Digital Detector Arrays
(Flat Panel Detectors)

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April 2007

YXLON. The reason why

History of X-Ray applications

| >110 years: X-Ray film was developed for medical applications |
| - High Speed Films for minimum dose for patient with flourecents screens |

| ~ 20 years: DDAs* were developed for medical applications |
| - High Speed DDAs for even less dose for patient |
| - Highly optimized for a limited range of energy and resolution |

| ~50 years: X-Ray film was adapted to industrial applications (Pb screens): |
| - Higher spatial Resolution |
| - Higher Energy Range |
| - Lower Noise (higher dose) |

| ~10 years: DDAs were taken as there are for industrial applications |
| ~ 3 years: DDAs were adapted to industrial requirements |

*DDA = Digital Detector Array or Flat Panel Detector
**Digital Detector Arrays**

Radiographic Image Quality is the basis for all comparisons

New Table in ASTM E94

<table>
<thead>
<tr>
<th>Radiographic Image Quality</th>
<th>Film System Granularity</th>
<th>Radiographic Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiographic Definition</td>
<td>Inherent Unsharpeness</td>
<td>Subject Contrast</td>
</tr>
<tr>
<td></td>
<td>Geometrical Unsharpeness</td>
<td>Film Contrast</td>
</tr>
</tbody>
</table>

**YXLON. The reason why**

<table>
<thead>
<tr>
<th>DDA Image Quality</th>
<th>Detector Unsharpness</th>
<th>Projected Unsharpness</th>
<th>Quantum Noise</th>
<th>Detector Noise</th>
<th>Subject Contrast</th>
<th>Detector Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic Noise</td>
<td>Structural Noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**YXLON. The reason why**

**Image Quality Parameter with DDAs**

<table>
<thead>
<tr>
<th>Detector Unsharpness</th>
<th>Projected Unsharpness</th>
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</tbody>
</table>

Basic Spatial Resolution

\[ \text{SR}_B \] (effective Pixel Size)

Important Image Quality Parameter for DDA:

1. \[ \text{SR}_B \]  Basic Spatial Resolution
2. \[ \text{SNR} \]  Signal to Noise Ratio / Efficiency
3. \[ \text{CS} \]  Contrast Sensitivity
4. \[ \text{DR} \]  Dynamic Range
5. \[ \text{LAG} \]  Behaviour in time
6. \[ \text{IScR} \]  Internal Scatter Radiation
7. \[ \text{BP} \]  Bad Pixel Distribution

\[
\text{CNR} = \frac{\text{Contrast}}{\text{Noise}}
\]

\[
\text{SNR} = \frac{\text{Signal}}{\text{Noise}}
\]

\[
\text{CS} = \frac{1}{\text{CNR}}
\]
**Image Quality Parameter: Basic Spatial Resolution**

\[ SR_B \]

- Spatial detector resolution of the image in x- and y-direction
- Smallest detail perpendicular to the X-ray beam resolved in the image
- Also known as effective pixel size
- Corresponds to \( \frac{1}{2} \) of the detector unsharpness
- Measured with the Duplex Wire (EN 462-5 or ASTM E2002)
- May be calculated out of the visibility of duplex wires

**Measurement of the SR\(_B\) with the Duplex Wire (here: D2 Film)**

<table>
<thead>
<tr>
<th>Wire</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4</td>
<td>400µm</td>
</tr>
<tr>
<td>D5</td>
<td>320µm</td>
</tr>
<tr>
<td>D6</td>
<td>250µm</td>
</tr>
<tr>
<td>D7</td>
<td>200µm</td>
</tr>
<tr>
<td>D8</td>
<td>160µm</td>
</tr>
<tr>
<td>D9</td>
<td>130µm</td>
</tr>
<tr>
<td>D10</td>
<td>100µm</td>
</tr>
<tr>
<td>D11</td>
<td>80µm</td>
</tr>
<tr>
<td>D12</td>
<td>63µm</td>
</tr>
<tr>
<td>D13</td>
<td>50µm</td>
</tr>
</tbody>
</table>

![Image of Duplex Wire Measurement](image)
The reason why Digital Detector Arrays (DDAs) without magnification is much better than with DDAs of film. The reason why the Spatial Resolution (SR) of a 200µm detector is 200µm.

