AUTOMATIC BEAM HARDENING CORRECTION FOR CT RECONSTRUCTION

Marina Chukalina
FSRC "Crystallographyand Photonics" RAS
IMT RAS
Moscow
Russia

Anastasia Ingacheva
National Research University Higher School of Economics

Moscow 3
Russia

Alexey Buzmakov
FSRC "Crystallographyand Photonics" RAS
Russian Academy of Science
Moscow
Russia

Igor Polyakov
Institute for Information Transmission Problems
RAS
Moscow
Russia

Andrey Gladkov
Visillect Service

Moscow
Russia

Ivan Yakimchuk
Schlumberger Moscow Research Center
Moscow
Russia

Dmitry Nikolaev
Institute for Information Transmission Problems RAS
Moscow
Russia

KEYWORDS
Computer tomography, beam hardening correction, Radon invariant.

ABSTRACT

In computed tomography (CT) the quality of reconstructed images depends on several reasons: the quality of the set-up calibration; precision of the mathematical model, used in the reconstruction procedure; the reconstruction technique used; quality of the numerical implementation of the reconstruction algorithm. Most of fast reconstruction algorithms use the X-ray monochromaticity assumption. If we apply the algorithms to reconstruct the images from the projections measured in polychromatic mode then the reconstructed images will be corrupted by so-called cupping artifacts due to beam hardening. There are several approaches to take into account polichromaticity. One of them is to correct the sinograms before reconstruction. This paper presents the usage of Radon invariant to estimate the gamma parameter in the procedure of the sinogram correction for beam hardening (BH).

INTRODUCTION

Today the existing methods that take into account polychromaticity effect can be jointed in several groups. The methods with usage of hardware filtering (Jennings 1988) can be classified as the first group. The second one includes so-called pre-processing techniques (Herman 1979). The next proposes dual energy correction (Kyriakou et al. 2010, Yu et al. 2012). The forth group of methods relates to an iterative correction in reconstruction stage (De Man et al. 2001, Elbarki and Fessler 2002, Menvielle et al. 2005). The last group works with artifacts in-line (Suk Park et al. 2016) or post-processing of the reconstructed images. This work aims to optimize the procedure of CT sinogram correction for beam hardening (pre-processing case). Due to the complex task of CT, it is hard to determine the optimal measurement settings (X-ray energy (spectrum), filters, etc.) for a given experiment. Different operators might apply different measurement strategies. Methods that reduce the dependence of experiment results on the applied machine settings are preferable. This work aims to optimize the procedure of CT sinogram correction for beam hardening. The presence of polychromaticity in the X-ray probe generates discrepancy between sinograms calculated from the projection data (detector data) and the Radon transform. The necessity of the compensation for the linearization of the detector data was pointed out in 1975 (McCollough 1975, Brooks et al. 1976). The quality of the CT reconstruction dramatically depends on the level of compensation. The CT reconstruction procedure is time consuming. Choosing the level of compensation based on the reconstruction results evaluation is expensive. We propose to use the concept of Radon invariant for evaluation of the quality of compensation. We give the grounds for approach taken. We suggest a new criterion for automatically choosing the level of compensation. We discuss the results obtained for simulated and real CT data. In conclusion

Proceedings 31st European Conference on Modelling and Simulation ©ECMS Zita Zoltay Paprika, Péter Horák, Kata Váradi, Péter Tamás Zwierczyk, Ágnes Vidovics-Dancs, János Péter Rádics (Editors)
ISBN: 978-0-9932440-4-9/ ISBN: 978-0-9932440-5-6 (CD)

we discuss the results of applying the quantitative criteria for cupping effect pronouncement (Nikolaev et al. 2016). The cupping artifacts corrupt the reconstructed image if the CT polychromatic data used in the reconstruction procedure were undercompensated.

