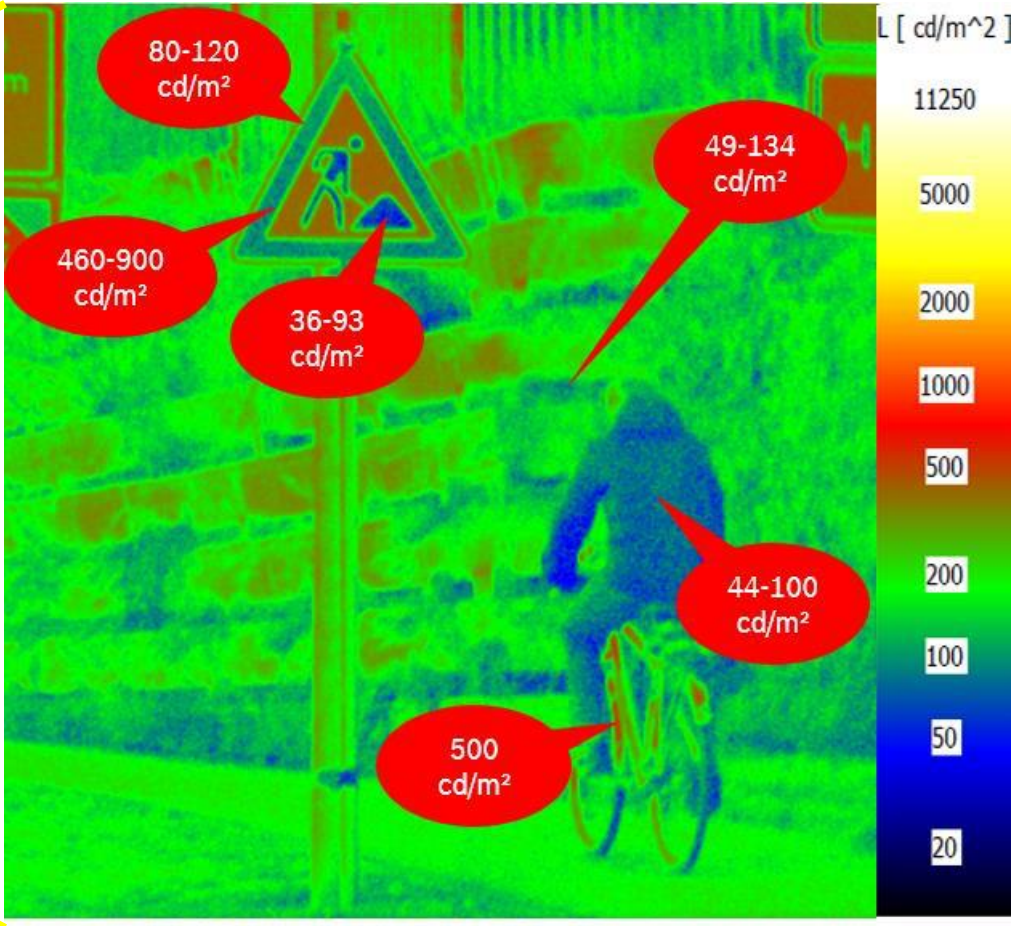
Contrast reduction by Flare





Detection Probabilities
Requirement analysis with a luminance camera





Literature:

https://www.image-engineering.de/library/conference-papers/1045-contrast-detection-probability-implementation-and-use-cases

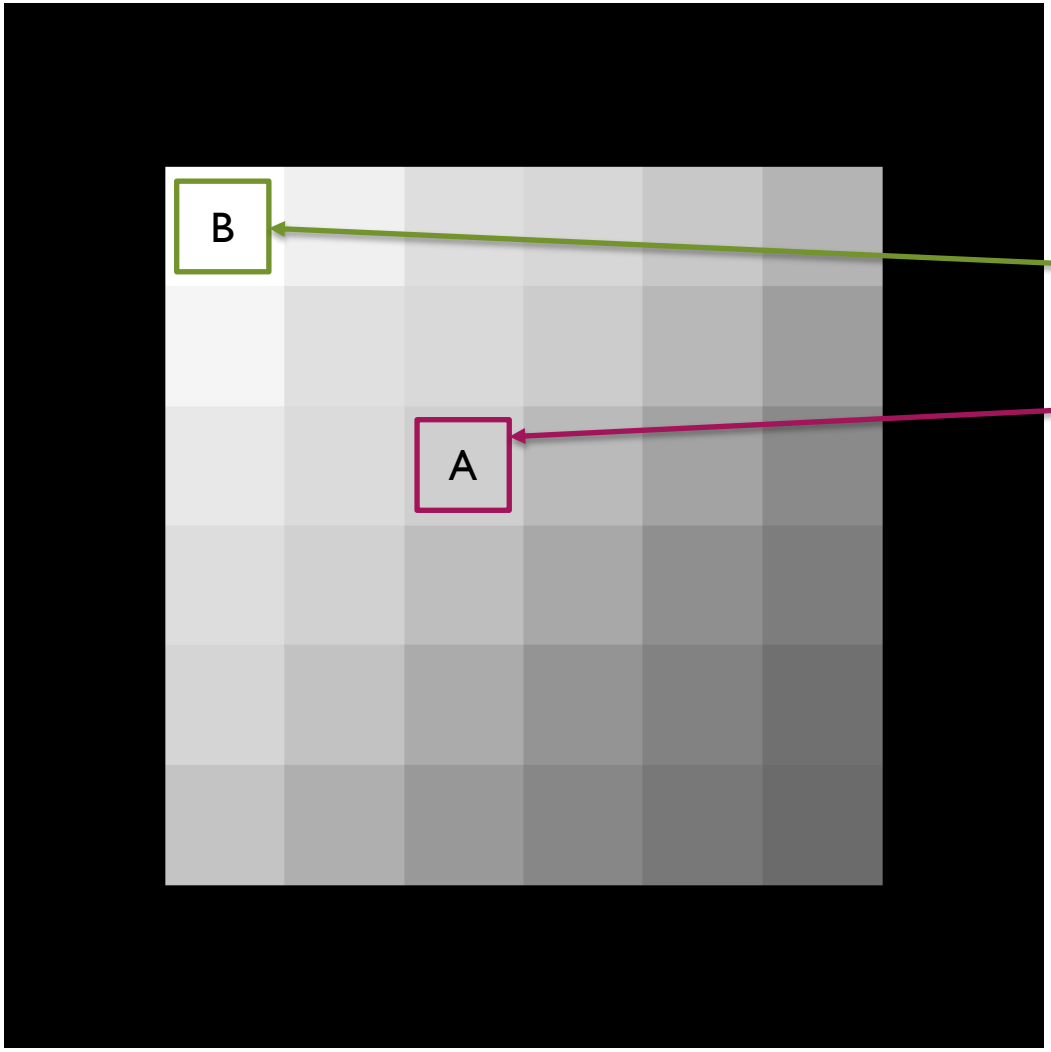
https://www.image-engineering.de/library/white-paper/1015-p2020-white-paper

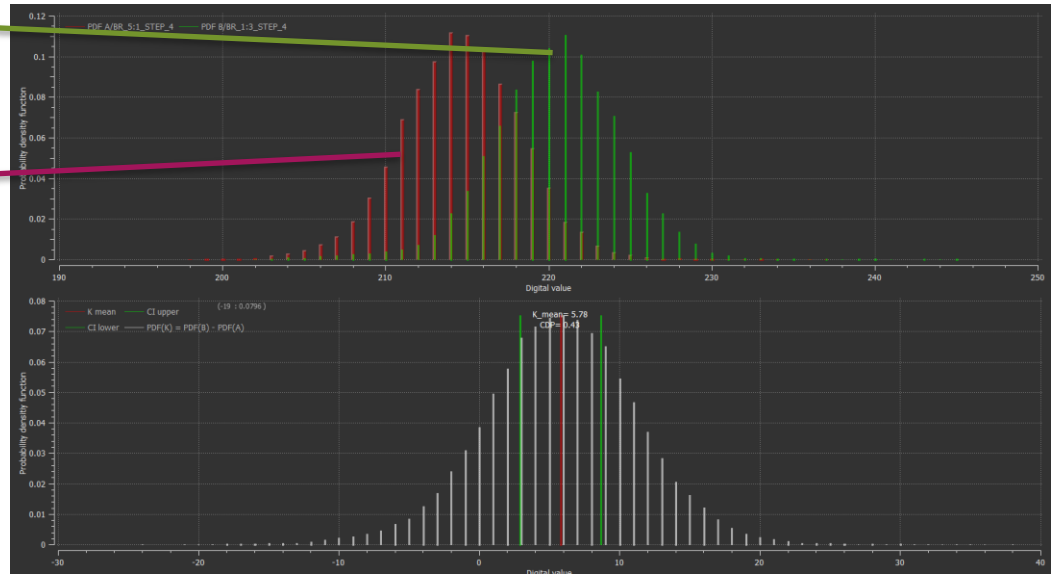
https://www.ingentaconnect.com/content/ist/ei/2018/00002018/00000017/art00005

Contrast Detection Probability

Note: Simulation Data

$\bar{A}$ and $\bar{B}$ are random variables associated to the input luminance

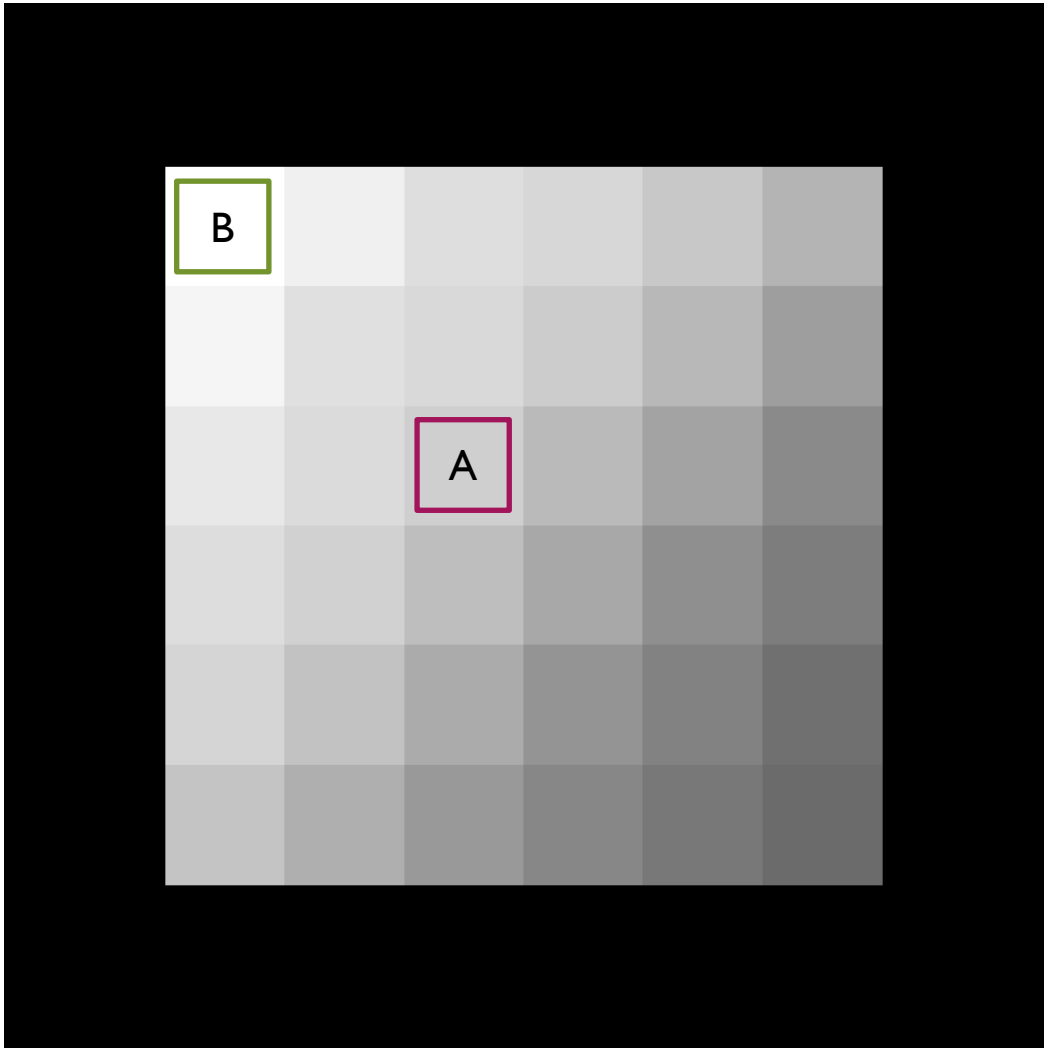




PDF → Probability Density Function K
→ Difference between A and B

Contrast Detection Probability

Note: Simulation Data



Input Luminances A and B

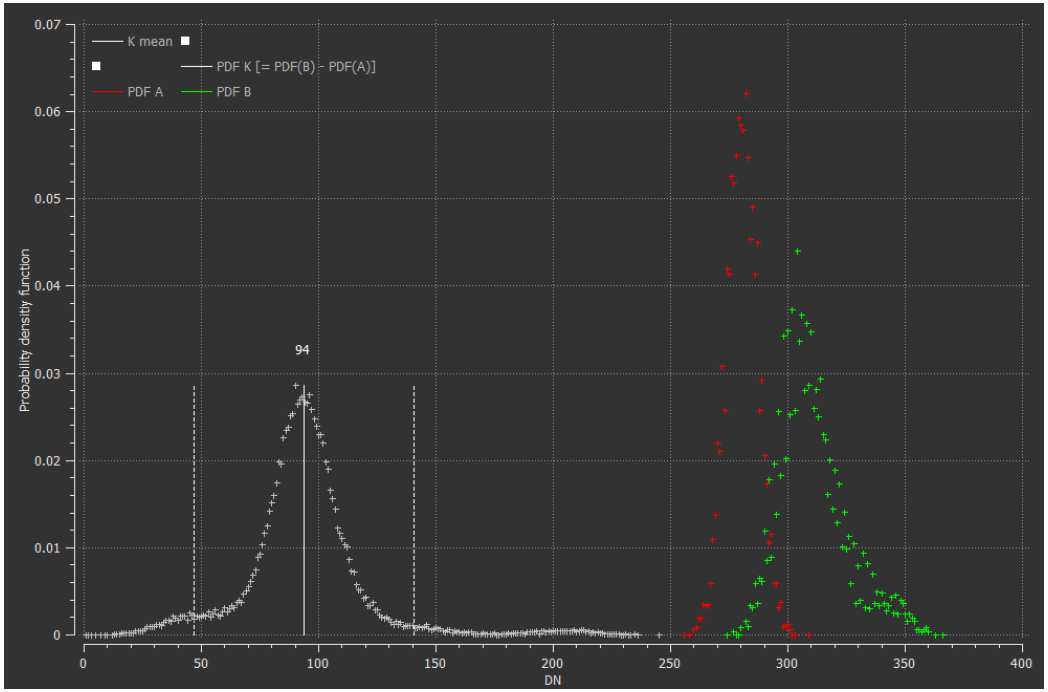
With ($A < B$)