With magnification and small focal spot similar SR with a 200µm detector:

- Spatial Resolution of 50µm using a 200µm detector and µ-Focus tube.
- But: The very high SR is not necessary for most applications.
Digital Detector Arrays

Image Quality Parameter: Signal to Noise Ratio (SNR)

Example of different SNR at film

Example for different SNR in the Image

Signal to Noise Ratio (SNR) = 2
Examples for different SNR in the Image

Signal to Noise Ratio (SNR) = 4

Signal to Noise Ratio (SNR) = 8
Examples for different SNR in the Image

Signal to Noise Ratio (SNR) = 20

Signal to Noise Ratio (SNR) = 80
**Image Quality Parameter: Signal to Noise Ratio (SNR)**

Noise is in every image. Reasons for noise are:

- **Quantum Noise (X-Ray)**
- Grain Distribution
- Fog Contribution
- **Quantum Noise (X-Ray)**
- Structure Noise
- Electronic Noise

\[ \text{SNR} = \frac{S}{\text{SRMS}} \]

\[ 2 \times \text{Noise} = 2 \times \text{SRMS} \]

**Noise in the Film**

- Optical Density above fog and base
- Gradient \( G_D \) @ \( D=2 \) and \( D=4 \) above fog and base
- Granularity \( \sigma_D \) @ \( D=2 \)

Most important parameter for the perception of fine flaws: \( \frac{G_2}{\sigma_D} \)

Conversion to SNR possible by (linear systems)

\[ \text{SNR} = \frac{(G_2/\sigma_D)}{\ln(10)} = \frac{(G_2/\sigma_D)}{2.3026} \]

Diaphragm area (aperture) converted to square shaped area of 88.6 x 88.6\( \mu \)m for comparison of digitized films with DDAs and different SR\(_B\)

- Measured SNR has to be corrected by

\[ \text{SNR}_{\text{norm}} = \text{SNR}_{\text{meas}} \times \frac{88.6 \mu \text{m}}{\text{SR}_B} \]
Normalized SNR in the Standards (at Film Density $D-D_0=2$; EN 584-1)

EN 14784-1 Computed Radiography
ASTM E 2446 Computed Radiography

The limit in SNR$_{\text{norm}}$ for film is somewhere in the range of 150 - 200. With more dose the SNR would become better but film with densities $>4.8$ is not readable.

Reasons for Noise in the film and in digital Systems

- Film: Base and fog, Quantum Noise, too dark for readout
- DDA: Electronic Noise, Quantum Noise, Structure Noise
Two important differences between Film \(\Leftrightarrow\) DDAs at Noise:

- Quantum Noise (X-Ray)
- Film Granularity
- Fog Contribution

Quantum Noise (X-Ray)

- Structure Noise
- Electronic Noise

Can be compensated with a proper detector calibration

With Image Integration in a Computer and very long exposure times (\(\rightarrow \infty\)) it can be reduced to \(\sim 0\)

This opens the door to a new Image Quality

SNR at a good DDA is mainly limited by Photon Statistics and the Efficiency differs for different Energies:

<table>
<thead>
<tr>
<th>Energy</th>
<th>SNR(_{\text{norm}}) / Dose [mGy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>80kV/30Al</td>
<td></td>
</tr>
<tr>
<td>120kV/40Al</td>
<td></td>
</tr>
<tr>
<td>120kV/3mmCu</td>
<td></td>
</tr>
<tr>
<td>140kV/3mmCu/40Al</td>
<td></td>
</tr>
<tr>
<td>160kV/3mmCu/40Al</td>
<td></td>
</tr>
<tr>
<td>180kV/6mmFe</td>
<td></td>
</tr>
<tr>
<td>220kV/9mmCu</td>
<td></td>
</tr>
<tr>
<td>90kV/30Al/Int</td>
<td></td>
</tr>
<tr>
<td>9kV/30Al/Int</td>
<td></td>
</tr>
<tr>
<td>9kV/no filter</td>
<td></td>
</tr>
<tr>
<td>9kV/max Int</td>
<td></td>
</tr>
</tbody>
</table>

