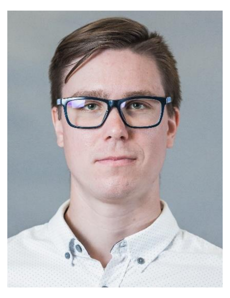
CCD and scientific-CMOS detectors for submicron laboratory based X-ray Computed Tomography



Jakub Salplachta, Tomas Zikmund, Jozef Kaiser

CEITEC - Central European Institute of Technology, Brno University of Technology, Czech Republic

Martin Horvath[1], Ladislav Pina[1], Yoshihiro Takeda[2], Kazuhiko Omote[2]

Rigaku Leading With Innovation

[1] Rigaku Innovative Technologies Europe, s.r.o., Czech Republic

[2] Rigaku Corporation, X-ray Research Laboratory, Japan

Abstract

The key component of any CT (X-ray computed tomography) machine is a detection system. In the area of scientific CT imaging applications three types of sensors are mainly used. These are amorphous silicon (α-Si) flat panels, complementary metal-oxide-semiconductor (CMOS) or scientific CMOS (sCMOS) and charge-coupled device (CCD) sensors.

The purpose of this study was to compare the performance of a sCMOS-based detector with a CCD-based detector for submicron CT measurement at laboratory-based system. Rigaku nano3DX machine equipped with XSight™ Micron LC X-ray CCD camera and XSight™ Micron LC X-ray sCMOS camera was used for this task.

Properties of each camera were evaluated as well as the quality and noise properties of acquired data. Several camera parameters were investigated e.g. achieved spatial resolution, modulation transfer function (MTF) and number of hot pixels. For data quality evaluation, acquired data of phantoms as well as selected samples were used.

I Materials and methods

XSight™ Micron LC X-ray CCD/ sCMOS camera

Table 1: Nominal parameters of both tested cameras without a lens unit.

Technical features	CCD camera	sCMOS camera
Array size	3320(H) x 2500(V)	2048(H) x 2048(V)
Pixel size	5.4 μm	6.5 μm
Sensor diagonal	22.5 mm	18.8 mm
Nonlinearity	< 1%	0.2%
Dynamic range	2300 : 1	21 400 : 1
Acquisition gain	0.45 e^-/ADU	0.55 e^-/ADU
Readout noise	11 e^- rms	1.4 e^- rms
Readout rate	8 Mpix./s (approx. 1 fps)	40 fps (@ 16 bit)
Dark current	0.001 e^-/pix./s @ 35°C	0.14 e^-/pix./s @ 0°C
Binning	Independent on-chip binning in x, y	2 x 2, 3 x 3, 4 x 4, 8 x 8
Peak quantum efficiency	56% @ 540 nm	82% @ 550 nm
Shutter type	Electromechanical	Rolling shutter
Data interface	USB 2.0	USB 3.0

Acquired data and evaluated parameters

Table 2: List of acquired data and evaluated parameters.

Data	Evaluated parameters
Bias frames	Read-out noise properties
Dark background frames	Dark current Number of hot pixels Number of random hot pixels
Bright frames	Noise properties Linearity
JIMA RT RC-02B frames	Spatial resolution Data quality
CT data – Ruby ball (0.3 mm diameter)	Spatial resolution Data quality
CT data – Glass cup	Data quality

For all measurements the **sensors temperature** was kept at **0 degrees**. Used exposure times for X-ray projection data were first selected for CCD camera, based on optimal contrast and also on analysis type. Exposures for sCMOS camera were subsequently derived to achieve equal detected signal level as for CCD. The evaluated CT data of a ruby ball (with 0.3 mm diameter) and a glass cup sample were reconstructed, from only background and flat-field corrected projections, using **ASTRA Tomography Toolbox** [1]. **No data processing or corrections** such as noise or ring artifacts reduction were used in our study. For some analysis DN (Digital numbers) of acquired data were converted to number of detected electrons using vendor's conversion specifications.

II Results

Noise properties

For noise properties analysis several parameters were evaluated: **readout noise** (calculated from bias frames), **dark current** (calculated using linearity analysis of dark background frames), **hot pixels** and **random hot pixels** (analysis of extreme values in dark background frames), **total noise** (calculated from bright frames) and **normalized noise power spectrum** (NNPS – calculated from bright frames based on IEC 62220-1: 2003(E) standard [2]. Achieved results are stated in Table 3 and shown in Fig. 1.

Table 3: Results of noise properties and hot pixels analysis.