Known contrast:

$$K_{Weber} = \frac{B}{A} - 1$$

Contrast Detection Probability

Note: Simulation Data



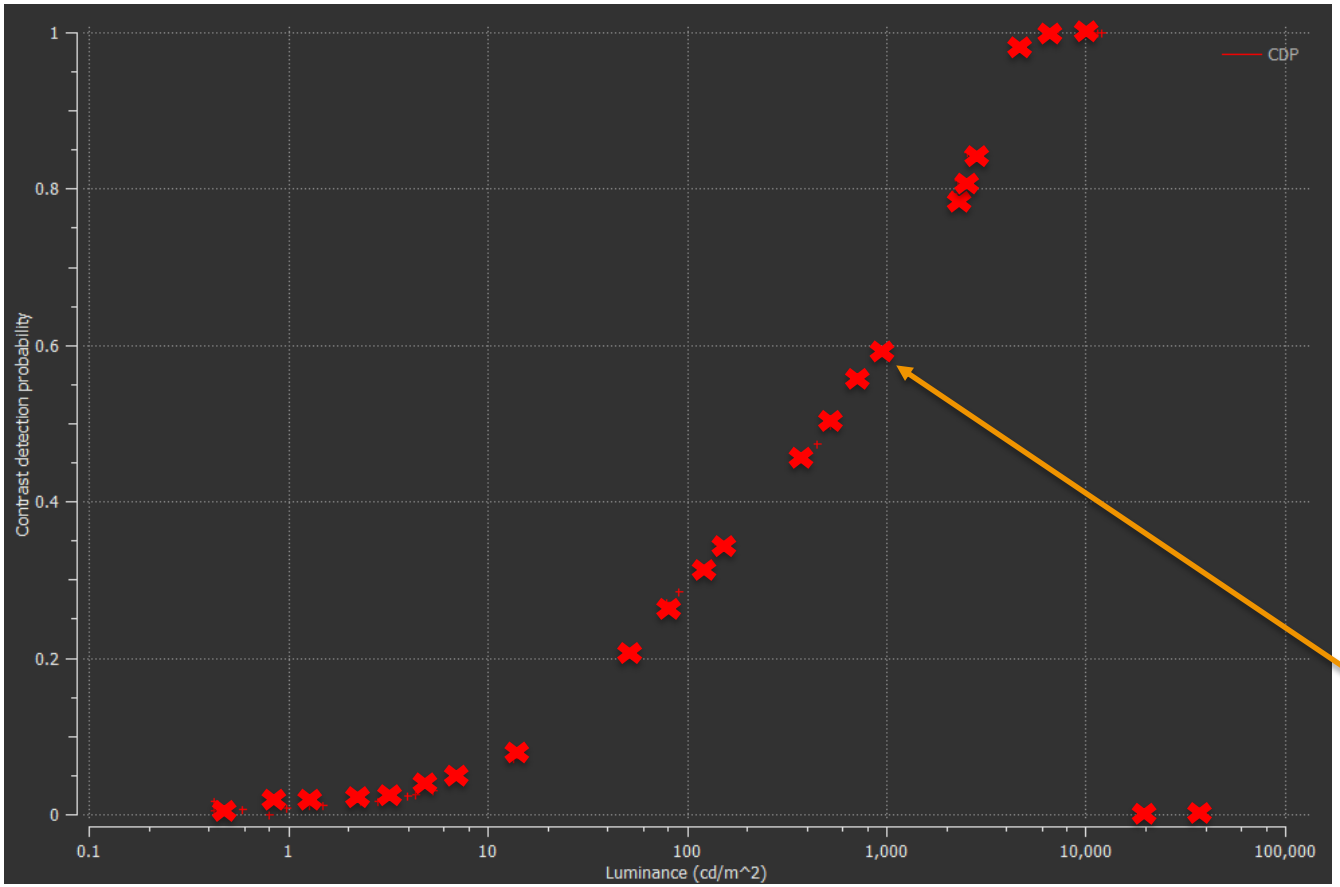
CDP = Area under the probability density function (PDF) K

$$K = \bar{B} - \bar{A}$$

Within a 50% confidence interval

Contrast Detection Probability

Note: Simulation Data



Example: Single Exposure, Simulated Image

- Each point is an CDP value for a given mean luminance

$$L_{meas} = \frac{\bar{A} + \bar{B}}{2}$$

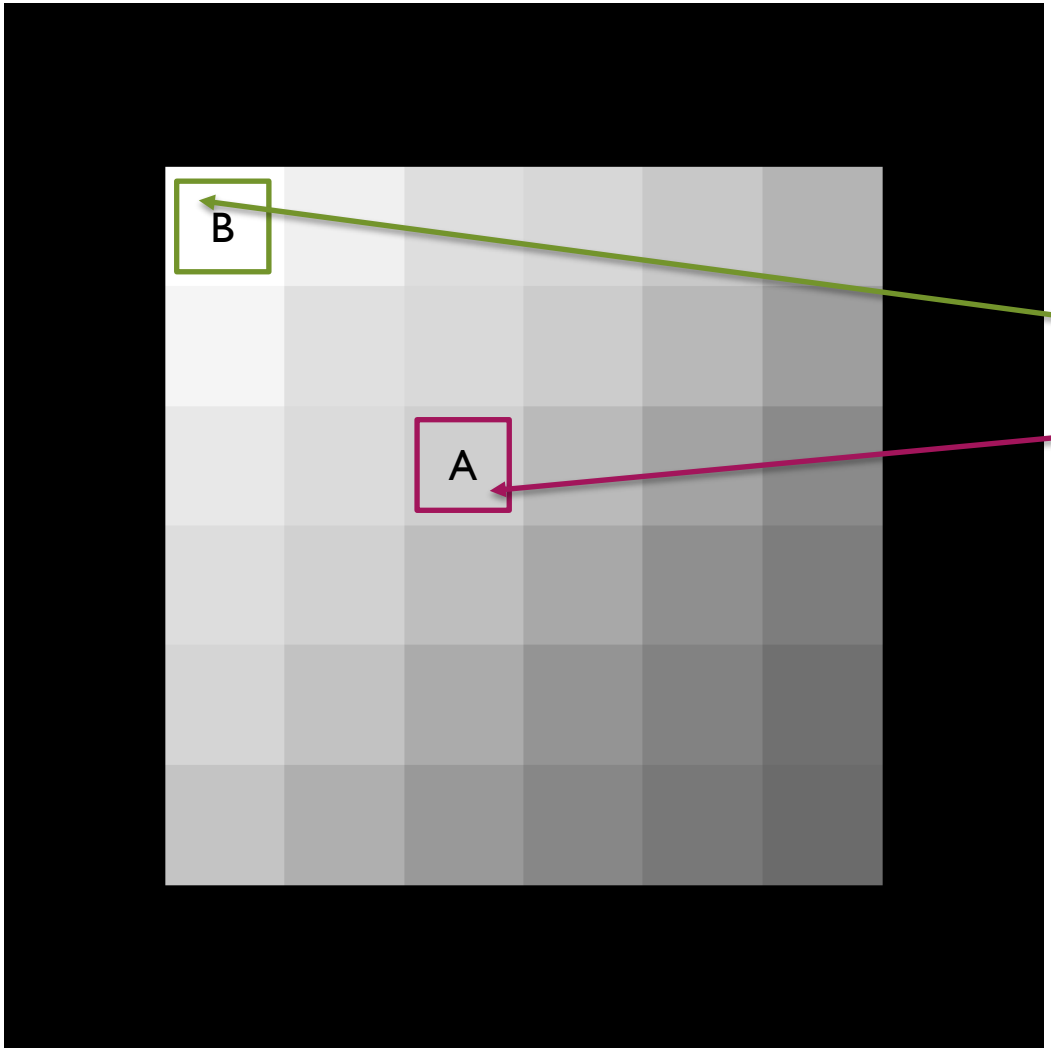
and a given contrast

$$K_{Weber} = \frac{B}{A} - 1$$

e.g.:
CDP = 59%
for L = 935 cd/m²
and K = 90%

Contrast Detection Probability

Note: Simulation Data



$$K = \bar{B} - \bar{A}$$

n times random pairing of Pixel values between $\bar{A}$ and $\bar{B}$ to compensate for fixed pattern noise

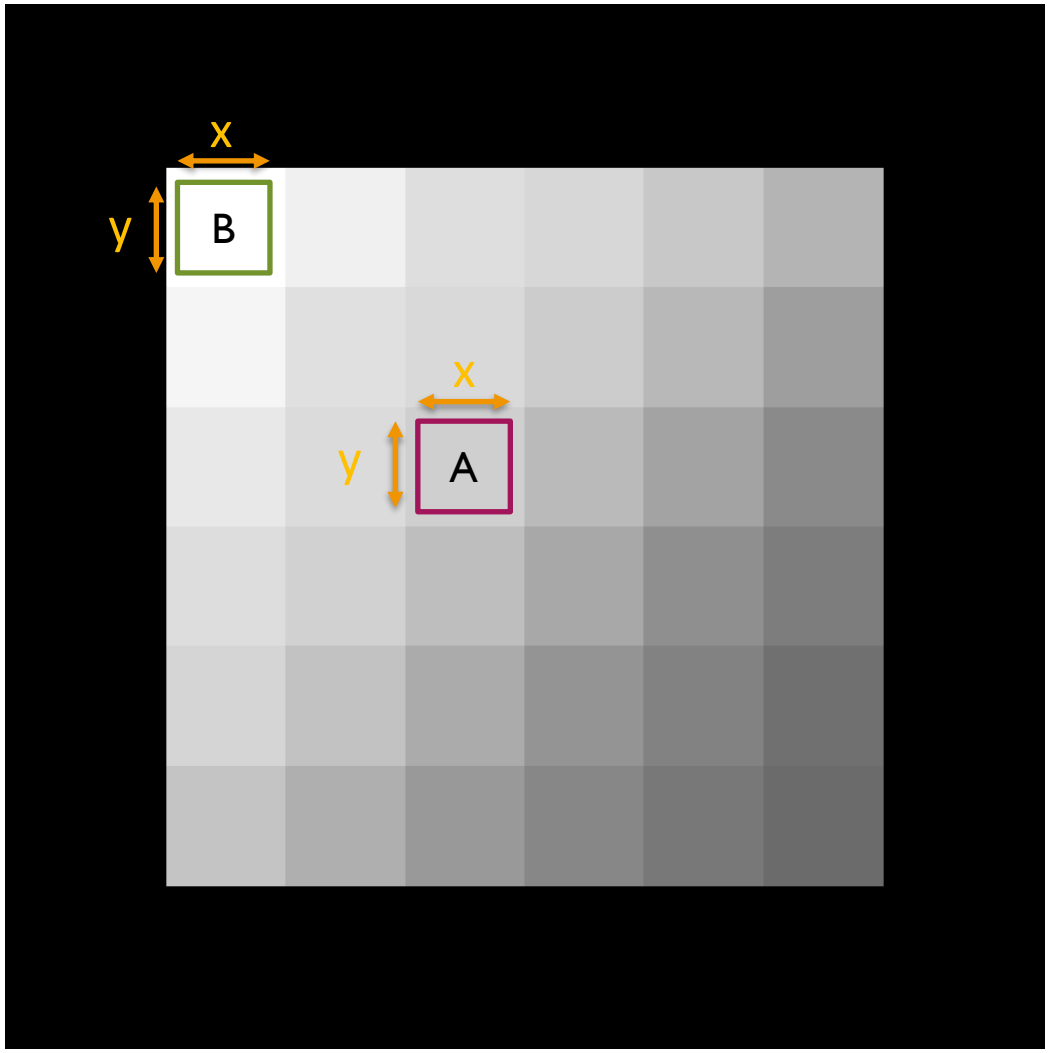
$$B_{(rand(x),rand(y))} - A_{(rand(x),rand(y))} = K_i$$