**Conditions:** 1000mm Focus DDA Distance, SNR\(_{\text{norm}}\) calculated by substracted images
The **Efficiency** can be used to select the best DDA for a dedicated Energy level:

Image Quality Parameter: Contrast Sensitivity

Contrast Sensitivity (CS) indicates the smallest material difference which can be resolved in the image.

\[
CS = \frac{S_{RMS}}{\Delta S} = \frac{1}{CNR}
\]
Measurement of Contrast Sensitivity

CS measured with Duplex Stepwedge (stepwedge with grooves)

CS is calculated of difference in signal divided by mean noise level per step.

Example: Stainless Steel

Three different Materials: Aluminium, Titanium and Stainless Steel

Old version: still 2 grooves ...
In the range of 1.25 to 12.5 mm stainless steel a 0.2% material thickness can be resolved. Film level is >1% and only possible within a smaller material thickness range.

... also called in ASTM: „Specific Material Thickness Range”

SNR on each step is calculated for different exposure times ...
**Measurement of the Dynamic Range**

**Dynamic Range: SNR /mm Al**

- **1f**
- **1s**
- **4s**
- **16s**
- **60s**
- **2%**
- **1%**

Dynamic Range from 10 to 72mm for 1% applications with 4s exposure time

Dynamic Range from 10 to 90mm for 2% applications with 4s exposure time
Image LAG or Ghosting

Image LAG is caused by the electronic of a DDA

YXLON. The reason why
LAG and Burn In

Example for „Burn In“

Negative image of a turbine blade two days ago. Corrected one day before

Lead letter on the step wedge from the day before. No new calibration was done ...

Burn In is a long term effect in the Scintillator of a DDA

Digital Detector Arrays

Internal Scatter Radiation

Internal Scatter Radiation increases with the energy. Important Parameter for CT machines ...
Bad Pixel

... only a dead pixel is a bad pixel?

Not really ...

<table>
<thead>
<tr>
<th>No gain pixel</th>
<th>... or “dead pixel”: Pixels with dose independent signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over responding pixel</td>
<td>Pixels whose grey values are greater than 1.3 times the median of brightness level of an area of in minimum 21*21 pixels; test is done on Offset corrected image</td>
</tr>
<tr>
<td>Under responding pixel</td>
<td>Pixels whose grey values are less than 0.6 times the median of brightness level of an area of in minimum 21*21 pixels; test is done on Offset corrected image (dark pixel with too low response)</td>
</tr>
<tr>
<td>Noisy pixel</td>
<td>Pixels whose sigma* are more than 6 times the median pixel sigma in a sequences of 30 to 100 images without radiation *sigma == standard deviation</td>
</tr>
<tr>
<td>Non uniform pixel</td>
<td>Pixel whose value exceeds a deviation of more than +/-1% of the median value of its 9x9 neighbour pixel in the corrected image</td>
</tr>
<tr>
<td>Persistence / Lag pixel</td>
<td>Pixel whose value exceed a deviation of more than +100% of the median value of its 9x9 neighbours and &gt;1% absolute in the first image after X-ray shut down</td>
</tr>
<tr>
<td>Bad neighbourhood pixel</td>
<td>Pixels, where all 8 neighbour pixels are bad pixels are also bad pixels</td>
</tr>
</tbody>
</table>
YXLON. The reason why

Digital Detector Arrays

Groups of Bad Pixel (Cluster)

<table>
<thead>
<tr>
<th>single bad pixel</th>
<th>2x2 cluster2</th>
<th>2x3 cluster4</th>
<th>rel3x4 cluster7-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C C C</td>
<td>C C C</td>
<td>C C C C</td>
<td>C C C C C C</td>
</tr>
<tr>
<td>C D C</td>
<td>C D C C</td>
<td>C D D C C</td>
<td>C D C C D C</td>
</tr>
<tr>
<td>C C C</td>
<td>C D C C</td>
<td>C C D D C</td>
<td>C D K K C C</td>
</tr>
<tr>
<td></td>
<td>C C C</td>
<td>C C C C</td>
<td>C C C D D C</td>
</tr>
<tr>
<td>2x24 Line26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C C C</td>
<td>C C C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C C D C C C C C</td>
<td>C C D C C</td>
<td>C C D D C C</td>
<td></td>
</tr>
<tr>
<td>C C C D D D D D D</td>
<td>C C C C C C</td>
<td>C C C C C C</td>
<td></td>
</tr>
</tbody>
</table>