LINK BETWEEN SINGLE-PARAMETER CORRECTION AND RADON INVARIANT

Fast reconstruction algorithms assume that the attenuation of the incident X-ray beam is exponentially related to the thickness of the object due to Beer's law. It becomes incorrect for polychromatic X-ray sources. In this case lower energy photons are more attenuated than higher ones (hard X-rays) when the beam passes through the object. Hence the attenuation produced by homogeneous sample, defined as the negative logarithm of the ratio of transmitted to incident beam, is not strictly proportional to its thickness. The measured nonlinear relationship can be fitted (Herman 1979). The process results to reconstructed image distortion called beam hardening due to the underlying phenomena. To state the problem of beam hardening correction let's write the mathematical model of the signal formation (point in the projection space) for polychromatic case assuming that object under study is unicomponent, but its distribution inside the volume is nonuniform:

$$I=\int dE I_0(E)\,\nu(E)exp(-\int_L \mu(E)C(l)dl). \quad (1)$$

Here I is a point in the projection space or value measured by a detector pixel. $I_0(E)$ is original intensity of the spectrum component with energy E. Function $\nu(E)$ describes the detector response at energy E. Direction to the detector pixel is determined by $\int_L$. $\mu(E)$ is linear attenuation coefficient of the component at energy E, $C(l)$ assigns its concentration along L. Assuming that $I_0(E)$, $\nu(E)$ and $\mu(E)$ are known from the reference measurements, we can rewrite

$$I=f(\int C(l)dl)=f(R(C)), \quad (2)$$

where R is Radon transform. Then the general statement of the problem is to find f^{-1}

$$R(C)=f^{-1}(I). \quad (3)$$

For practical cases we propose to use the following considerations. If the reconstructed image is described by function H, then the reconstruction problem is

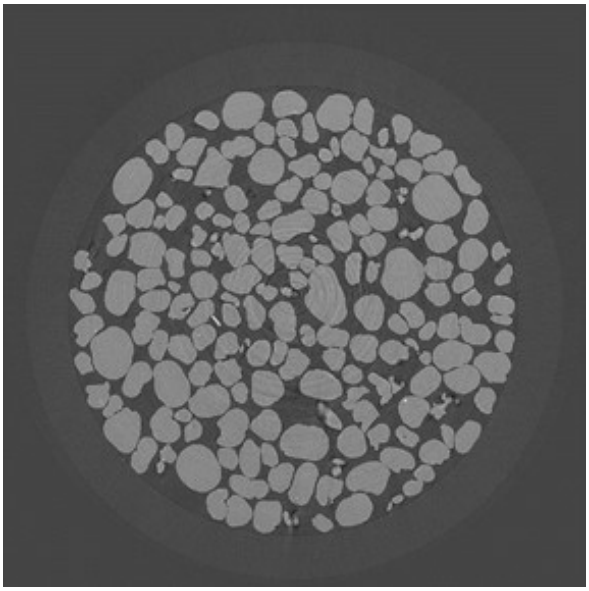
$$H=R^{-1}(I^*), \quad (4)$$

Where the following approximation is often used to correct the beam hardening:

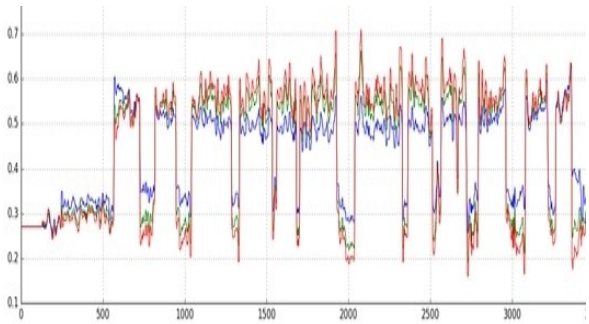
$$I^*=(ln(\int dE I_0(E)\,\nu(E)/I))^{\gamma} \quad (5)$$

As the sample does not cover the view field of the detector completely (for example, see Figure 1), the value $\int dE I_0(E)\,\nu(E)$ is estimated in the pixels free from the object.

