INVESTIGATING THE INFLUENCE OF IONIZING RADIATION ON STANDARD CCD CAMERAS AND A POSSIBLE IMPACT ON PHOTOGRAMMETRIC MEASUREMENTS

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ABSTRACT:

In the context of high precision metrology tasks in heavy radiated areas questions arose concerning the applicability of digital cameras for photogrammetric purposes under these special conditions. The background for this problem is the conceptual design of a particle accelerator. After initial installation some areas of the new facility will not be accessible due to an expected high level of neutron production and activation. Therefore a new remote-controlled survey and alignment system has to be developed. For this purpose close-range photogrammetry appears to be the most applicable technique.
But in technical literature hardly any research results can be found, concerning the influence of ionizing radiation on digital image sensors, particularly for photogrammetric use. Hence basic research as well as practical tests were carried out, to investigate the influence of neutron and gamma radiation on CCD sensors under photogrammetric aspects. The results show a significant influence of radiation on the image quality, but only for high gamma doses. Lower dose rates, as they are expected at the accelerator, are not going to be a serious problem. Further tests are planned.

KURZFASSUNG:

Im Rahmen eines Forschungsprojektes des i3mainz zur Entwicklung eines Vermessungssystems in radioaktiven Bereichen traten Fragen bezüglich der Eignung von Digitalkameras für hochgenaue photogrammetrische Messungen unter solch erschwerenden Bedingungen auf. Hintergrund ist die Planung und Konzeption einer Teilchenbeschleunigeranlage, bei der es Bereiche geben wird, die aufgrund zu hoher Strahlungswerte vom Menschen selbst nach kurzer Abklingzeit nicht mehr betreten werden dürfen. Dementsprechend muss eine ferngesteuerte Technologie zum Einsatz kommen, die die gestellten messtechnischen Anforderungen erfüllen kann, in diesem Fall die Photogrammetrie.
In der Fachliteratur finden sich jedoch kaum Aussagen oder gar Untersuchungsergebnisse zum Verhalten von digitalen Bildsensoren unter dem Einfluss ionisierender Strahlung, insbesondere wenn entsprechende Sensorik für photogrammetrische Zwecke eingesetzt werden soll. Daraufhin wurden sowohl umfangreiche Recherchen angestellt, als auch praktische Tests durchgeführt, um den Einfluss von in diesem Fall Neutronen- und Gamma-Strahlung auf CCD-Sensoren unter photogrammetrischen Aspekten zu untersuchen. Die Ergebnisse zeigen zwar signifikante Beeinträchtigungen der Bildqualität, dies aber nur bei relativ hohen Strahlendosen. Für die Arbeiten im Rahmen des Forschungsprojektes am Beschleuniger sind dagegen keine besorgniserregenden Effekte zu erwarten. Weitergehende Tests sollen aber noch durchgeführt werden.

1. INTRODUCTION

The influence of ionizing radiation on digital cameras, used for photogrammetric purposes, has not been subject of detailed investigations in the past. Although there is some research concerning the radiation damage in CCD – mostly in the field of space research, monitoring and particle detection – there are hardly any publications dealing with the influence onto the geometric and/or radiometric quality of images used for photogrammetric measurements. Most of the available publications discuss the degradation of CCDs due to permanent irradiation and the lifetime of imaging sensors under such conditions (Bassler, 2002; Hashemi & Bensinger, 1998; Rausch, 1999).
Much more interesting for photogrammetric purposes is, however, the quality of the recorded images in terms of contrast, noise, resolution, radiometry and geometric stability. Furthermore there should be distinguished between the damage to individual images, which only occurs during radiation and image effects resulting from permanent damage of image sensors after heavy radiation. Thus a damaged camera might still be useable as a monitoring camera (e.g. in a nuclear power plant), when it's already useless for photogrammetric measurements due to large noise or other effects.
This paper shows the actual state of our investigations and will present results of literature research as well as practical tests evaluating the influence of gamma radiation on industrial CCD cameras and its imagery under photogrammetric aspects. Further investigations with extended setups will be accomplished in the future.