- pixel used for correction

K CKP = defect pixel < 5 good neighbours

defect pixel >= 5 good neighbours

Main Difference between Film and DDAs

Two unique property of DDAs:

- Take multiple images at identical pixel positions and cumulate.
- Calibrate on pixel basis with suitable energy and material in the beam similar to the test object

The key for best image quality with contrast sensitivity and superior SNR is the exact calibration of each detector pixel
to obtain the same radiation response as the neighbourhood detector pixel.
Digital Detector Arrays

Basic Functionality of all Types of Detectors

X-Rays reaching the sensitive area of the detector are converted to electrical charge. The amount of charge is measured. It is proportional to the Dose.

Different Technologies for Flat Panel Detectors are available

- **intrinsic Method**
  („direct Method“) - very inefficient, no products

- **direct Method with Photoconductor**
  (Amourphous Selen or CdTe) - example: AJAT DICT100 CdTe

- **indirect Method**
  (Converting X-Ray to Light with Scintillator, „normal“ Photodiodes)

Matrix-Structure of all Flat Panel Detectors

.. with Photo Diode for „Light Capture“ and TFT for selective Read out
**Basic Principle: Indirect Method with Scintillator**

A thick scintillator results in many photons, but with a loss of geometric resolution (noise vs. resolution).

The effective geometric resolution depends on various parameters, these must be measured!

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Cesium iodide can be formed into needles on top of the diode structure to direct the light to the photodiodes without significant light scatter. The needles ensure a high total internal reflection of the light and direct it to the photodiode.

Disadvantage of CsJ: ImageLag and Burn In
What happens during operation?

What happens:

1. Capacity of Photodiode is charged up to \( U^+ \)

2. Incoming Light discharges the capacity; more light means less charge left in the Capacity

3. Now the cell should be read out:
   - The TFT becomes conductive and the capacity is recharged through the Read-Out Amplifier up to \( U^+ \) ...

3a. The amount of Charge for Recharging in measured in the Read-Out Amplifier. It is transferred as „\( U \)“ to the ADC

---

How do we do the calibration

1. Capture the Dark Image

Uncorrected Image with Flaws, Patterns, Bad Pixel, ... without X-Ray

==> Offset Image
How do we do the calibration

1. Subtract the Dark Image from any further Image

Offset corrected Image without X-Ray

2. Capture the Gain Images

==> Gain Image

Offset corrected Image with X-Ray and without Gain Correction
How do we do the calibration

2. Multiply each Pixel with Gain Image for further Images

Offset and Gain corrected Image with X-Ray

Detector Output Signal [ADU]

2b. Correct Non-Linearities with Energy adapted Gain Images

full dose

real dose with material in the beam

reduced dose during calibration

energy
How do we do the calibration

- Real (non-linear) Detector Output Signal
- „Gain Line“, calculated of Correction Points 1 to 3
- Signal after Correction with „Multi-Gain“
- Signal after Correction with Offset and Multi-Gain

A High SNR is obtained with Optimized Calibration

(SNR is limited to ~1000 because of the Structure of the Material)

With 16s same quality like with 500s and normal calibration
Inspection wide Range of Material with optimal Calibration

% Visible Material Difference Al 160kV 5mA 0.5Cu 1000FDD

in %

- 1s
- 4s
- 16s
- 60s
- 600s

Aluminum, 10 - 110 mm, PerkinElmer RID 512 / AF1 and Image 3500 DD

YXLON. The reason why

Can a High SNR Compensate a Lower SR_B?

With a high SNR details can be seen more easily and even objects smaller than the pixel size can be detected

Aluminum wedge with 5 long holes inside;
Image from 400µm pixel pitch panel PerkinElmer RID512/400 AF1

YXLON. The reason why
Can a High SNR Compensate a Lower SR_B?