We used CT real projection data from test sample placed in vial to demonstrate the influence of different values γ on reconstruction result (Figures 1, 2). FDK reconstruction algorithm (Feldkamp et al, 1984) was applied. Visual control for finding an optimal value of the parameter γ can be rather complicated. In Figure 2 presence of the cupping effect (blue line) informs us about undercompensating for the linearization. We propose the following algorithm to find the optimal γ value. Let's calculate the sum I^* values over all pixels for each CT projection. We have several realizations of random value. One value SUM^{ϕ} for one projection angle ϕ. Its mean $M(SUM^{\phi})$ is close to the Radon invariant. Origin of concept of Radon invariant is monochromatic measurement case. As we try to compensate polychromatic CT data by (5) to use further the reconstruction algorithms developed for monochromatic CT data, we should minimize total error distance. To estimate the optimal value γ ($\gamma\in(1, 2)$) we minimize the root-mean-square deviation of the random value $SUM\gamma^{\phi}$ from $M(SUM\gamma^{\phi})$ divided by the mean $M(SUM\gamma^{\phi})$ (NRMSD).



Figures 1: Reconstruction result for γ=1.6.

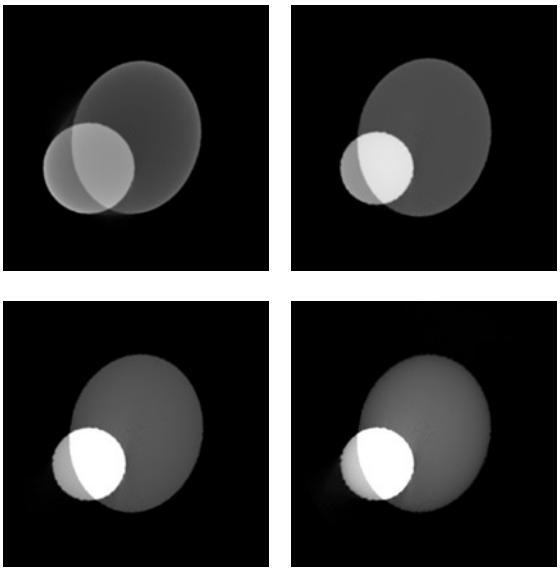


Figures 2: Reconstruction result (cross-section) with different γ values.

RESULTS FOR SIMULATED DATA

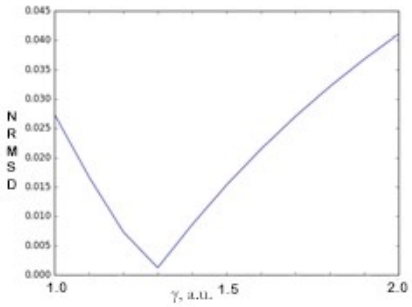
To test the behavior of the algorithm we used the simulation data. Concept of the geometry of the phantom used to calculate the polychromatic sinograms becomes clear if we refer to Figure 3. Image size is 208×208 pixels. The reconstruction results for different γ values are presented. We calculated the

monochromatic CT projections in fun geometry. The value used to simulate the polychromaticity is 1.3.



Figures 3: Reconstruction results for the simulated data with different γ:1; 1.3; 1.6; 1.9.

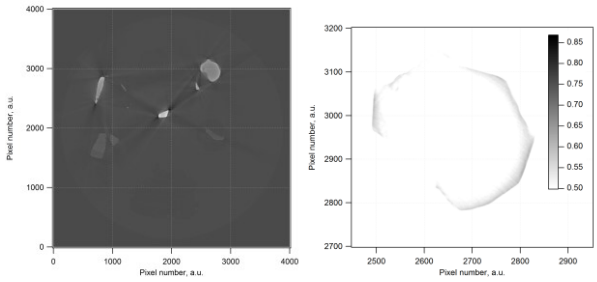
Figure 4 presents the NRMSD criterion behavior for the simulated CT projections. As one can see the minimum corresponds to the proper γ=1.3 value.



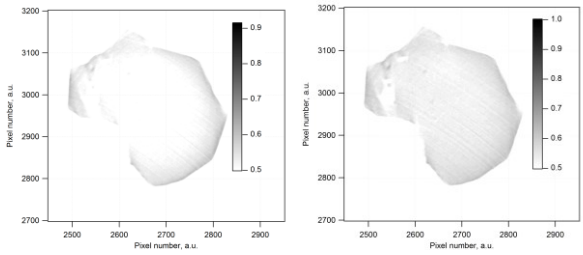
Figures 4: NRMSD dynamics for simulated CT projections.

RESULTS FOR REAL CT DATA

We present the results for real CT data below. The test sample was measured with CT scanner. The projections were collected at 2030 rotation angles. The projection size is 2096×4000. The reconstruction results with different γ values are presented in Figure 5.