	Readout noise [e^- rms]	Dark current [e^-/pix/s]	Total noise [e^- rms]	Hot pixels [%]	Random hot pixels [% / frame]
CCD	10.67	0.10	101.53	0.12	0.47
sCMOS	1.32	0.06	118.75	0.50	0.74

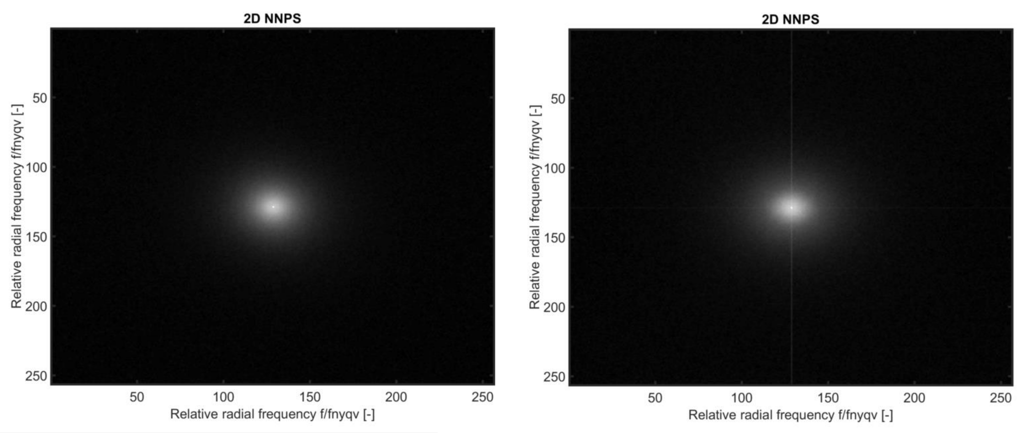


Fig. 1: 2D NNPS for both tested cameras: CCD (left) and sCMOS (right).

Spatial resolution

For evaluation of the spatial resolution of the **nano3DX system** with both tested cameras, two approaches were used: **JIMA RT RC-02B resolution test** in projection domain and in tomogram domain **evaluation of MTF** (Modulation transfer fuction) – procedure defined in: **ASTM E1695-95(2013) standard** [3]. In projection domain tested system reached **0.5 μm resolution** in both horizontal and vertical directions for both used cameras (Fig. 2). In tomogram domain **CCD based detection** system achieved **1.58 μm spatial resolution** and the **sCMOS based system 1.91 μm** for specified acquisition settings that reflected standard measurement scenario.

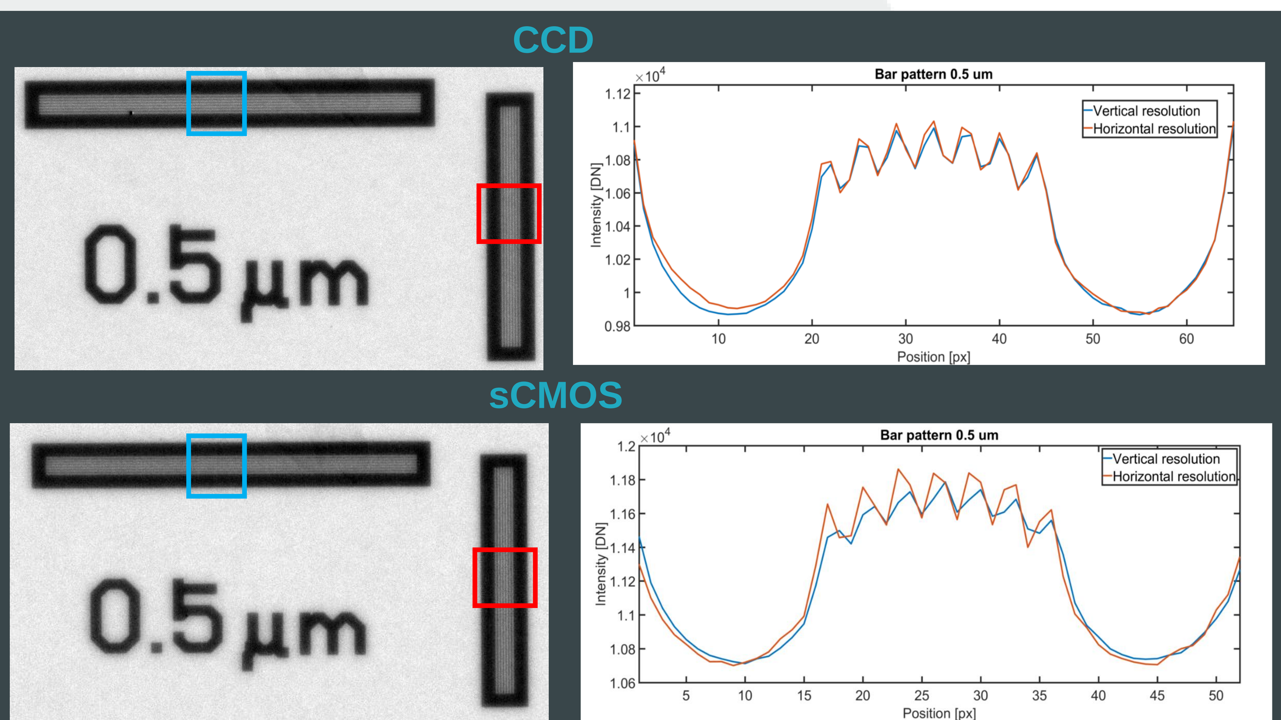


Fig. 2: Results of JIMA RT RC-02B resolution test – line profile analysis of labeled areas.