2. BACKGROUND

2.1 Motivation

The Gesellschaft für Schwerionenforschung (GSI), located near Darmstadt, Germany, operates a large accelerator facility for heavy-ion beams. Here researchers and scientists from all over the world are working on different subjects like fundamental research in nuclear physics, atom physics, plasma and materials research, biophysics and cancer therapy. Some of the best-known results are the discovery of six new chemical elements and the development of a new type of tumor therapy using ion beams (GSI, 2006). Presently a new accelerator facility is planned next to the existing one. The new facility FAIR, Facility for Antiproton and Ion Research, will provide ion beams of unprecedented intensities and increased energy, and thus allows new experiments and, hopefully, new research results.

Just like the existing accelerator also the beam line components of the new facility will have to be aligned precisely. But, personnel admittance to specific areas for routine maintenance, and consequently for survey and alignment, will not longer be possible due to the very high radiation level in some areas of FAIR (Pschorn & Marbs, 2004). Besides increased demands on alignment accuracy, the non-linear and stretched geometry of the beam line (up to 50 m) and lack of space due to heavy shielding this leads to the need for a new survey and alignment system which will provide a fast, automatic and remote-controlled alignment with accuracies up to one tenth of a mm.

The basic concept for such an alignment system will be based on a photogrammetric solution. A number of high-precision digital cameras, which are installed on an automated guided vehicle system will be driven along the considered beam line and capture images simultaneously. A bundle adjustment will then deliver correction values for the position of the accelerator components.

The main question facing this concept is: Will the cameras be damaged by the radiation in the tunnel and will the images be useable for precise sub-pixel measurements? The equipment in the accelerator tunnel primarily is exposed to gamma and neutron radiation. Neutrons only occur during beam time while gamma radiation is a result of matter activation by neutrons and thus is permanently present during shutdown times (when the alignment is done). According to a preliminary estimate the expected level of gamma radiation during maintenance periods will be at dose rates of about 10 mSv per hour, which amounts to half of the allowed dose per year (see 2.2).

2.2 Ionizing radiation

Types of radiation

Generally there are four types of ionizing radiation, which may appear at an heavy-ion beam accelerator: alpha, beta, gamma and neutron radiation.

Neutron radiation: Neutrons emerge, when the ion beam collides with targets or beam dumps. This will only be the case during the operation of the accelerator and stops immediately when the accelerator is shut down. The expected neutron energy level at FAIR will be up to 1000 MeV and makes a massive shielding necessary (up to 8 m concrete and iron walls), to protect persons and environment outside the building. When neutrons interact with matter (e.g. shielding,), this causes a nuclear reaction and leads to activated matter which decays with a certain half-life.

Alpha radiation: As a result of this decay, alpha particles can emerge. An alpha particle is a helium nucleus that travels only a few centimeters in air before it is stopped and „disarmed“. Thus it will not be dangerous for a CCD sensor.

Beta radiation: Beta particles (electrons or positrons) also may emerge from above-named decay. These particles can be shielded by few millimeters of an absorbing material (e.g. glass) or by some decimeters of air. Therefore the influence of beta particles on image sensors was not investigated in this project.

Gamma radiation: Gamma radiation is an electromagnetic radiation with a wavelength shorter than 0.5 nm. Gamma rays are more penetrating than alpha and beta particles but less ionizing. Gamma radiation also results from radioactive decay. At FAIR gamma rays with energy levels of up to 1.5 MeV are expected. At this level, already approx. 10 meters of air are needed, to reduce the radiation by half.

Radiation protection

There are three principles of radiation protection: time, distance and shielding. Reducing exposure time helps in a proportional way, increasing the distance by the inverse of the square range. The principle of shielding was already mentioned above.

To protect man and nature from radioactive radiation in Germany there is the *Strahlenschutzverordnung* (Radiation Protection Ordinance) by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. (BMU, 2002). This ordinance rules principles and requirements for the protection of man and environment against ionizing radiation. Furthermore it lays down the maximum allowable radiation exposure for individuals. The exposure value for the population is 1 mSv per year while for work related exposure to radioactivity, X-rays and cosmic radiation the limit value is 20 mSv per year. Transferring this to FAIR this means that a person who stays more than two hours in the accelerator tunnel during shutdown would accumulate a dose which is exceeds the allowed dose for a whole year. This shows, that the expected dose rate level at FAIR will be too high for a human based alignment process and also might be too severe for camera sensors or other sensible devices.