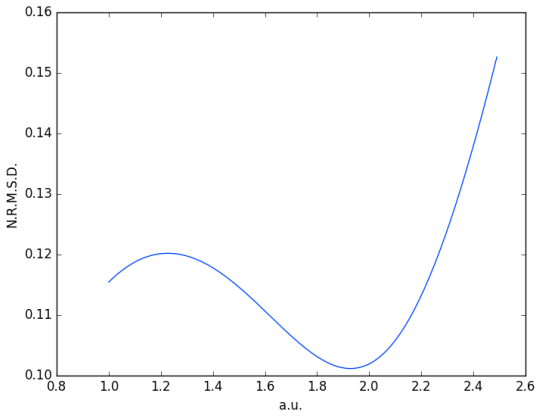
a) b)



c) d)

Figures 5: Reconstruction results for CT data. a) Full cross-section, γ=1. b) Part of the inverted image γ=1. c) Part of the inverted image γ=1.3. d) Part of the inverted image γ=1.6.

Figure 6 presents the criterion behavior for real CT projections.

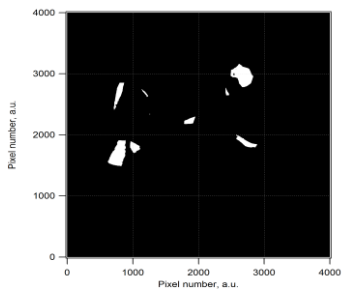


Figures 6: NRMSD dynamics for real CT projections.

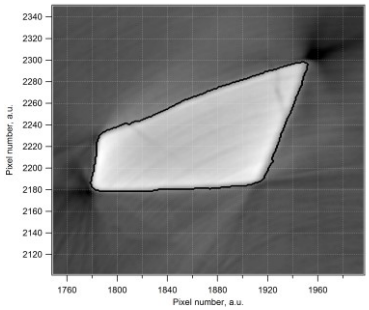
We can see well pronounced minimum on the curve. This confirms the correct procedure used for construction of the criterion

CUPPING ARTIFACT AND BEAM HARDENING COMPENSATION

Beam hardening correction should decrease the cupping artifact in the reconstructed images. Earlier we suggested the criteria to estimate the cupping artifact severity (Nikolaev et al. 2016). As cupping artifacts occur only inside dense objects, we used a mask designed for the object. To estimate the value of the artifact, we calculate the morphometric parameter CA over selected region corresponding to the mask.



a)



b)

Figures 7: a) Mask. b) Central mask object. Reconstruction with γ=1.

Suppose we have a mask M with K homogeneous objects as illustrated in Figure 7. The reconstruction result corresponding to the central ith object of the mask with mask boundary is presented in Figure 7b. The distance transform (DT^1, ….DT^k) is calculated for each object of the mask based on the Euclidian metric. If the beam hardening fully compensated, the pixels inside the homogeneous object should have the same values. Let I_j^k be a value of the j-th pixel of M^k mask area. We calculate a base value as the mean value within a stable region

$$BaseV^k=mean\{I_j^k|DT_j^k>Val^k\}, \qquad (6)$$

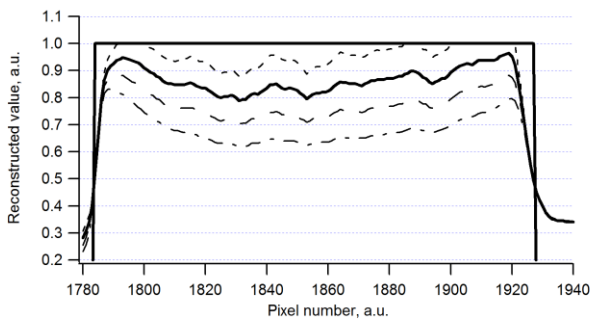
where Val^k=0.9 $max(DT^k)$. We calculate the distance transform histogram of M^k as

$$CE^k=\sum_{v=1}^{0.2max(DTk)}|mean\{I_j^k|v\text{-}1<DT_j^k<v\}\text{-}BaseV^k \quad (7)$$

The average value over all objects is the areal morphometric parameter CA that represents the measure of the cupping artifact severity, i.e.

$$CA=1/k/\sum_{k=1}^{K}CE^k \qquad (8)$$

The reconstruction results for different γ values are presented in Figure 8 to illustrate the execution of algorithm. As the criteria takes into account all masked parts of the object under investigation, detailed analysis of the criteria behavior will be presented in the talk.