With

$B_{(rand(x),rand(y))}$ → Value of random pixel within B

$A_{(rand(x),rand(y))}$ → Value of random pixel within A

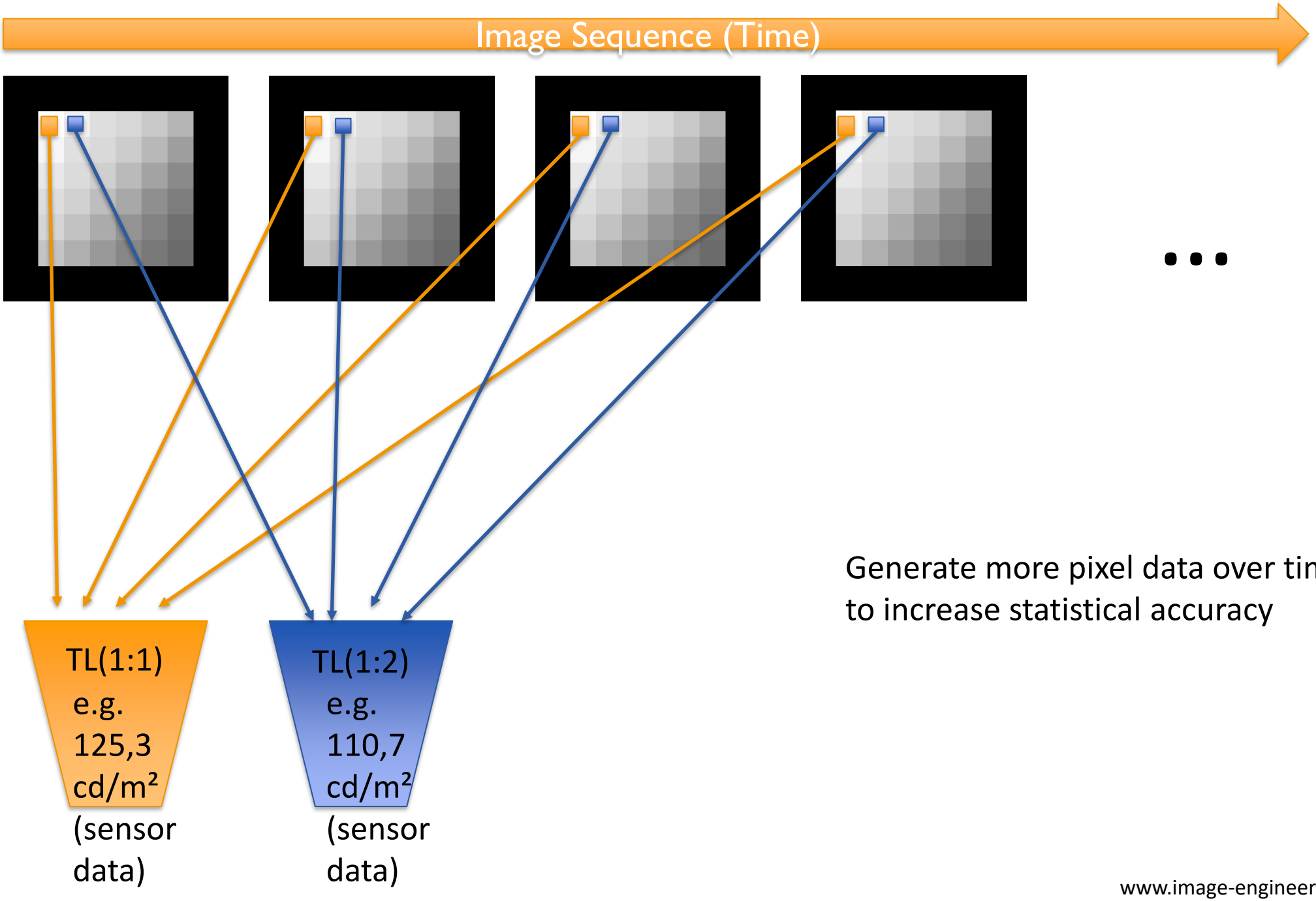
Random Pairing Maximum



The number of maximum random pairing operations depends on the heigth and width of the ROI in px and the number of images taken for each CDP step:

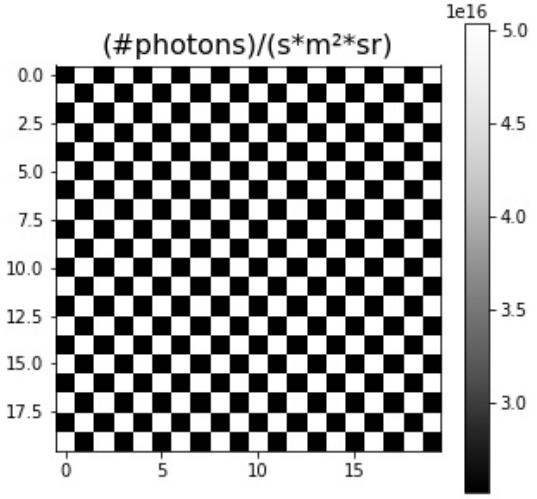
$$n_{rp_max} = (x_A y_A)(x_B y_B) n_{img}$$