3. INFLUENCE ON CCD SENSORS

3.1 Permanent damage

Semi-conductor sensor elements like CCDs consist of a silicon structure. If this structure is damaged, either a permanent malfunction will result or a complete destruction of the chip. There are different major CCD parameters, that are influenced by ionizing radiation, as (Bassler, 2002) points out: dark current, threshold voltages, charge transfer efficiency (CTE) and linearity. If these parameters are affected, this results in different image effects like hot pixels, increased noise and decreased contrast, what may have a significant effect on matching algorithms and measurement accuracy.

The level of dose rates leading to a damage of the imaging sensor needs rather an experimental than a theoretical investigation since the designs of semi-conductor elements are different, as shown by Nikolai Sinev from Physics Department, University of Oregon (Sinev, 2005).

Damage caused by neutron radiation

Concerning neutrons, a particle energy of only a few eV can displace a Si atom in the crystalline structure of the CCD and thus damage the chip permanently. The threshold is 30 eV according to Sinev and 190 eV according to (KEK, 2004), respectively. In any case the neutron energy at a heavy-ion beam accelerator will be much higher.
Raymond Rausch of CERN irradiated a CCD camera with a radiation mix of neutrons and gammas (Rausch, 1999): “The CCD camera degraded progressively, the number of white spots increased continuously, at 25 Gy the picture was still visible but at 30 Gy the camera stopped working.“. (1 Gy equals to 1 Sv in case of gammas and between 5 and 20 Sv in case of neutrons, depending on the energy.)
At the Brandeis University similar tests were carried out. A Texas Instruments TC255 CCD chip was irradiated there with fast neutrons. As a result “the dark current increased dramatically” while “no other forms of damage were observed” (Hashemi & Bensinger, 1998).
James Brau and Nick Sinev also irradiated a CCD chip with neutrons (Brau & Sinev, 1999) and came to the following results: “The bulk damage to the silicon, introduced by the irradiation with neutrons accompanying normal operation of a CCD […], will manifest itself in the creation of charge traps.” As Bassler explains in his thesis (Bassler, 2004), charge traps lead to CTE degradation and increased dark current.
Volker Dangendorf from PTB, Physikalisch-Technische Bundesanstalt, refers to his experiences with digital cameras used for Neutron Radiography and reports about accelerated aging of the sensors, which manifests in hot pixels and increased dark current. Another test showed, that 60 sec neutron irradiation at a dose rate of 3 mSv/h produced three damaged image elements. According to his experiences with different CDD cameras, older sensors with larger pixels (> 15 µm) are less damageable than new cameras with 6 µm pixel. Furthermore he recommends to shield the cameras and hide them behind a labyrinth of 45-degree mirrors.
So, neutron radiation is unreasonably dangerous for the silicon structure of CCDs and as well for a proper functioning of the sensor. Consequently it is essential to protect the cameras from any neutron radiation during beam time. This can be done by a radiation-protected storage room or by any other adequate shielding. Otherwise an error-free functioning of the cameras can not be guaranteed.

Damage caused by gamma radiation

In contrast to neutron radiation it needs a very high energy of more than 10 MeV (Bassler, 2004), before gamma radiation causes similar effects and damages the bulk silicon structure permanently (Sinev, 2005). Energy levels of this order of magnitude will not be found in the gamma spectrum of the accelerator facility.
But, already lower energies can cause “voltage shifts” on the surface of the silicon structure. If a certain amount of voltage shifts is reached, the CCD might stop working. According to Sinev (Sinev, 2005), this only happens “at rather high irradiation doses”. This effect strongly depends on the thickness of the silicon oxide. Using thinner silicon oxide in CCD production is one of the techniques to create „radiation-hard“ CCDs, that can accumulate gamma doses of more than 100 Gy without failing.
Figure 1 shows what type of damage will be produced by gamma rays onto a CCD. The main effect is ionization, resulting in voltage shifts on the surface of the silicon which leads to increased dark current and noise. If the energy level is high enough (> 10 MeV) this can even cause displacement of Si atoms and leads to permanent hot pixels or even to sensor malfunction.
Niels Bassler (Bassler, 2004) irradiated a Marconi CCD 47-20 chip (1,024 x 1,024) in three steps with doses 7.5 Gy, 15 Gy and 35 Gy of gamma radiation with a spectrum of up to 6 MeV. In all cases, he tested the performance of the sensors only after and not during irradiation. As a result the dark current increased slightly as well as the number of hot pixels, which is quite surprising facing the rather „low“ gamma energies. Bassler has two possible explanations for this: First, there was a significant hadron (neutrons, protons …) flux present, or second, the gamma rays were more energetic than expected.