Figures 8: Cross-sections for different γ values: 1, 1.3, 1.6 and 1.9 (down-up) in accordance with Figure 7b (horizontal slice 2220).

CONCLUSION

The problem we are solving now, from an engineering standpoint, is the task of blind. This kind of technique, we think, should be used to solve most ill-posed inverse problems, since the quality of reconstruction is significantly dependent on calibration accuracy (Chukalina et al. 2016). For example, the problems, similar to tomographic problems, arise when we try to reconstruct the environment according to (from) the sonar sinals (Svets et al. 2016), where the parameters of the sonar significantly affect the signal model. The level of the compensation for the beam hardening is only one from the calibratable CT parameters.This work aims to optimize the procedure of CT sinogram correction for beam hardening. We propose to use the concept of Radon invariant for evaluation of the quality of correction. We give the grounds for approach taken. We suggest a new criterion for automatic selection the level of correction. We discuss the results for simulated and real CT data packages. As an uncorrected sinogram produces the images with well pronounced cupping effect we check the quantitative criteria for the cupping effect pronouncement to estimate the correction quality.

The research leading to results on the development of mathematical models of distortions arising in tomographic systems with polychromatic probe has funded from the Russian Science Foundation Grant (project #14-50-00150).

REFERENCES

Brooks, R.A. and G. Di Chiro. 1976. “Beam hardening in X-ray reconstructive Tomography.” *Phys. Med. Biol* 21, No.3, 390-398.

Chukalina, M., D. Nikolaev, A. Buzmakov, A. Ingacheva, D. Zolotov, A. Gladkov, V. Prun, B. Roshin, I. Shelokov, V. Gulimova, S. Saveliev and V. Asadchikov. 2016. “The Error Formation in the Computed Tomography: from a Sinogram to the Results Interpretation.” *Russian Foundation for Basic Research J.*, No 4(92), 73-83.

De Man, B.; Nuyts J.; P. Dupont; G. Marchal and P. Suetens. 2001. “An iterative maximum-likelyhood polychromatic algorithm for CT.” *IEEE Trans. Med. Imag*. 20, No.10, 999-1008.

Elbarki I.A. and J.A. Fessler. 2002. “Statistical image reconstruction for polyenergetic X-ray computed tomography.” IEEE Trans. Med. Imag. 21, No.2, 89-99.

Feldkamp, L. A., L. Davis, and J. Kress. 1984. “Practical Cone-beam Algorithm. ” J. of the Optical Society of America 1, 612–619.

Herman, G.T. 1979. “Correction for beam hardening in Computer Tomography.” *Phys. Med. Biol* 24, No.1, 81-106.

Jennings, R.J. 1988. “A method for comparing beam hardening ¯lter materials for diagnostic radiology.” *Medical Physics* 15, No 4, 588-599.

Kyriakou Y.; E. Meyer; D. Prell and M. Kachelriess. 2010. “Emperical beam hardening correction (EBHC) for CT.” *Med. Phys*. 37, 5179-5187.

McCullough E.C. 1975. “Photon attenuation in computed tomography.” *Med. Phys*. 2, 6, 307-320.

Menvill N.; Y. Goussard; D. Orban and G. Soulez. 2005. “Reduction of beam-hardening artifacts in X-ray CT.” in *Proc. 27th Annu. Int. Conf. IEEE EMBS*, 1865-1868.

Nikolaev, D.P.; A. Buzmakov; M. Chukalina; I. Yakimchuk; A. Gladkov and A. Ingacheva. 2016. “CT Image Quality Assessment based on Morphometric Analysis of Artifacts”. In *Proceedings of the International Conference on Robotics and Machine Vision (ICRMV 2016)* (Moscow, Russia, Sept.14-16). Proc. SPIE 10253, 2016 International Conference on Robotics and Machine Vision, 102530B (February 8, 2017); doi:10.1117/12.2266268; http://dx.doi.org/10.1117/12.2266268.