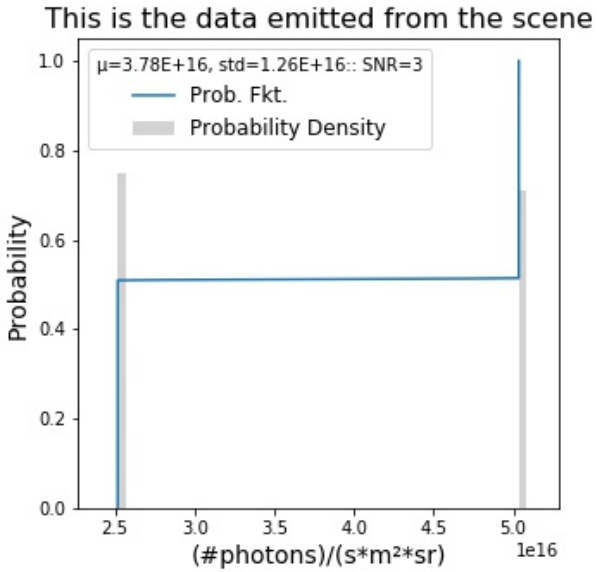
Data collection over time

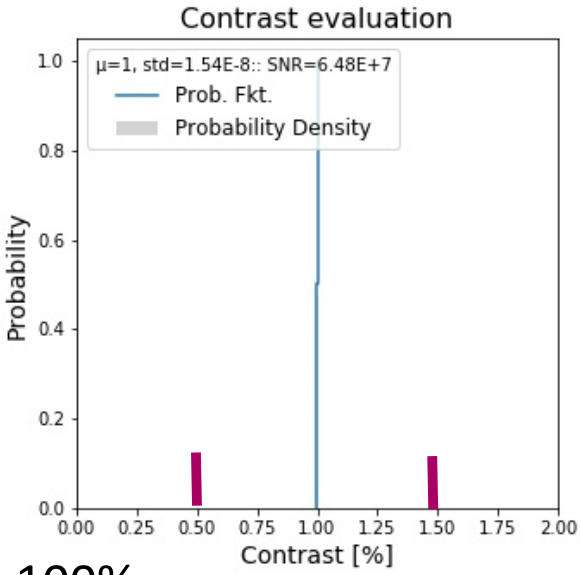


Generate more pixel data over time to increase statistical accuracy

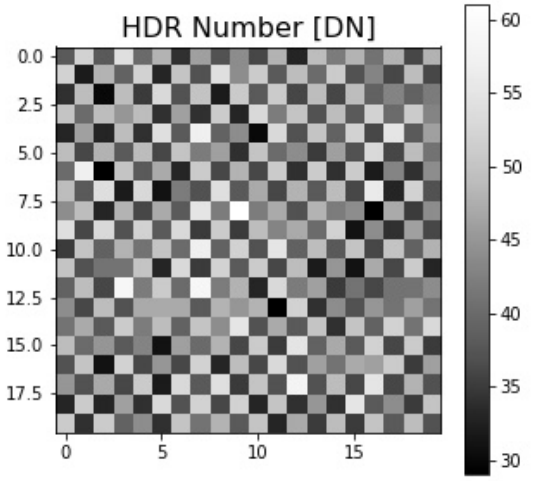
CDP

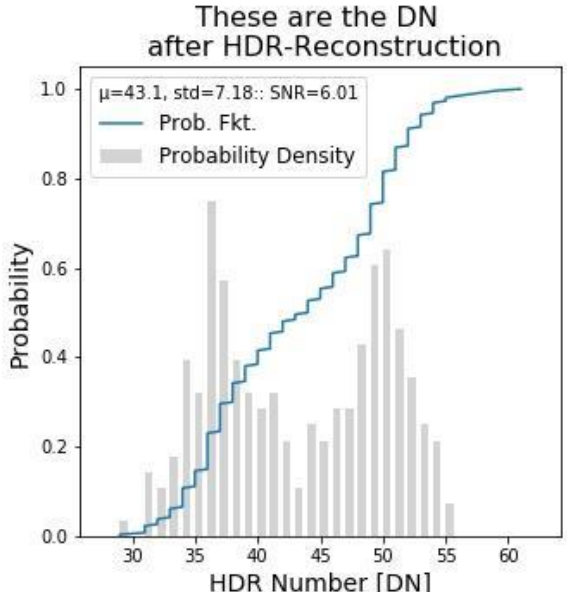


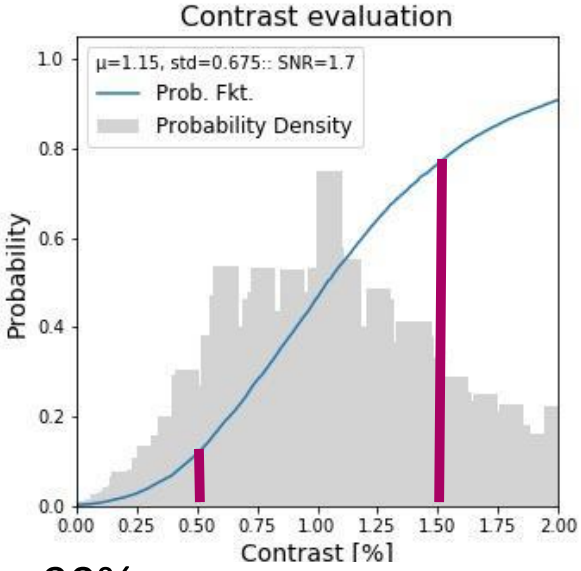




CDP = 100%







CDP = <90%

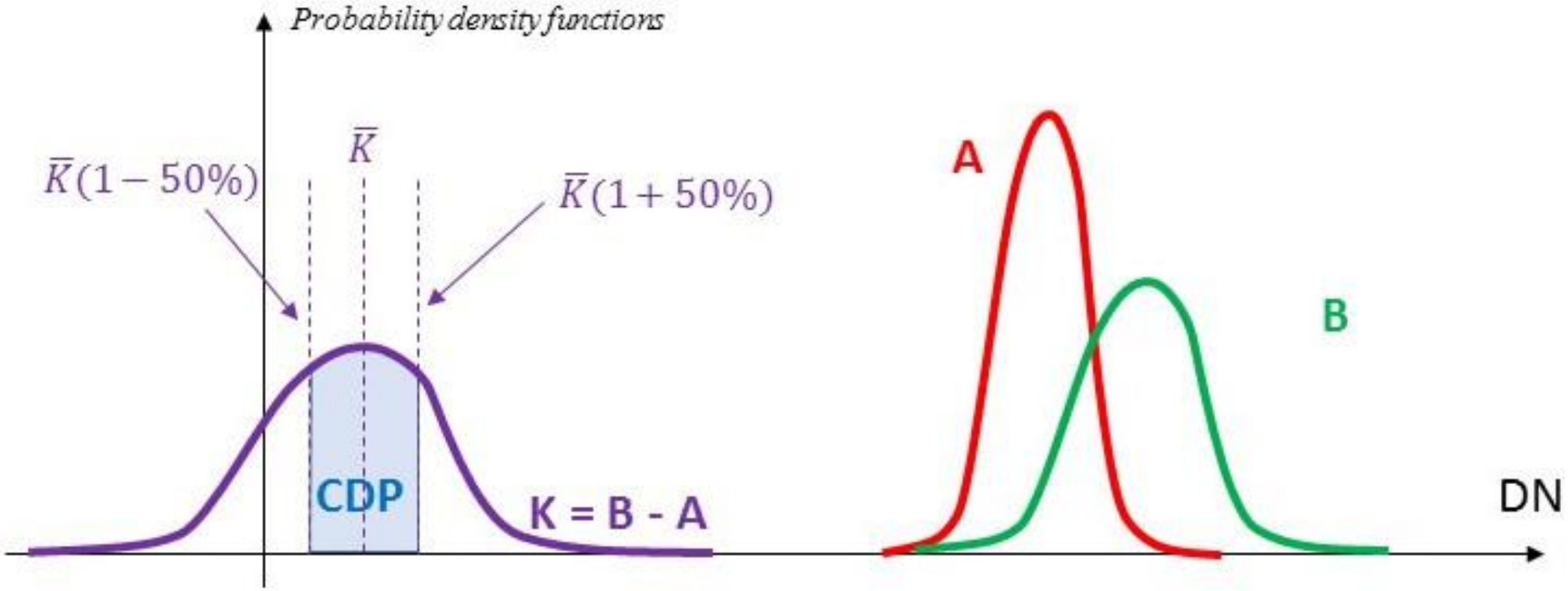


Fig. 1: Calculation of the CDP in case of small constrast

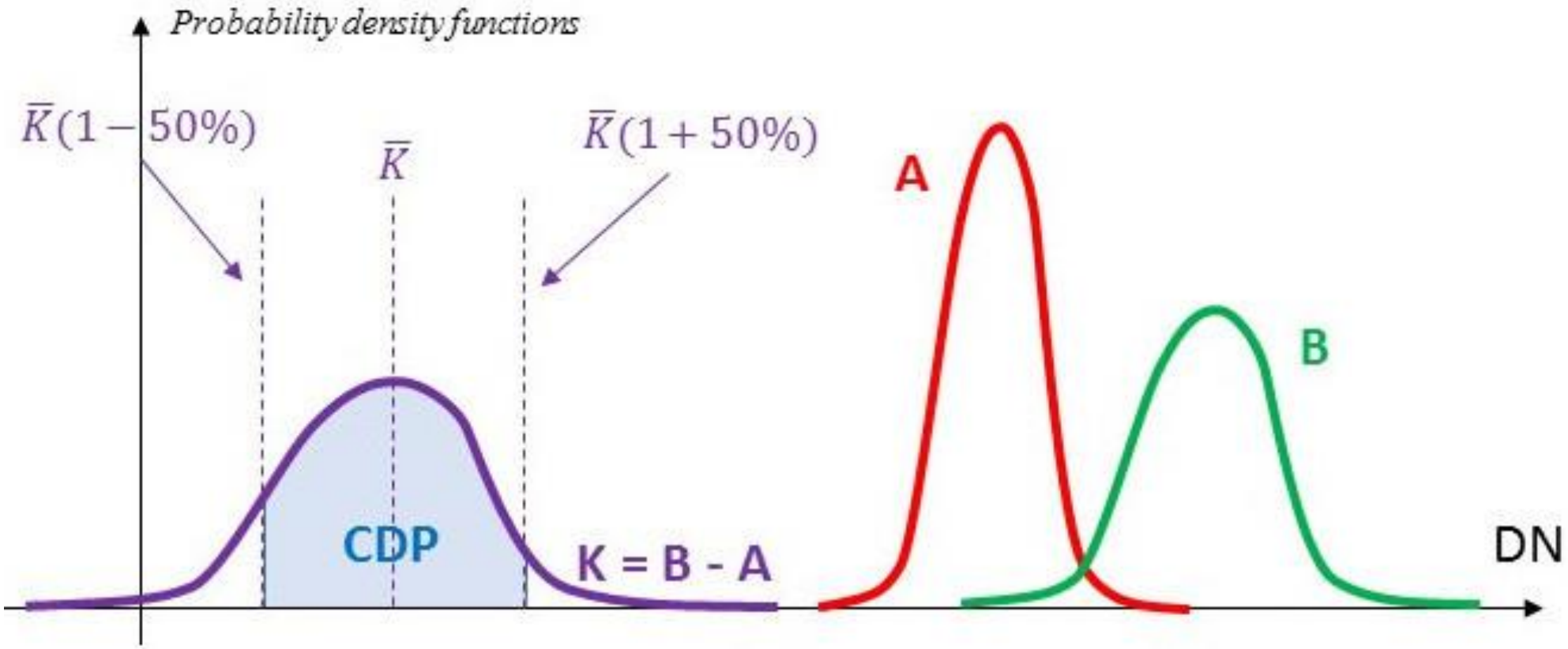


Fig. 2: Calculation of the CDP in case of medium contrast

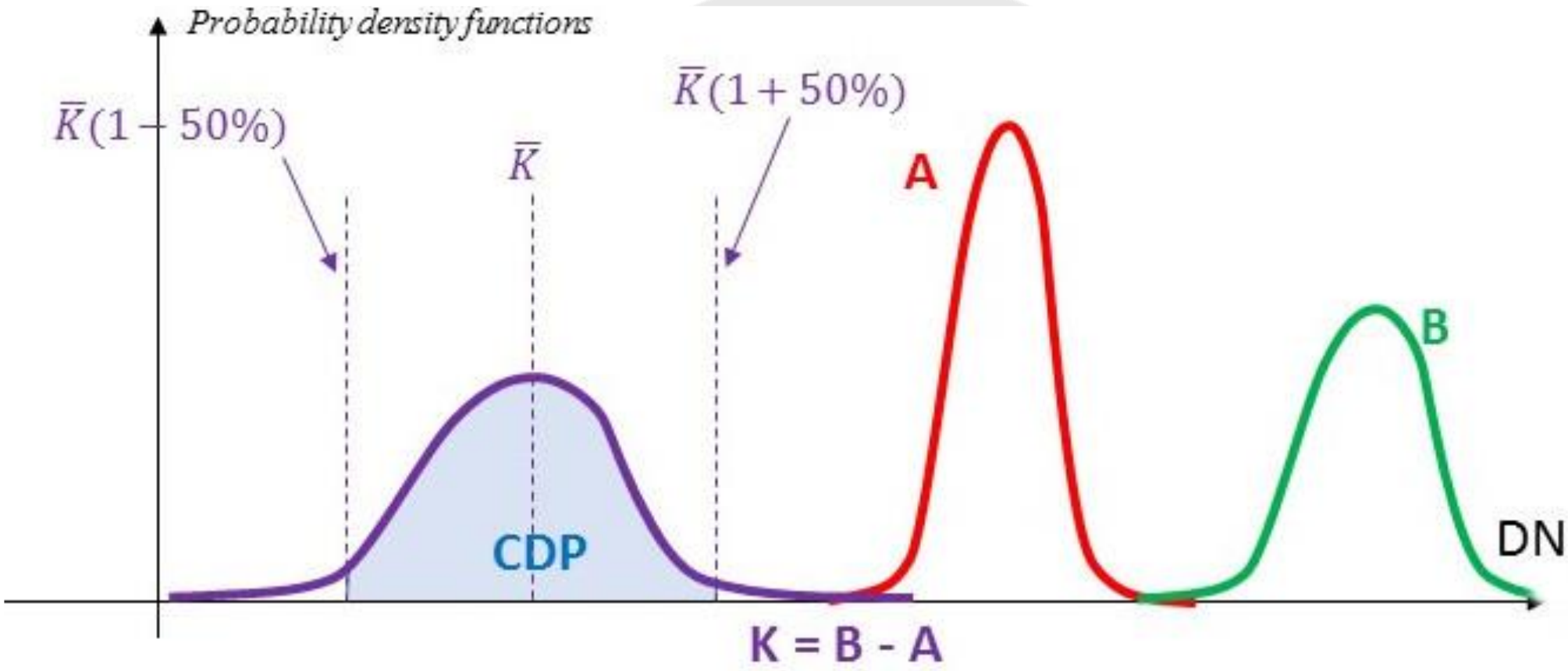
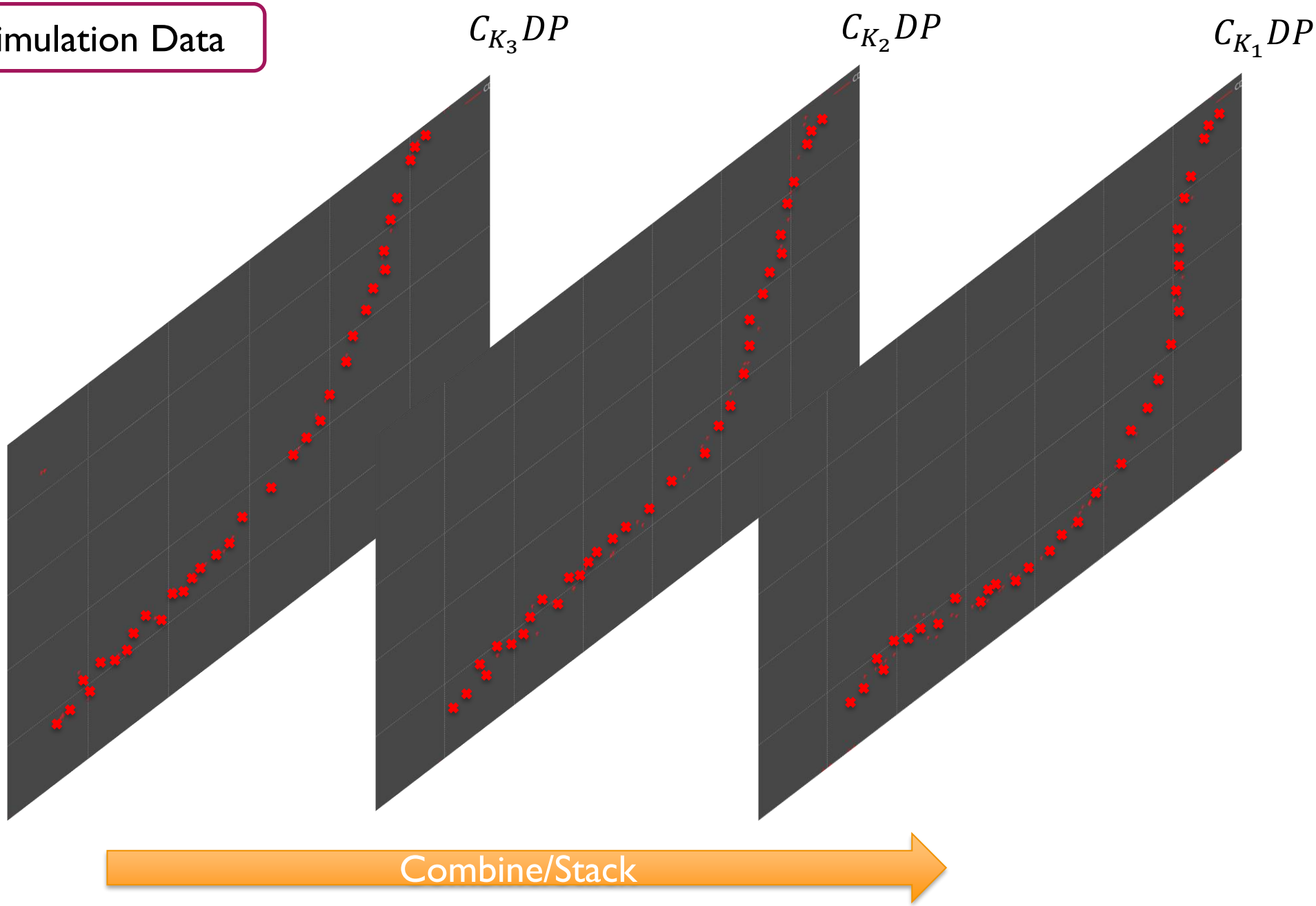