With a high SNR details can be seen more easily and even objects smaller than the pixel size can be detected.

This is just a third of the pixel size. How is this possible?

With a high SNR it is enough that just a part of a pixel gets the information.

The long hole, just a quarter of a pixel width

Example:
The hole has 2% less density than the rest.
The hole covers ¼ of the pixel.
The visibility would be 2% * ¼ = 0.5%.
With a SNR > 200 the 0.5% is visible.
Compensate a lower $SR_B$ with a higher SNR

Another example with 8mm steel weld (test weld BAM5)

Film AGFA D2, class C1 EN 584-1
330s exposure time

PE XRD1620 detector (200µm $SR_B$),
magnification of 3.0
100s exposure time only

Film AGFA D2, class C1 EN 584-1
330s exposure time

PE XRD1620 detector (200µm $SR_B$),
magnification of 3.0
100s exposure time only
**Advantages of Digital X-Ray**

- **Time of Inspection will be reduced**
  Example (from Boeing): 6" diameter Inconel, 10 welds
  - Film Process: 2-3 hours
  - Digital X-Ray: 12 minutes 10 seconds

- **Avoiding high Recurring Costs (Chemicals and Film)**
- **No Chemical Processing incl. associated facilities + waste water handling**
- **Lower Storage Costs - cheaper Archiving**
- **Faster Access to an Image in the Database - if needed**
- **Image Transfer from one Location to another in few seconds (network)**
- **Very short set-up time with manipulation system (no film transport)**
- **Ability to use Digital Image Processing like Filter, Zoom, Measurement**
- **Smaller Footprint**
- **Inspection of larger Range of Material Thicknesses within one Image**
- **Higher recognition rate of defects in production ...**

**Comparison of Film (single wall, double wall), RT und DR**

done by Bill Meade, Clay Kidwell, Greg Warren (Boeing Commercial Aircraft)

![Comparison of "Hits" for Digital, RTX, Single-Wall, & Double-Wall Film](chart)

**Digital System: Thales FS35 with YXLON Image 3500 DD**
Digital Detector Arrays

Result of the POD Study by Flaw „Volume“ (Depth x Length)

Saving time using DDA systems

Necessary time for inspection of a part:

- 2 – 3 hours with Radiography using the current film process
- 35-40 minutes with current radioscopy inspection
- 12 minutes are sufficient for the same task with the DDA system

Hint:
The POD was not done with the best available DDA.
New generation of DDAs increase SNR and CS by factor of 2.5.
Example: Small Turbine Blade with ASTM Penetratet „5“

Film Agfa D2, 420s exp. time digitized with 50µm and 16 Bit

DDA + µ-Focus PE XRD1620, 60s exp. time

Images highpass filtered

Cutout of Penetratet with the 3 Holes

Film Agfa D2, 420s exp. time digitized with 50µm and 16 Bit

DDA + µ-Focus PE XRD1620, 60s exp. time

254µm
Digital Detector Arrays

Example: Small Titanium Duct with Penetramter „5“

Film Agfa D2
100s exposure time

DDA System
16s exposure time

Cutout of the defects in the weld

Film Agfa D2
100s exposure time

DDA System
16s exposure time

50µm
Inspection of Ducts, potential for ADR?
Inspection of Ducts, potential for ADR?

The new DDA systems are suitable for film replacement, ADR and CT.

Basic Parameters for Digital Radiology are:
- Basic Spatial Resolution (SR_B)
- Contrast Sensitivity (CS)
- Dynamic Range $\rightarrow$ Specific Material Thickness Range
- Normalized SNR (SNR_{Norm}) $\rightarrow$ Efficiency

SNR_{Norm} of DDA system depends on:
- integration time,
- calibration procedure and
- radiation quality

DDA systems can exceed Film systems by factor $>$20 in SNR_{Norm}

Very high SNR gives a superior Contrast Sensitivity CS.

A high Contrast Sensitivity can compensate a lower SR_B.

With $>$ CS fine details $<$1 pixel size give enough signal to become visible.

Adapted Filters increase the Visibility of Inhomogenities.