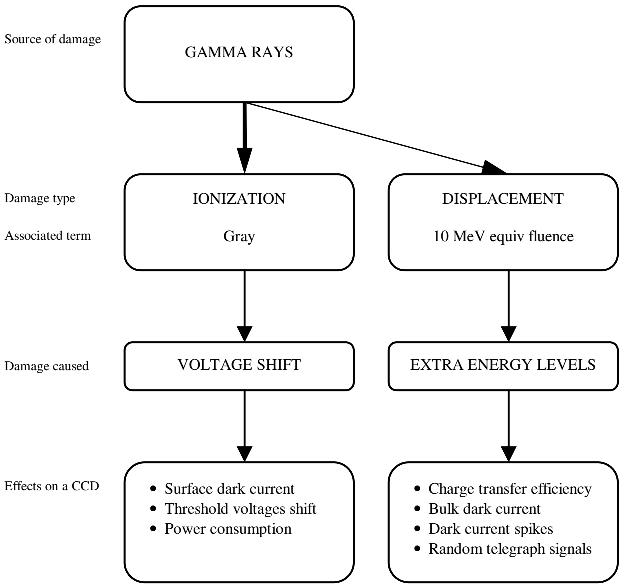

Figure 1. The radiation damage tree for CCDs. Illustration from (Bassler, 2004)

Fortunately, expected energy levels at FAIR with dose rates of 10 mSv/h and gamma energies of below 1.5 MeV will be lower, so a significant permanent damage of the CCD structure will not take effect.

3.2 Temporary damage

All the tests and experiences mentioned above were carried out to investigate *permanent* damages of CCDs after irradiation. On the other hand no meaningful literature exists concerning the investigation of *temporary* image defects due to irradiation of the camera during exposure time. Therefore further evaluations and own practical tests were necessary to examine the danger of gamma radiation for precise measurements in images. Details are shown in the following chapter.

4. RADIATION TESTS

4.1 Test facility, camera and setup

For the radiation tests an industrial CCD color camera AVT Marlin F-145C2 was used. See Table 1 for specifications. Marlin cameras are often used in photogrammetric applications and represent a typical imaging device possibly being used for the later alignment task, although higher resolution will be likely.

Two different test procedures were planned during irradiation:

1. “Dark” exposure with closed lens cap for detection of dark current noise and hot pixels,
2. “Illuminated” exposure of different targets for determination of resolution, contrast, accuracy of image measurements and noise.

In addition, the following demands had to be met for the test setup:

- cable connection between camera (in radiation environment) and notebook (in safe area)
- measurement of dose rate at any time of experiment
- determination of accumulated dose after experiment
- dose rates roughly from 1 mSv/h to 100 mSv/h
- gamma spectrum roughly between 100 keV and 1.5 MeV

Figure 2. Test camera

AVT Marlin F-145C2 (color)	
Image device	½“ type progressive scan SONY IT CCD
Image format	1280 x 960
Pixel size	4.65 µm x 4.65 µm
Resolution depth	8 bit
Lens mount	C-Mount
Digital Interface	IEEE 1394
Dimensions	58 mm x 44 mm x 29 mm (w/o lens)

Table 1. Specifications of the test camera

As test installation the TRIGA research rector could be used, which is a research facility at the Johannes Gutenberg University of Mainz. TRIGA stands for “Training, Research, Isotopes, General Atomics” and is designed for use by scientific institutions and universities for purposes such as education, private commercial research, non-destructive testing and isotope production. More than 50 TRIGA type reactors are installed worldwide. One main use of the TRIGA reactor in Mainz is neutron production for the purpose of irradiation of different samples and materials. Therefore the reactor offers several possibilities to place the sample close to the reactor core. One side-effect of the neutron production during reactor operation is the activation of the core with its surroundings which guarantees a radioactive environment with the required gamma dose rates even when the reactor is shut down again. Depending on the power and duration of reactor operation, different levels of gamma dose-rates will be achieved. The dose rate decreases slowly as the activation decays in accordance with the half-lives of the activated elements.