Fig. 3: Calculation of the CDP in case of high contrast

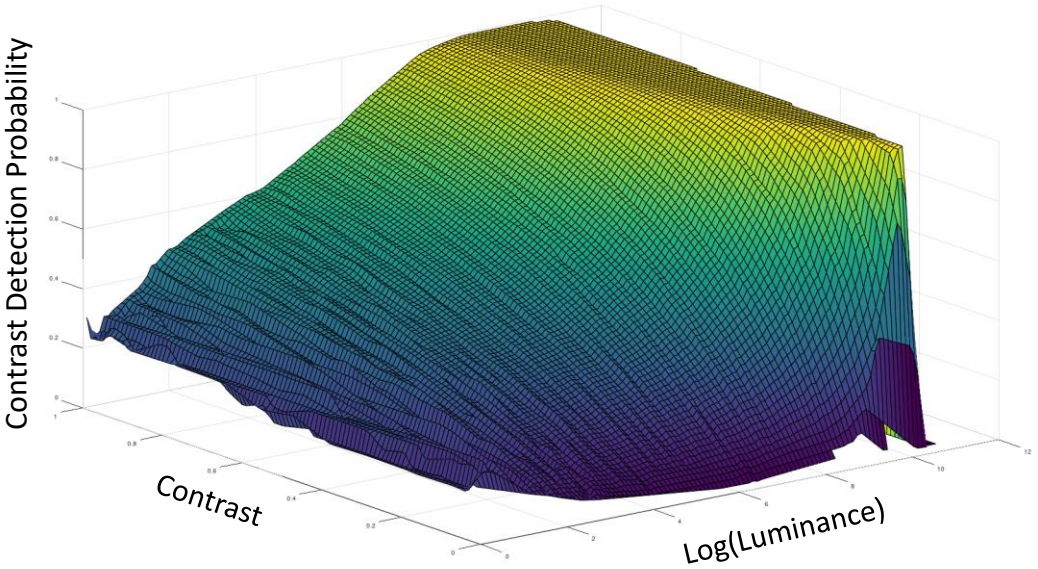
CDP Outlook

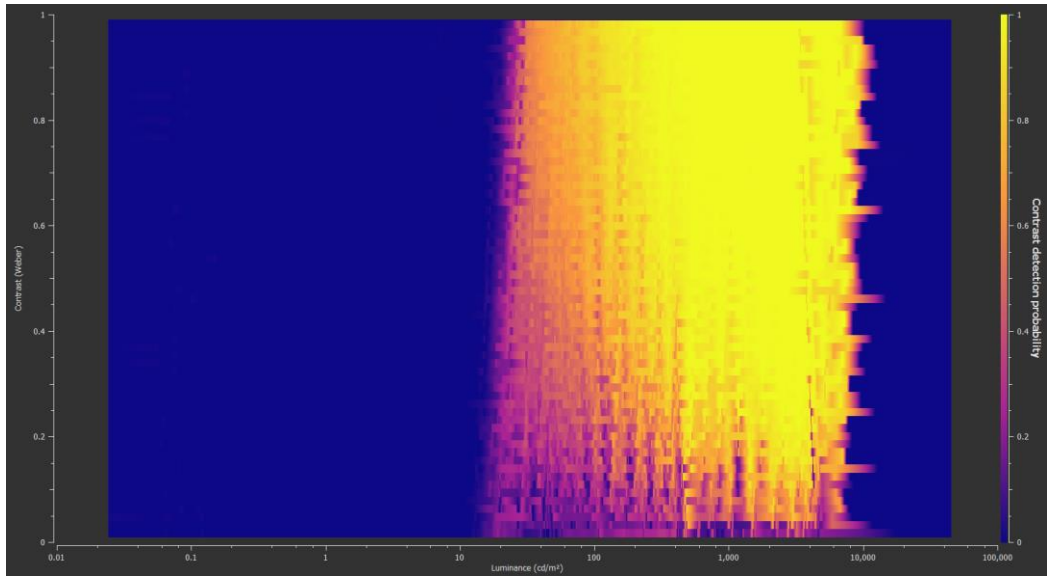
Note: Simulation Data



3D CDP

Note: Simulation Data



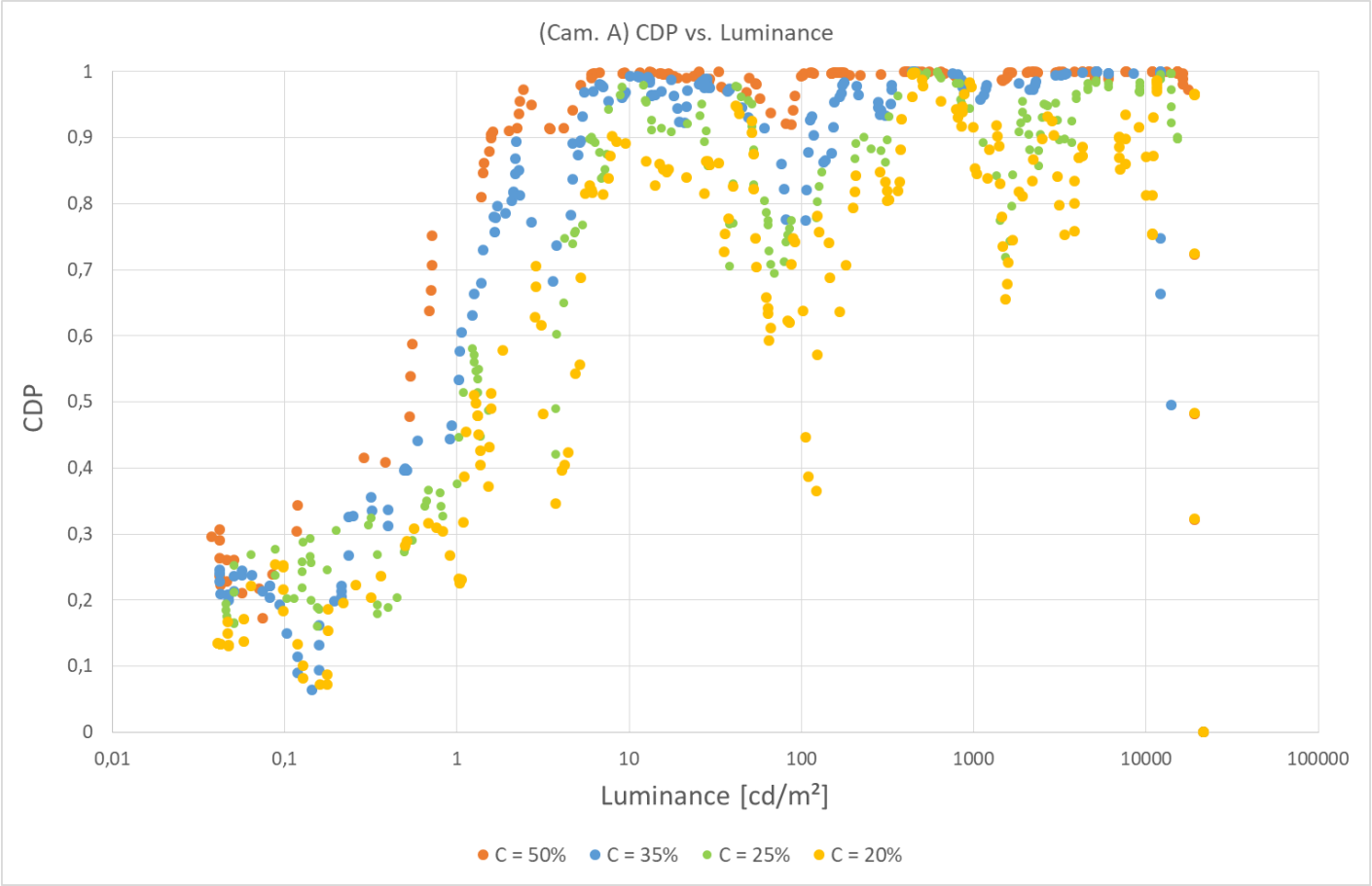


3-Dimensional CDP representation
System characterisation in one overview

2D CDP + Color

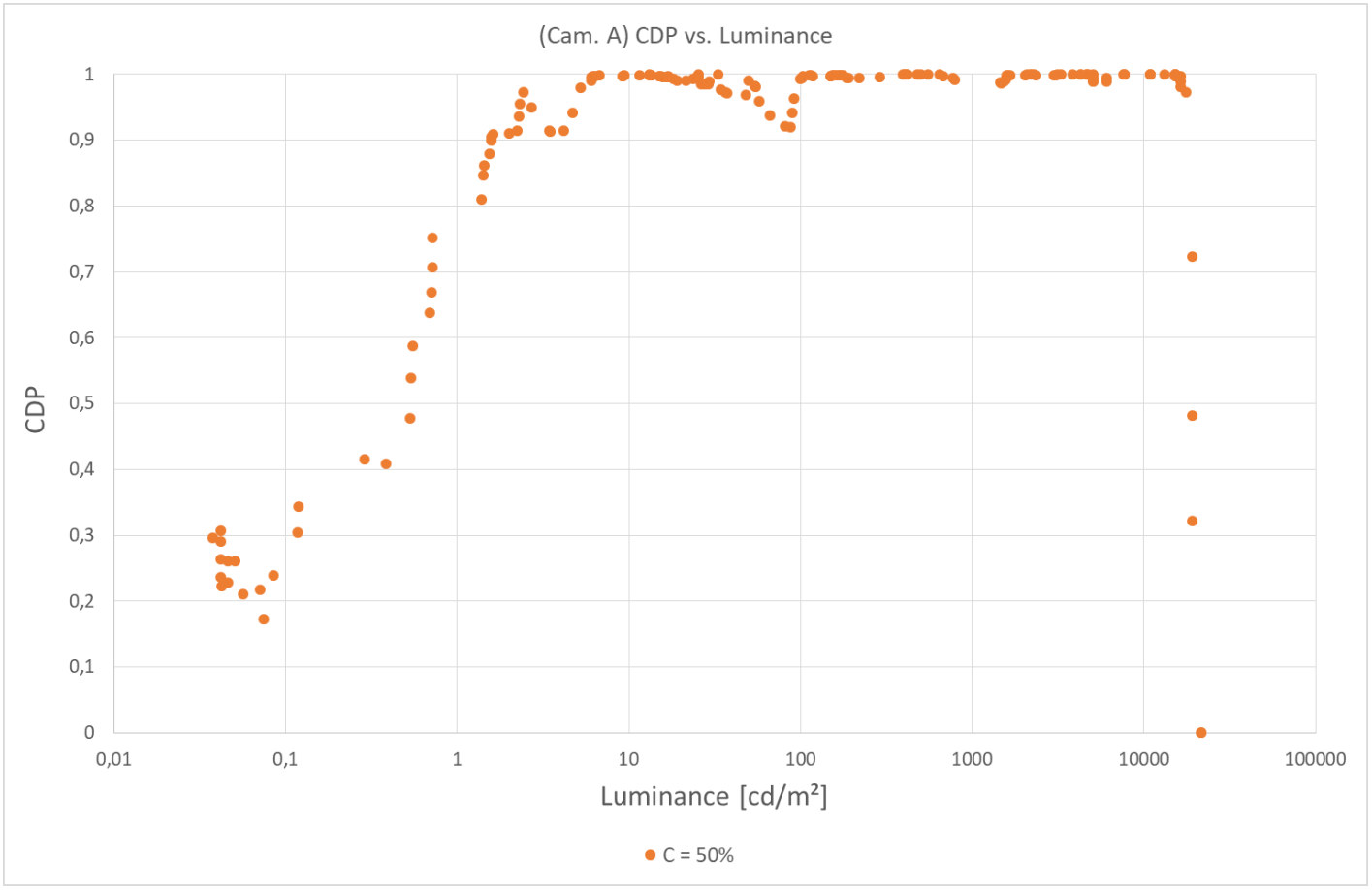
Example – Camera A

CDP plot for 50%/35%/25%/20% contrast



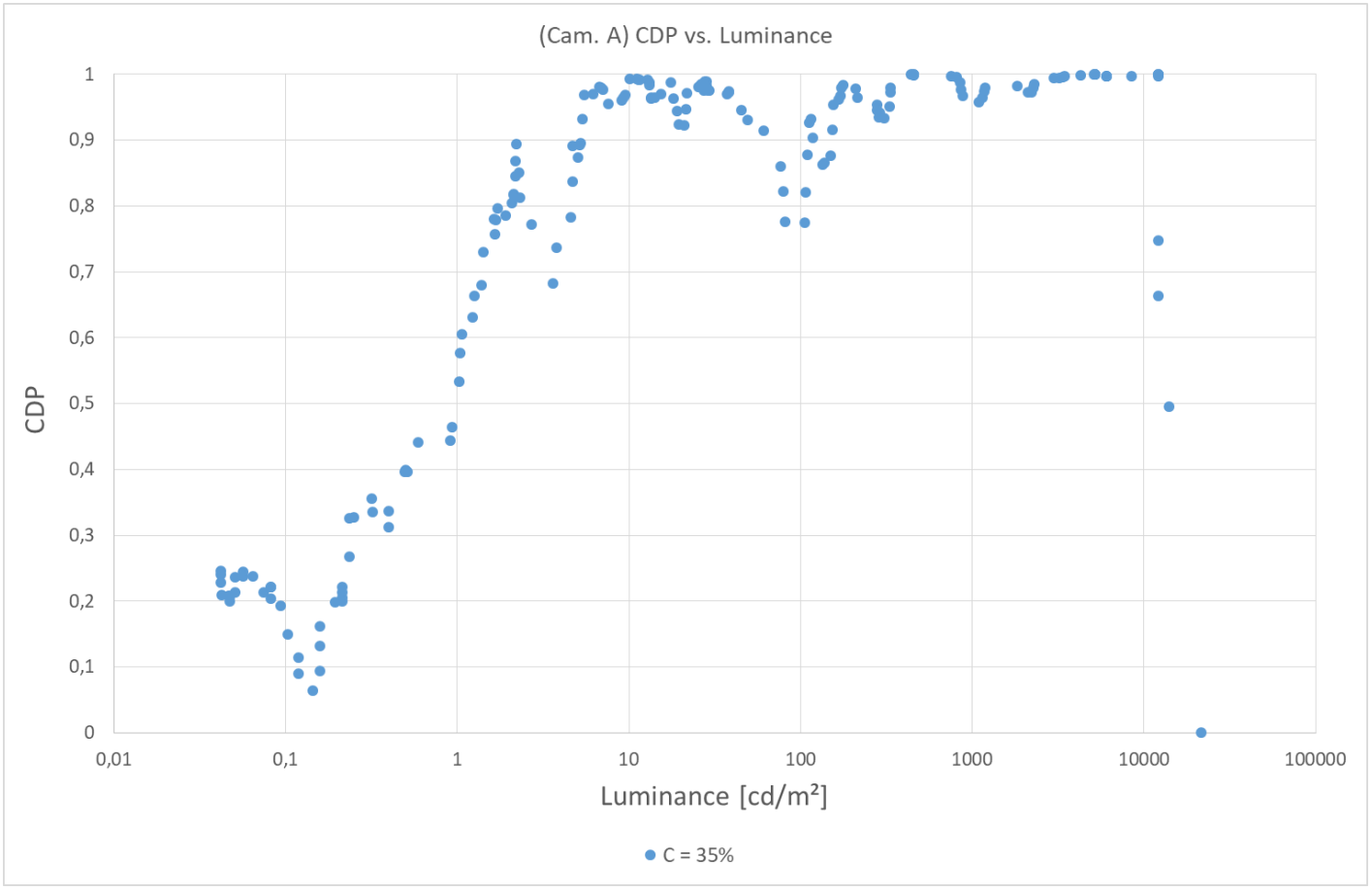
Example – Camera A

CDP plot for 50% contrast



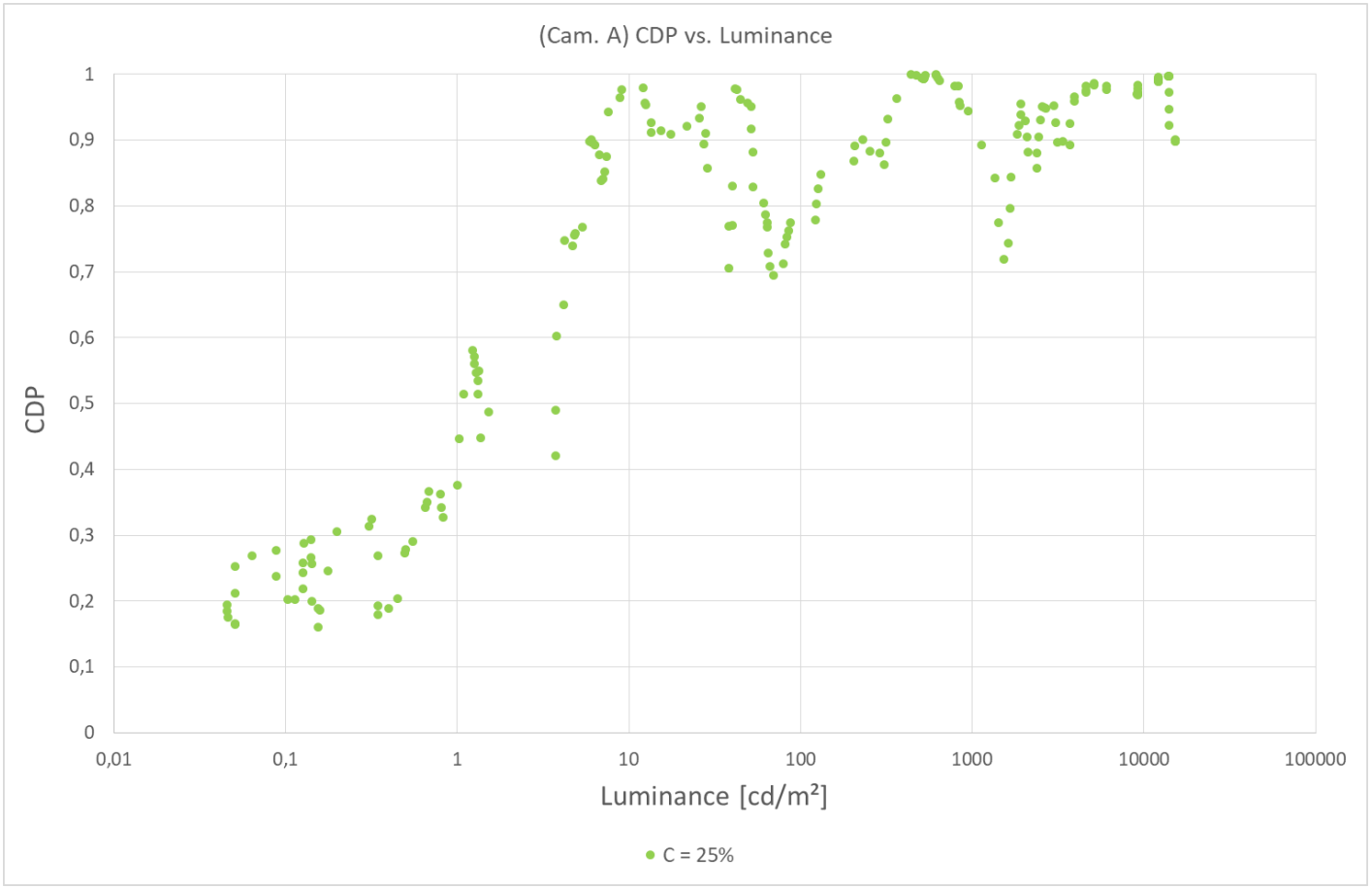
Example – Camera A

CDP plot for 35% contrast



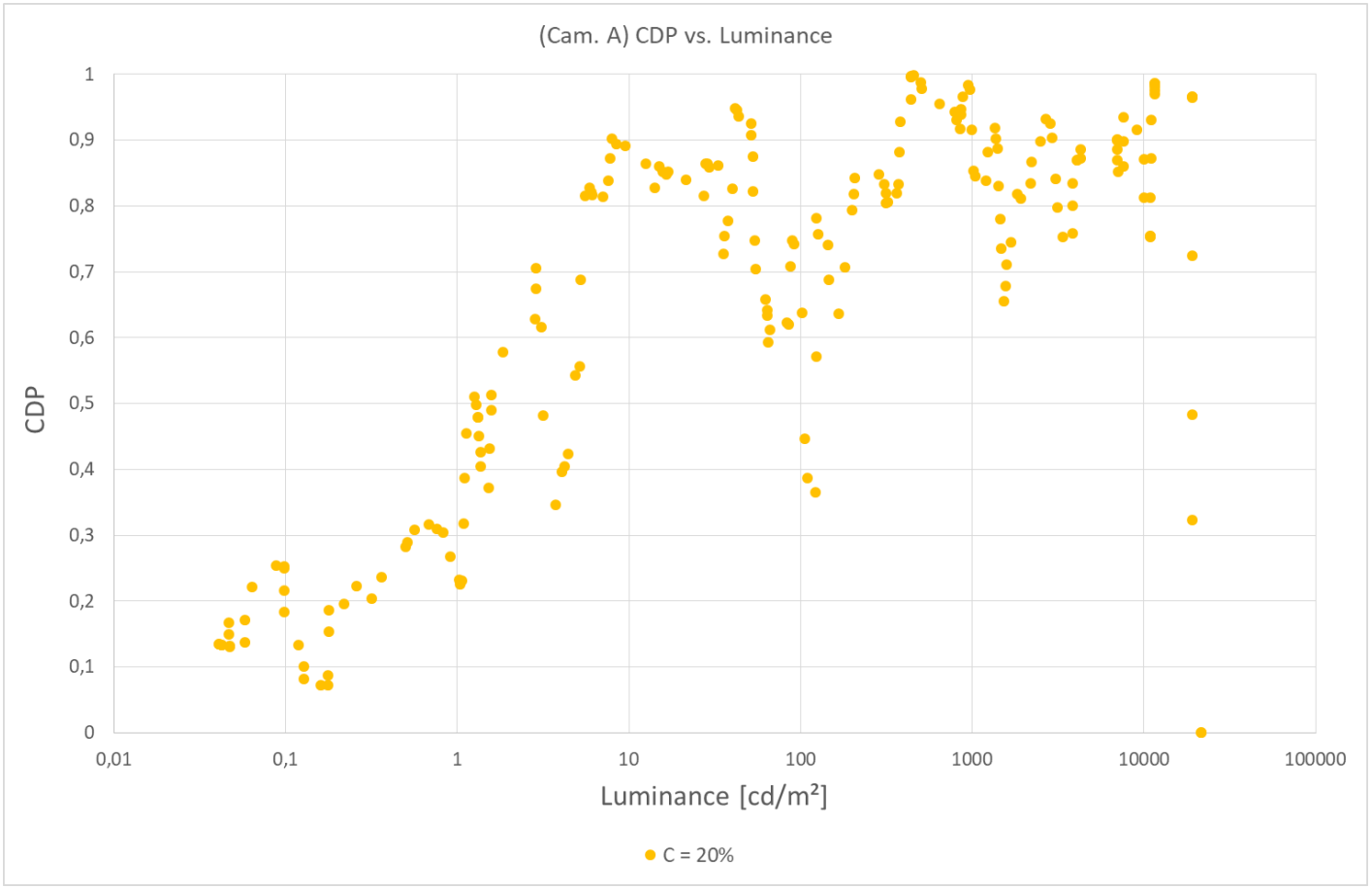
Example – Camera A

CDP plot for 25% contrast



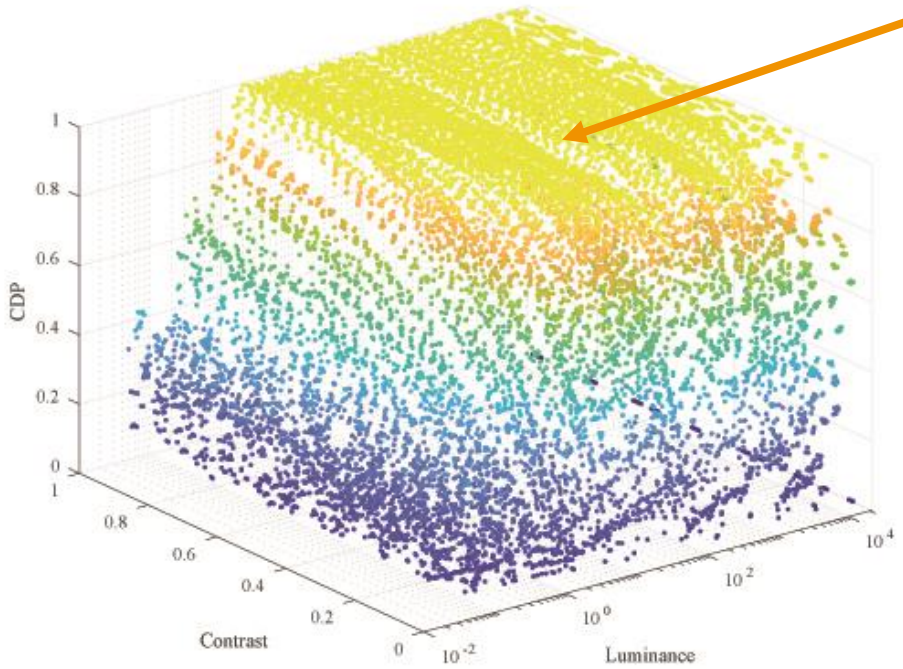
Example – Camera A

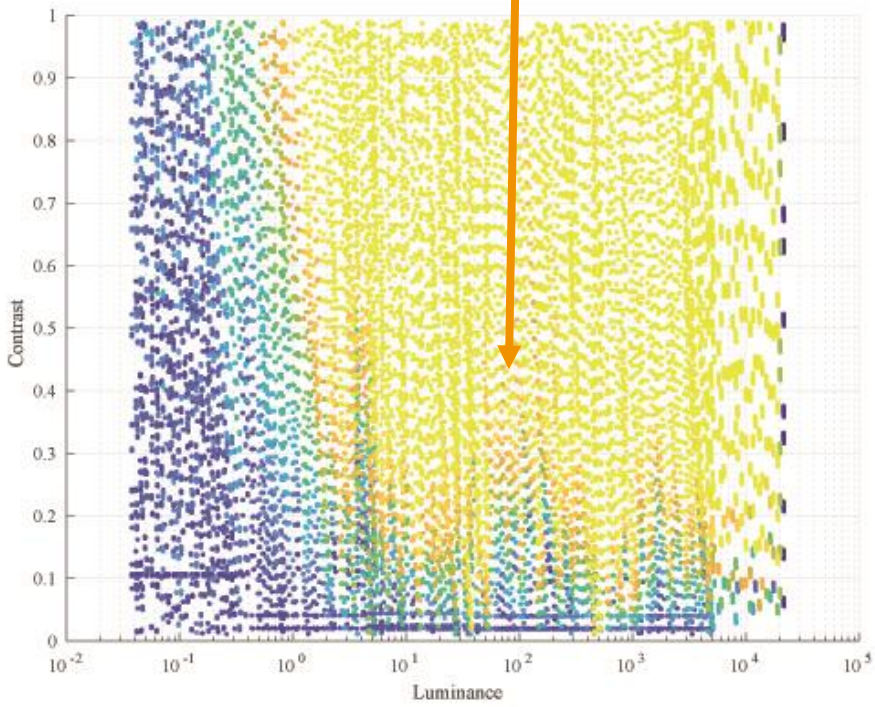
CDP plot for 20% contrast



Example – Camera A

CDP drop





are the distribution of digital values for a flat-field area in an image with a known luminance. A noise free system would have a distribution where all digital values in a region of interest (ROI) equals the mean value. A real system will show, depending on noise and signal processing a distribution of values. From the two random variables A and B a new random variable K is calculated, which defines the contrast. K also has a probability density, which represents the probability to measure or detect a certain contrast. The CDP value is the area beneath the PDF, limited by a defined confidence interval.

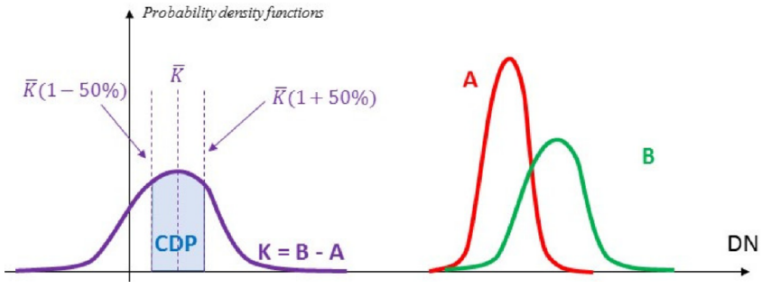


Figure 4. *Calculation of CDP based on random variables A and B. The probability density function K is calculated based on the difference between A and B. CDP is calculated as the area beneath the PDF limited by a confidence interval of $\pm 50\%$ in this example*

The CDP value is not an absolute value, it has parameters that allow it to be tailored for the demanded use cases. So different use cases will require different calculation steps and will lead to different CDP values.