Data quality

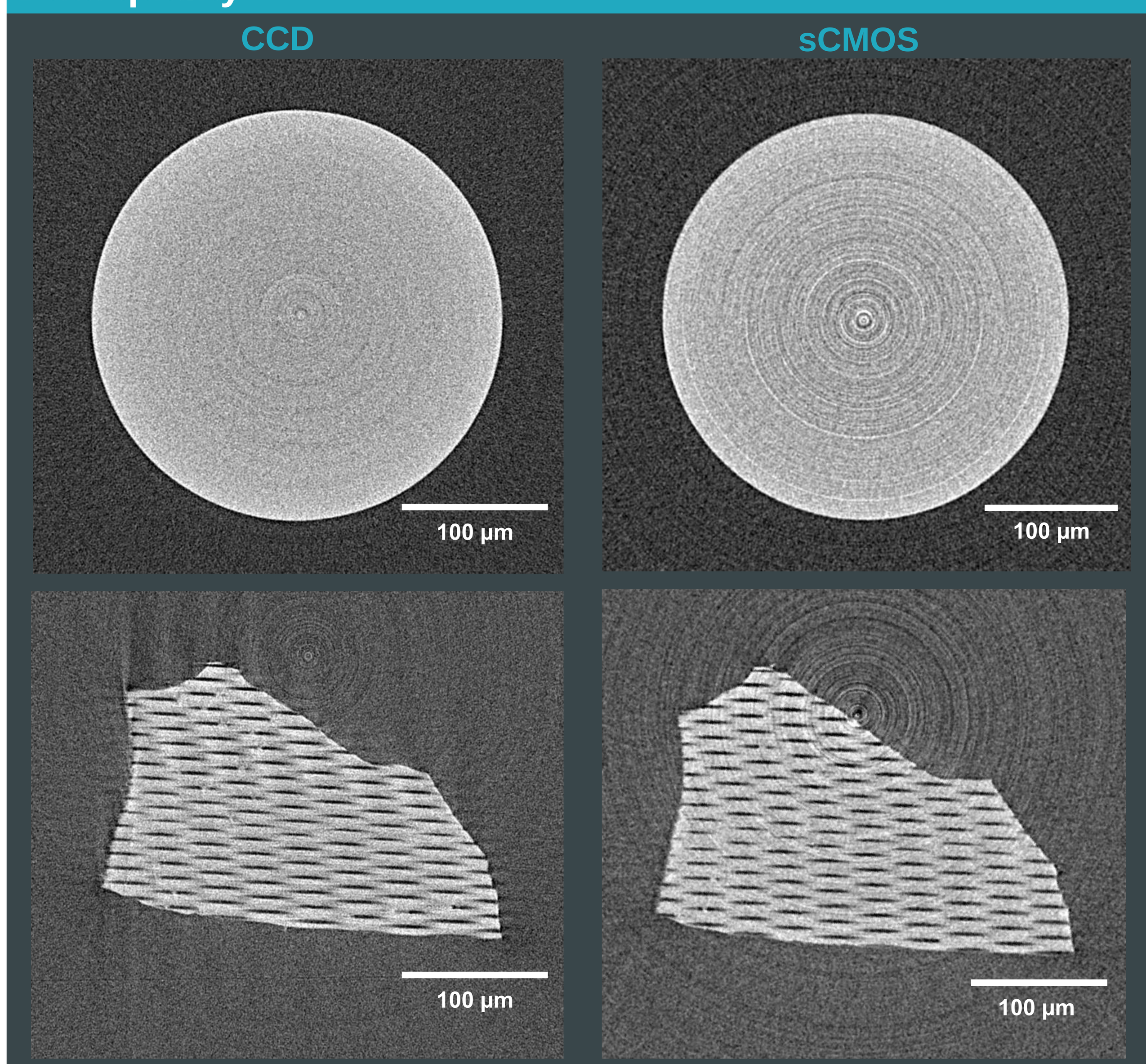


Fig. 3: Comparison of raw CT images without any processing (no ring artifacts and noise reduction) acquired by tested cameras – ruby ball (up) and glass cup (down).