Setup 1: “Dark” exposure

The test procedure was as follows: First, the camera with closed lens cap was connected to a notebook via a 10 m long FireWire cable. Before irradiation and after a warm-up period of the camera reference images were taken in order to determine the as-is state of the sensor and to measure mean value, standard deviation and maximum gray value of the images.
Then the reactor was started for a few minutes, depending an the desired gamma level. After shut down, the camera was put into a small polyethylene container and lowered down to the reactor core (see figures 3 and 4). Depending on the position of the container, different dose rates could be achieved. The dose rate was measured with a radiation sensor which was also arranged in the PE container. With this setup dose rate of up to 100 mSv/h could be tested.

Figure 3. Polyethylene container which carries camera and radiation sensor.

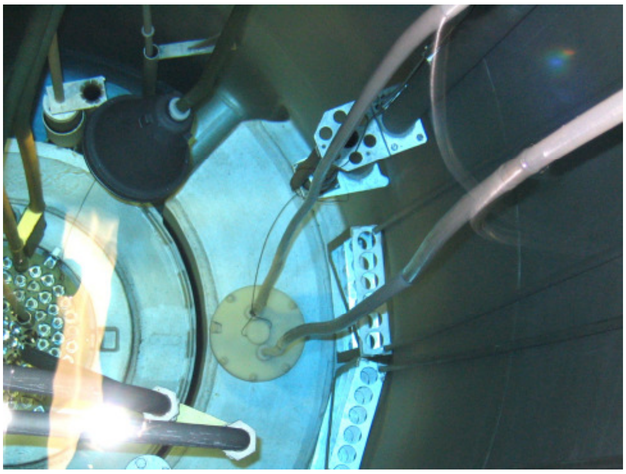

Figure 4. Top view of the reactor core with PE container. A 6 m water column protects people against radiation.

Setup 2: “Illuminated” exposure

For the second test series a different setup had to be chosen since it was not possible to take images within the PE container. For this purpose a “thermal column” was used, a 1261 mm long and 100 mm x 100 mm wide slot which penetrates the concrete shielding and ends close to the reactor core. With the help of a Plexiglas construction, the camera, an LED ring light, a target and a radiation sensor were mounted on a carrier (Fig. 5). Depending on the position within the thermal column different dose rates were realized. However, in contrast to the measurements in the PE container, only dose rates up to 8 mSv/h were possible due to safety reasons.
Two different targets were used. A Siemens star served as a device to test the resolution or possible changes of resolution

during irradiation, respectively. A second plate contains both photogrammetric targets to test the image measurement accuracy and different colored surfaces (white, grey, black) to investigate noise and hot pixels.

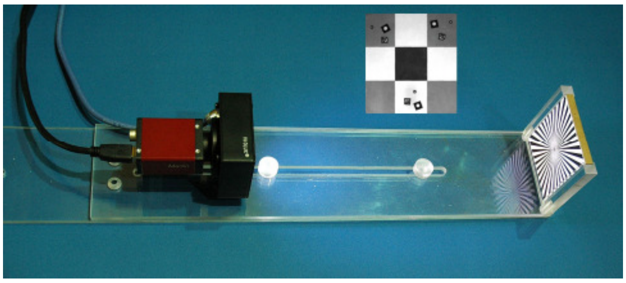

Figure 5. Plexiglas mount with camera, ring lighting and Siemens star target. The small image in the middle shows the second pattern with different colored areas and photogrammetric targets.