One aspect that needs to be defined is how to calculate the probability density function K. In our implementation, we choose a random pairing approach, others might be possible. Random pairing mean that random pixels from variable A and random pixels from variable B are used to calculate K. In case of a simple difference, the pixel value from a random pixel in A is subtracted from a random pixel in B. Doing this for all pixels will lead to the PDF K.

interval to calculate CDP. Basically these are the edge cases that are still acceptable for the use case. A smaller interval will lead to lower CDP values, making it less likely that the measurement will fall into the confidence interval.

Examples for different methods to calculate K and the differences in the confidence interval are shown in figure 5.

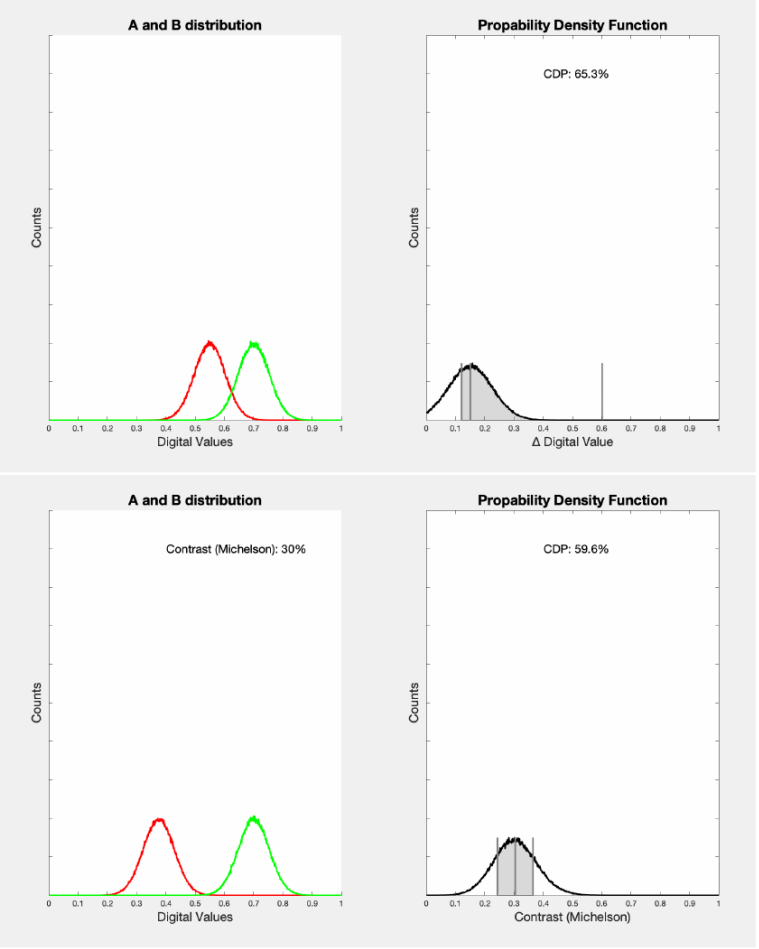


Figure 5. *Two different scenarios to calculate CDP. **top:** Calculating the CDP based on simple difference. The confidence interval is not limited to the top, higher difference is always accepted **bottom:** Calculating the CDP*

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(d – dark, b – bright):

$$\ldots = \sum_{e_d=1}^{\infty} \sum_{e_b=0}^{\lfloor (c_{in}+\varepsilon_+ +1)e_d \rfloor} \frac{{\mu_b}^{e_b}}{e_b!} e^{-\mu_b} \cdot \frac{{\mu_d}^{e_d}}{e_d!} e^{-\mu_d} \tag{14}$$

$$= e^{-\mu_d} e^{-\mu_b} \sum_{e_d=1}^{\infty} \sum_{e_b=0}^{\lfloor (c_{in}+\varepsilon_+ +1)e_d \rfloor} \frac{{\mu_b}^{e_b}}{e_b!} \frac{{\mu_d}^{e_d}}{e_d!} \tag{15}$$

This goes in the same methodology for the second term:

$$\Pr(\mathbf{c}_{meas.} < (c_{in} - \varepsilon_-)) \quad \ldots$$

$$= \Pr\left(\frac{\mathbf{e}_b}{\mathbf{e}_d} - 1 < (c_{in} - \varepsilon_-)\right) \tag{16}$$

$$= e^{-\mu_d} e^{-\mu_b} \sum_{e_d=1}^{\infty} \sum_{e_b=0}^{\lfloor (c_{in}-\varepsilon_- +1)e_d \rfloor} \frac{{\mu_b}^{e_b}}{e_b!} \frac{{\mu_d}^{e_d}}{e_d!} \tag{17}$$