Acquired data quality for both tested cameras was evaluated quantitatively and qualitatively both in projection domain and tomogram domain. **Qualitative evaluation** was done by **visual perception** of several operators and **no significant quality differences** between both cameras were found **in projection domain**. However, **in tomogram domain** there were present severe **ring artifacts** in case of **sCMOS acquired data** (see Fig. 3). For **quantitative evaluation** we adopted **image quality evaluation procedure presented by Kraemer et al.** [4] – utilization of **image quality measures**: Contrast to Noise Ratio (**CNR**), Signal to Noise Ratio (**SNR**), Local Contrast (**C**), Variance (**VAR**), Sum of Modified Laplacians (**SML**) and Just Noticeable Blur (**JNB**). For all evaluated data the CCD sensor reached higher SNR (see Table 4 and Table 5). In situation, when **same exposure time** was used **sCMOS data reached better results** compared to CCD data. Also for situations, when **comparable signal** was detected by both tested sensors, **sCMOS based camera reached better or comparable results** to CCD based camera.

Table 4: Results of data quality analysis for acquired projection data

	CCD				sCMOS		
	JIMA (exp. = 30 s)	JIMA (exp. = 60 s)	Ruby ball	Glass cup	JIMA (exp. = 30 s)	Ruby ball	Glass cup
CNR	7.07	10.15	28.83	28.80	10.51	17.75	25.52
SNR	8.73	9.10	3.53	51.0	6.89	3.17	9.60
C	0.56	0.61	1.0	0.14	0.72	1.0	0.48
VAR	3e-3	4e-3	1.85e-5	1.47e-4	0.01	1e-3	8.91e-4
SML	184.76	185.48	381.94	280.53	164.25	3778.60	137.63
JNB	1.39	2.61	0.98	2.09	3.20	0.63	2.75

Table 5: Results of data quality analysis for tomogram data

	CCD		sCMOS	
	Ruby ball	Glass cup	Ruby ball	Glass cup
CNR	6.15	4.44	6.11	4.41
SNR	79.28	278.15	26.63	26.06
C	0.08	0.03	0.39	0.40
VAR	1.98e-4	1.03e-4	2e-3	0.01
SML	1158.71	106.31	1682.12	519.72
JNB	7.89	4.52	6.94	5.13

III Conclusion

In this study comparison of CCD and sCMOS based detectors in field of high resolution X-ray computed tomography imaging using laboratory-based CT system was conducted. For data acquisition Rigaku nano3DX system was used. Both detector types were compared in terms of their properties and also acquired data quality and noise properties. For that, image data of phantoms as well as selected samples from material sciences were acquired and evaluated in projection and also tomogram domain. Acquired results showed that there were not negligible differences between both tested cameras, specifically in terms of noise properties, achieved spatial resolution and number of hot pixels. However, it was shown that sCMOS camera based detection system can be used for the task of submicron laboratory based X-ray Computed tomography. Specifically, it brings quality and noise properties improvements for low exposure time measurement scenarios compared to situation when CCD sensor is used.

REFERENCES

[1] W. Van Aarle, W J. Palenstijn, J. Cant, E. Janssens, F. Bleichrodt, A. Dabravolski, J. De Beenhouwer, K. J. Batenburg, and J. Sijbers. Fast and Flexible X-ray Tomography Using the ASTRA Toolbox. Optics Express, 2016, vol. 24, no. 22, pp. 25129-25147.

[2] IEC 62220-1:2003(E), Medical electrical equipment – Characteristics of digital X-ray imaging devices – Part 1: Determination of the detective quantum efficiency. International Electrotechnical Commission, 2003, Switzerland.

[3] ASTM E1695-95(2013), Standard Test Method for Measurement of Computed Tomography (CT) System Performance, ASTM International, West Conshohocken, PA, 2013, www.astm.org

[4] Kraemer, A., Kovacheva, E. and Lanza, G. Projection based evaluation of CT image quality in dimensional metrology. Digital Industrial Radiology and Computed Tomography (DIR 2015). Belgium, Ghent, 2015.

ACKNOWLEDGMENTS

This research was carried out under the project CEITEC 2020 (LQ1601) with financial support from the Ministry of Education, Youth and Sports of the Czech Republic under the National Sustainability Programme II and CEITEC Nano Research Infrastructure (MEYS CR, 2016–2019).

CEITEC – Central European Institute of Technology
Brno University of Technolgy, Purykňova 123
612 00 Brno, Czech Republic
www.ceitec.eu

Ing. Jakub Salplachta
Laboratory of X-ray Micro and Nano CT
jakub.salplachta@ceitec.vutbr.cz
+420 541 149 867
www.ctlab.cz

CEITEC BRNO UNIVERSITY OF TECHNOLOGY