4.2 Results

In total 59 images were taken in two sessions at the dark exposure setup. Different settings of gain (0 to 450) and shutter time (0 to 4095 ms) were used for exposure. Table 2 shows an extract from the resulting protocol. Since the change of the mean gray value was too small to measure reliably (it was 0.00 in all images taken with gain 0), the columns "standard deviation", "maximum gray value" and "number of gray values larger than 0" are more meaningful. There is a significant correlation between dose rate and these values. Looking at the histograms of the images confirms, that there is a slight increase of noise in the images as well as an increase of the number of hot pixels. Looking at Fig. 6 clearly shows a significant amount of hot pixels in the right image. For a better presentation the image histograms have been stretched, hence pixels appearing to be white have gray values lower than 40 in reality. At dose rates of only 10 mSv/h, which amounts to one tenth of the dose rate of the right image of Fig. 6 and equals to the expected dose rates at FAIR, almost no hot pixels could be detected.
Thus the penetration of the gamma radiation through the camera housing and the resulting impact onto the chip itself is low and should not have serious consequences for the photogrammetric measurements as to be expected at GSI. The tests even showed, that the influence of a cold camera in contrast to a warmed up camera on the amount of noise and number of hot pixels is at least as significant as the influence of gamma radiation below 100 mSv/h. The "best" results were achieved, when the camera was pulled out of the reactor again after more than 30 minutes in operation.
Furthermore no permanent damage of the image sensor could be detected. The accumulated dose after these tests was approx. 28 mSv.

Dose rate (mSv/h)	Mean gray value	Std. dev.	Max. gray value	No. of gray values >0
0	0.00	0.06	18	898
5	0.00	0.09	34	1602
10	0.00	0.10	48	1172
20	0.00	0.10	41	1393
60	0.00	0.14	50	2011
100	0.00	0.15	47	2836

Table 2. Results of setup 1 "Dark exposure". Camera settings: Gain 0, Shutter 4095 ms

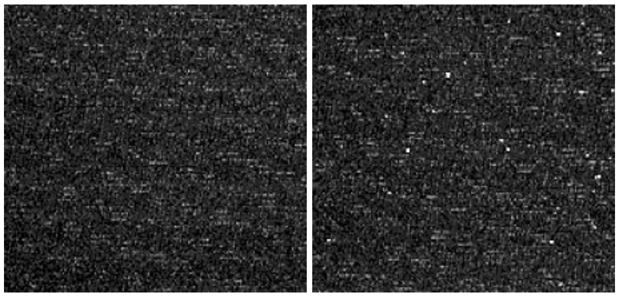

Figure 6. Section from images without radiation (left) and with 100 mSv/h gamma radiation (right). Histograms are stretched to make "hot pixels" visible.

Nonetheless the tests at the second setup were carried out to confirm the previously drawn conclusions. Here only dose rates of 8 mSv/h were possible due to reasons of radiation protection, as mentioned earlier. And as to be expected, both the image resolution and the accuracy of the point measurements remained unchanged during irradiation. The image measurements were accomplished with a template matching algorithm. The accuracy (RMS value) of the matching process was between 0.013 and 0.017 pixel for large targets (25 pixel diameter) and between 0.021 and 0.025 pixel for the smaller targets (7 pixel diameter). The resolution tests with the Siemens star showed a circle of confusion of 28 to 30 pixel in all images, independent of the dose rate.

5. CONCLUSIONS

The main goal of the study was to find out, whether the expected gamma radiation environment at FAIR, which will be high enough to prohibit any personal access to the affected areas, will influence high precision photogrammetric measurements for the accelerator alignment. Fortunately both theoretical research and practical tests showed, that there will no significant interference of the radiation concerning measurement accuracy and camera life-time.
Nonetheless the research showed clearly, that there *is* a definite influence on some image parameters, like noise, dark current und number of hot pixels. The more radiation the camera has to face, the more erroneous and noisy the images will be. Starting from dose rates of 100 mSv/h one will probably have to worry about the radiation when high precision measurements have to be carried out. But since the expected dose rates at FAIR will be less than a tenth of 100 mSv/h, this is not the case for the intended workings at FAIR.
In the future further investigations will be made concerning the permanent damage of cameras. For this purpose a test camera will be irradiated with both high doses of gamma and neutron radiation.

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