Combined the CDP from eq. 8 gets into the form for Poisson-only noise:

$$C_{c_{in}}DP = \Pr(\mathbf{c}_m < (c_{in} + \varepsilon_+)) - \Pr(\mathbf{c}_m < (c_{in} - \varepsilon_-)) \tag{18}$$

$$= e^{-\mu_d} e^{-\mu_b} \sum_{e_d=1}^{\infty} \sum_{e_b=0}^{\lfloor (c_{in}+\varepsilon_+ +1)e_d \rfloor} \frac{{\mu_b}^{e_b}}{e_b!} \frac{{\mu_d}^{e_d}}{e_d!} \ldots$$

$$\ldots - e^{-\mu_d} e^{-\mu_b} \sum_{e_d=1}^{\infty} \sum_{e_b=0}^{\lfloor (c_{in}-\varepsilon_- +1)e_d \rfloor} \frac{{\mu_b}^{e_b}}{e_b!} \frac{{\mu_d}^{e_d}}{e_d!} \tag{19}$$

$$= e^{-\mu_d} e^{-\mu_b} \sum_{e_d=1}^{\infty} \frac{{\mu_d}^{e_d}}{e_d!} \sum_{e_b=\lceil (c_{in}-\varepsilon_- +1)e_d \rceil}^{\lfloor (c_{in}+\varepsilon_+ +1)e_d \rfloor} \frac{{\mu_b}^{e_b}}{e_b!} \tag{20}$$

To be able to calculate this equation for larger electron or photon counts we need to use the Stirling approximation:

$$n! \sim \sqrt{2\pi n} \left(\frac{n}{e}\right)^n \tag{21}$$

$$\log n! \sim \frac{1}{2} \log 2\pi n + \log n^n - \log e^n \tag{22}$$

$$\sim n \log n - n + \frac{1}{2} \log 2\pi n \tag{23}$$

$$CDP = \sum_{e_d=1}^{\infty} f(e_d, \mu_d) \sum_{e_b=\lceil (c_{in}-\varepsilon_- +1)e_d \rceil}^{\lfloor (c_{in}+\varepsilon_+ +1)e_d \rfloor} f(e_b, \mu_b) \tag{26}$$

For numerical evaluation we do not need to sum over all e_b and e_d, but limit the summation to a certain number of standard deviations beyond of which we consider the probability contribution as 0". The range between 0 and 10 is however not excluded from summation as it does not yield to computational efforts:

$$e_{d,start} = \max\{0, \mu_d - N_{d,start} \cdot \sqrt{\mu_d}\} \tag{27}$$

$$e_{d,stop} = \max\{10, \mu_d + N_{d,stop} \cdot \sqrt{\mu_d}\} \tag{28}$$

$$e_{b,start} = \max\{0, \mu_d - N_{b,start} \cdot \sqrt{\mu_d}\} \tag{29}$$

$$e_{b,stop} = \max\{10, \mu_d + N_{b,stop} \cdot \sqrt{\mu_d}\} \tag{30}$$

for the bright variables we also have to update the limits given by the above deliberations that yield to the correct summing from eq. 20

$$e_{b,start} = \max\{e_{b,start}, \lceil (c_{in} - \varepsilon_- + 1)e_d \rceil\} \tag{31}$$

$$e_{b,stop} = \min\{e_{b,stop}, \lfloor (c_{in} + \varepsilon_+ + 1)e_d \rfloor\} \tag{32}$$

Here only μ_b is an unknown variable and can be eliminated by using the contrast definition:

$$\mu_b = (c_{in} + 1)\mu_d \tag{33}$$

Further, the limits ε_- and ε_+ are currently given as absolute limits w.r.t. to the given contrast. While this a good choice to evaluate special contrast detection tasks, these limits can also be expressed as relative percentages to the incoming contrast, which allows a more generic evaluation:

$$c_{in} + \varepsilon_+ = c_{in} + \delta_+ c_{in} \quad \Rightarrow \quad \varepsilon_+ = \delta_+ \cdot c_{in} \tag{34}$$

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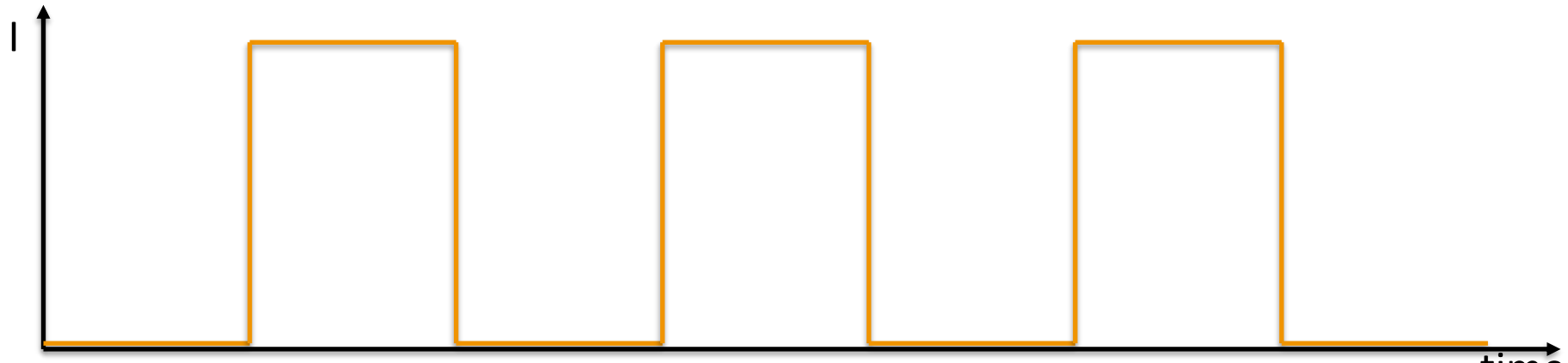
SHORT INTRODUCTION IN MMP

Pulse **W**idth **M**odulation is used to reduce and control the average power of an electronic component e.g. LED.