Shvets E., D. Shepelev and D. Nikolaev. 2016. “Occupancy grid mapping with the use of a forward sonar model by gradient descent.” J. of Comm. Technology and Electronics, V. 61, №12, pp. 1474-1480.

Suk Park, H.; D. Hwang and J. K. Seo. 2016. “Metal artifacts Reduction for Polychromatic X-ray CT Based on a Beam-Hardening Corrector.” *IEEE Trans. Med. Imag.* 35, No.2, 480-487.

Yu, L.; S. Leng and C.H. McCollough. 2012. “Dual-energy CT-based monochromatic imaging.” *Am. J. Roentgenol.* 199, S9-S15.

AUTHOR BIOGRAPHIES

MARINA CHUKALINA was born in Cheboksary, Russia and went to the Moscow Physical Engineering Institute, where she studied physics and mathematics. She received her PhD in physics at the Institute of Microelectronics Technology and High Purity Materials RAS where she has been working since 1988. From 2013 she is Vice-head of Cognitive Technologies Department of Faculty of Innovation and Higher Technology of Moscow Institute of Physics and Technology (State University). Her interests include the development of signal and image processing tools for X-ray Microscopy and Tomography. Her e-mail address is: `chukalinamarina@gmail.com`. Her Web-page can be found at `http://tomo.smartengines.biz/peoples.en.html`.

ANASTASIA INGACHEVA was born in Kazan, Russia and went to Kazan (Volga region) Federal University, where she studied Economic Cybernetics and obtained her degree in 2012. She obtained master's degree of Higher School of Economics (National Research University) at computer science faculty in 2015. Now Anastasia is a PhD student in the same place. Since March 2013 Anastasia has been worked in the X-ray reflectivity laboratory of the Shubnikov Institute of Crystallography RAS. Her research activities are in the areas of poly- and monochromatic X-Ray computed tomography and analysis of obtained CT data. Her e-mail address is: `ingacheva@gmail.com`.

ALEXEY BUZMAKOV was born in Kirs, Russia. He studied physics, obtained his Master degree in 2006 and Ph.D. degree in 2009 from Lomonosov Moscow State University. Now he work in the Institute of Crystallography Federal Research Scientific Centre "Crystallography an Photonics" RAS in a research group in the field of x-ray tomography and x-ray optics. His e-mail address is: `buzmakov@gmail.com` and his web-page can be found http://tomo.smartengines.biz/peoples.en.html.

IGOR POLYAKOV was born in Moscow, Russia. He studied mathematics and mechanics, obtained his Master degree in 2008 and Ph.D. degree in 2012 from Moscow State University. Since 2016 he is a researcher of the Vision Systems Lab. at the Institute for Information Transmission Problems, RAS. His research activities are in the area of computer vision with primary application to image classification. His e-mail address is `igorp86@mail.ru`.

ANGREY GLADKOV was born in Stavropol, Russia. He studied automatic control and informatics at the Moscow State Institute of Radio Engineering, Electronics and Automation and obtained his Master’s degree in 2012. Now Andrey is a PhD student at the Institute for Information Transmission Problems, where he studies and works. His research activity is focused on image processing in X-ray tomography and radiography. His e-mail address is: `gladkov.ap@iitp.ru`.

IVAN YAKIMCHUK was born in Protvino, Russia and went to the Lomonosov Moscow State University, where he obtained his Master degree in general physics in 2009 and received PhD degree in X-ray physics in 2012. Since then he worked as a research scientist in the group of Imaging and Image Processing at the Schlumberger Moscow Research Center. Now he is leading this group making the focus on X-ray mictromography and Electron Microscopy of rock samples with corresponding digital processing of results including image segmentation, morphometry, pattern recognition, spatial registration, etc. His e-mail address is: `IYakimchuk@slb.com`.

DMITRY NIKOLAEV was born in Moscow, Russia. He studied physics, obtained his Master degree in 2000 and

Ph.D. degree in 2004 from Moscow State University. Since 2007 he is a head of the Vision Systems Lab. at the Institute for Information Transmission Problems, RAS. His research activities are in the areas of computer vision with primary application to color image understanding. His e-mail address is dimonstr@iitp.ru.