T

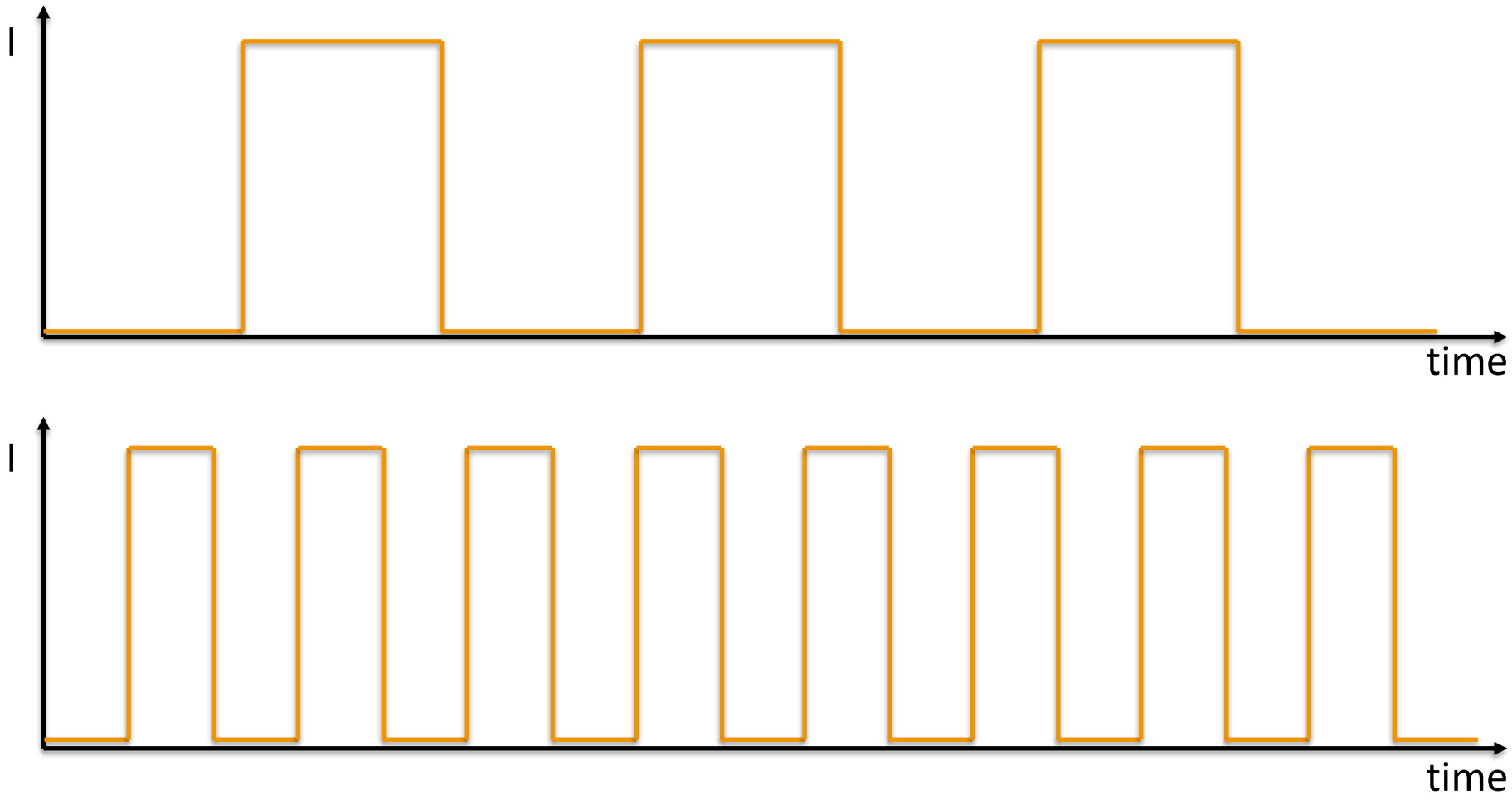
t_{off}

t_{on}

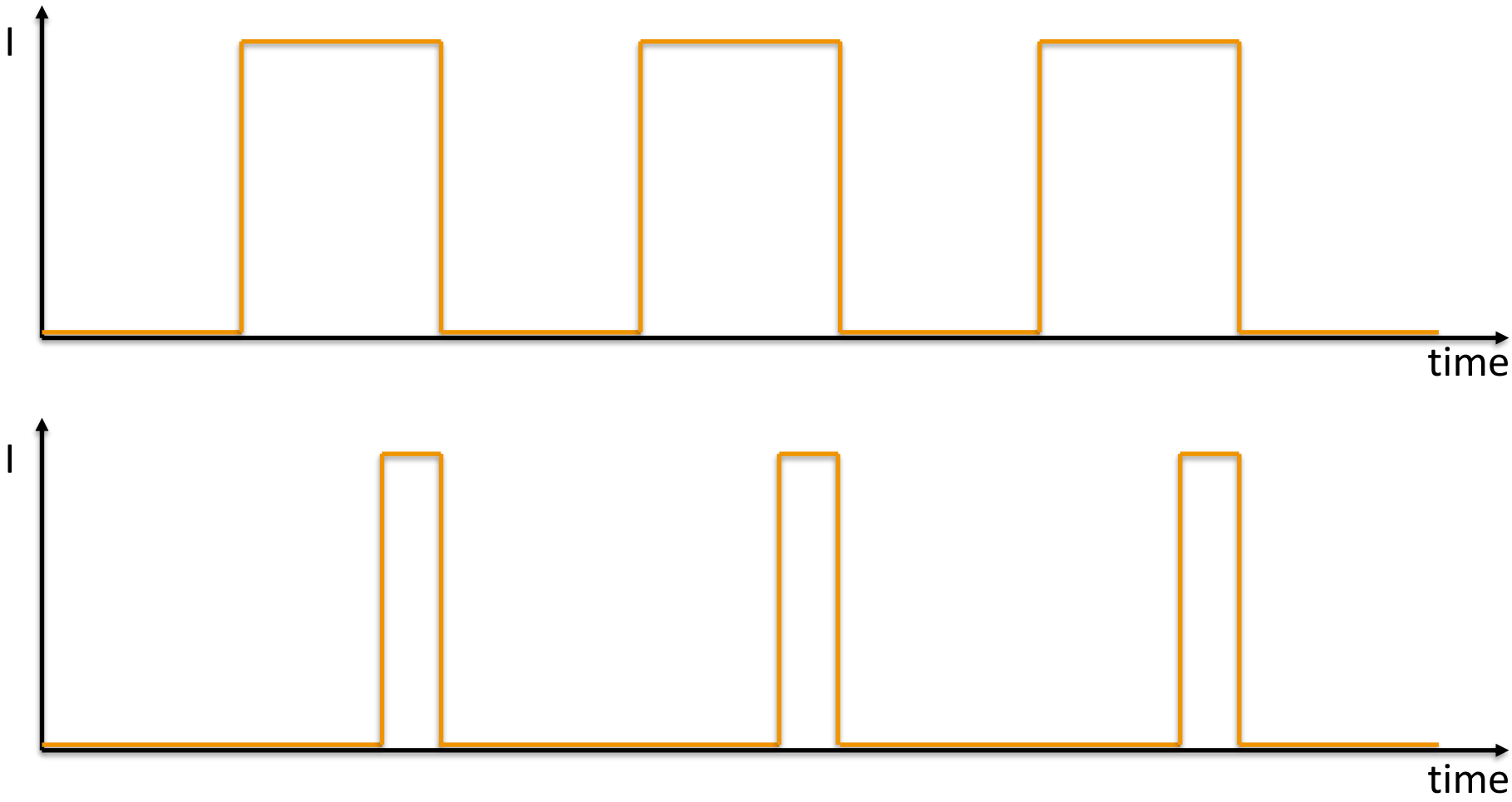
$$DutyCycle = \frac{t_{on}}{T}$$

$$f = \frac{1}{T}$$

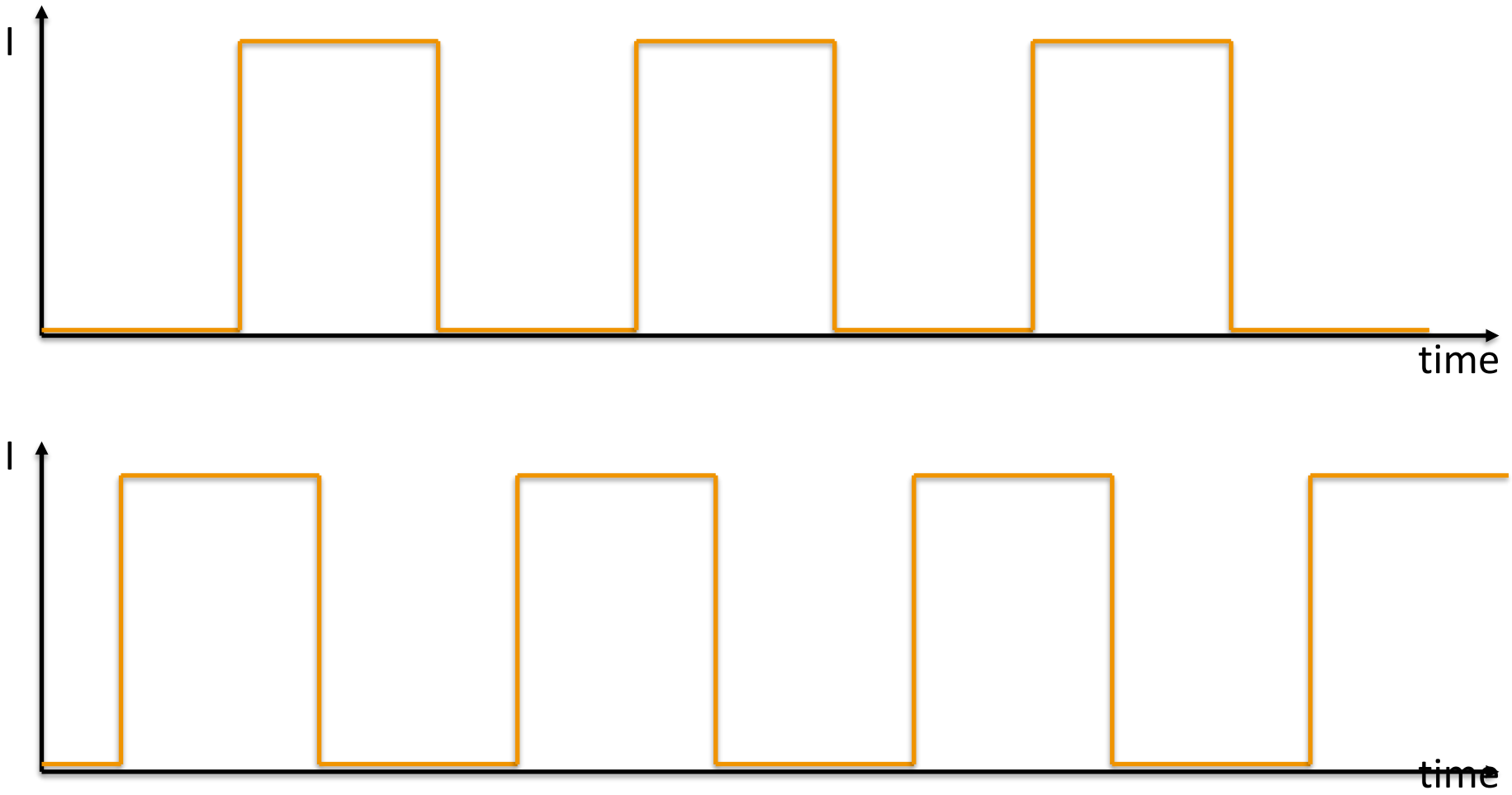
Frequency change

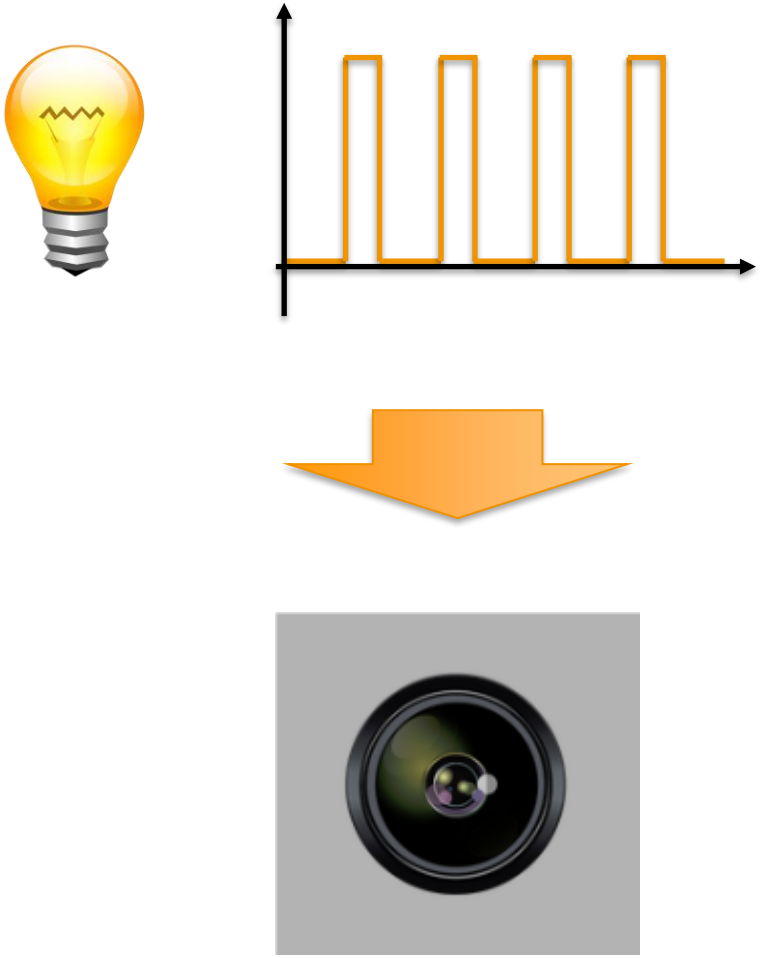


Duty Cycle change

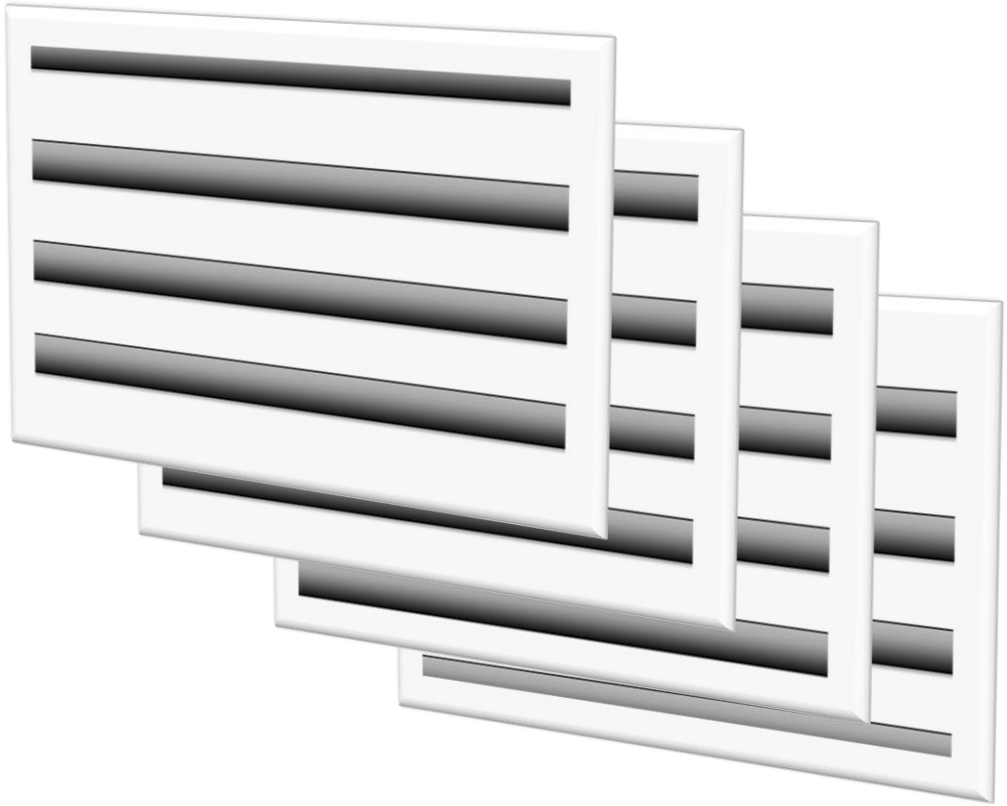


Phase change



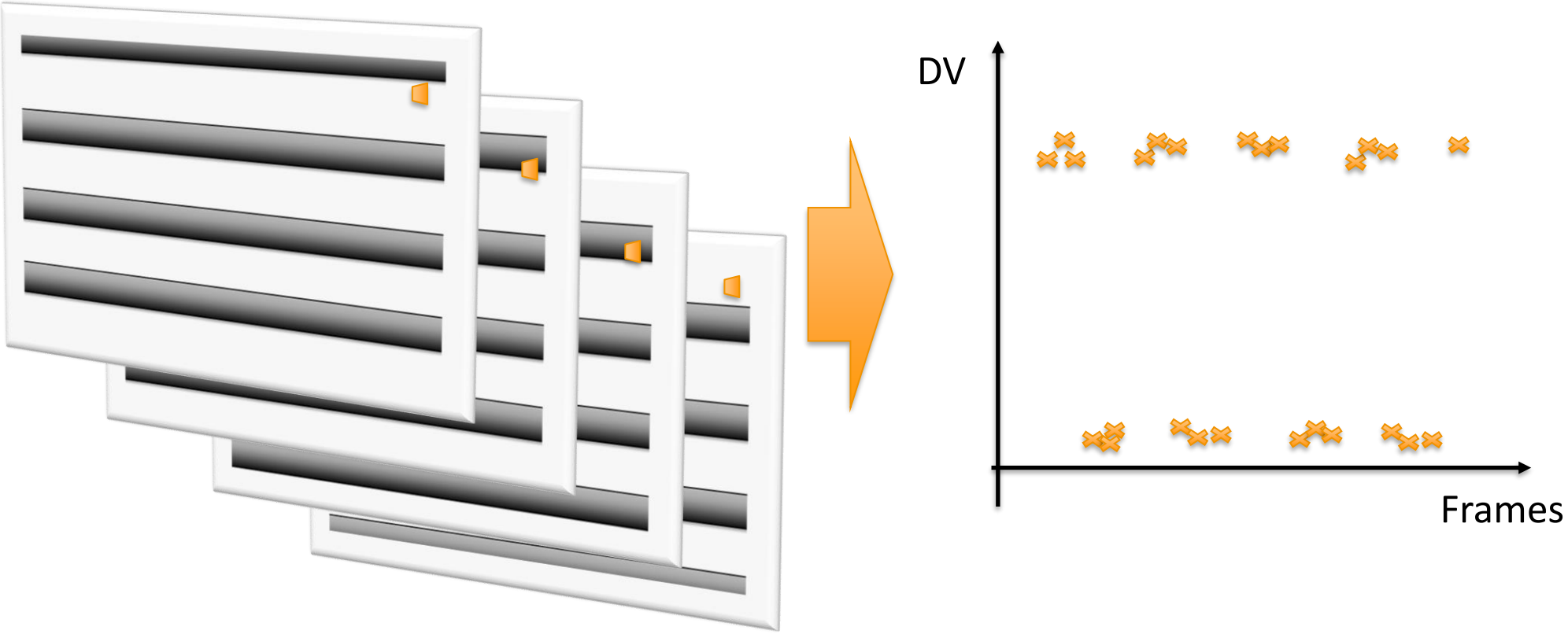


A uniform flickering light source may result in a varying image signal.

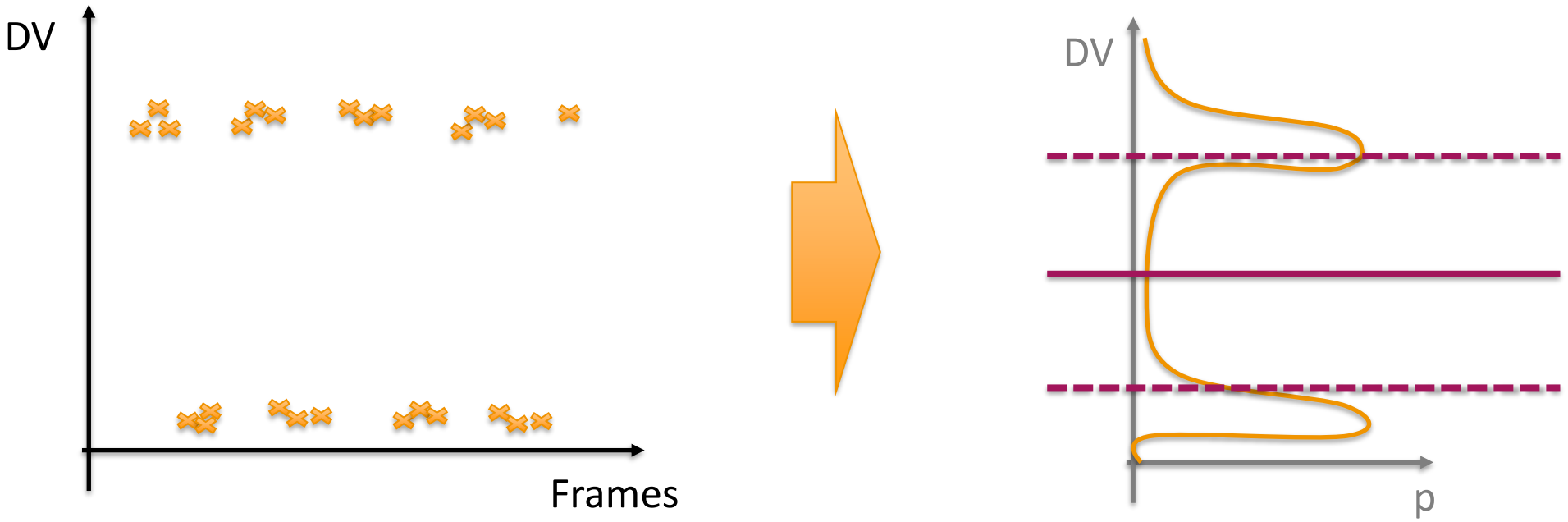


Let us observe the digital values of only one pixel over time

MMP Basics



MMP Basics



Flicker
mitigation OFF

Flicker
mitigation ON

Dynamic Test Stand - DTS

MMP is influenced by :

- Frequency
  - ➢ controllable
- Duty cycle
  - ➢ controllable
- Phase
  - ➢ always random phase to camera therefore once every 360° is rotated
  - ➢ calculation with Flicker Wizard in the Sequence Generator

Recommendations:

- Be careful with your timeline. Calculation can take long time if steps are small and short sampling is chosen.
- Search for corner cases first and scan in detail afterwards.
- Phase shift is needed if frequencies are close together, SW calculates internally if needed or not.
- Step duration is automatically calculated based on frame rate.

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