RECENT IMPROVEMENTS FOR SCATTER SIMULATION IN SINDBAD, A COUPLED PHOTON MONTE CARLO AND CAD SOFTWARE

J. Tabary[1], P. Hugonnard[1], F. Mathy[1], R. Guillemaud[1];
[1] LETI - CEA Recherche Technologique, F-38054 Grenoble, FRANCE;

Abstract: In an X-ray radiography, scattering of photons from the inspected object, as well as backscattering or scattering from the environment, may have significant deleterious effects on image quality, reducing the relative contrast of the flaw indication. Therefore, development of computational models simulating scattering in radiographic studies is of primary interest, to correctly evaluate flaw detectability.

The X-ray radiographic simulation software, Sindbad, developed for Non-Destructive Evaluation applications, models the whole radiographic set-up, with the X-ray source, the beam interaction inside the object represented by its CAD model and the imaging process in the detector. An analytical computation is used for the uncollided image whereas the scatter flux is computed with a Monte Carlo approach. Two major evolutions in Sindbad have been recently developed to provide realistic scatter images in reasonable computing time.

Up to now, because of a geometrical restriction of the coupling of EGS4 Nova and BRL-CAD, we couldn't simulate detectors inside the object. An algorithm has been recently modified to consider the whole radiographic set-up, including the environment and all the parts of the object and detector which are behind the sensitive detector layer. Therefore, both backscattering and scattering from the environment are computed. Examples of simulations on industrial parts under experimental conditions show that the contribution of backscattering can exceed half of the overall scattering flux.

Moreover, as scattering is not sensitive to sharp structures of the inspected items, an object simplification algorithm has been developed to speed up the Monte Carlo computation without modifying the scatter image. This simplification is automatic and takes into account the spectrum energy, the materials and the set-up geometry. On complex industrial objects, the computations can be twenty times faster.

Introduction: An X-ray radiographic image is generated by both uncollided and scattered photons. Only the uncollided photons contribute to the exploitable part of radiographs, with the sharp structures of the examined parts. On the other hand, scattered radiation generated inside an object may have significant deleterious effects on image quality [1, 2, 3]. First, the scattered radiation adds an important continuous component to the whole beam detected in the detector, with a contribution which may exceed the uncollided flux. Consequently and especially for film detectors, scattered radiation can induce problems of saturation and contrast. Moreover, depending on the equipment set-up and the examined part, the scattered radiation component can present low frequencies which disturb the radiograph. Finally, the scattered radiation can also add significant noise to the signal, thus reducing the relative contrast of the flaw indication.

Many parameters of the radiographic scene may influence the shape and the contribution of the scattered radiation. Of course, the energy of the source as well as the materials of the object to be examined have an influence on the scattering phenomena (Compton, Rayleigh, Photoelectric) and on the deviation of particles. The scattered image is also largely dependant on the position, specifically on the distance between the object and the detector. Indeed, when the object is closer to the detector, more scattered radiation is detected and the associated image is a closer representation of the object. Finally, backscatter radiation coming from the environment (detector, wall, equipment set-up) can also present a considerable contribution to the overall radiation detected in the detector.

In the context of a scattering study, X-ray simulation tools are of primary interest during the design stage of radiographic facilities, when they can help to choose the device parameters (X-ray tube settings such as voltage and filtration, detector type and thickness, geometry of the bench, etc.) and predict performances of the future device. Several teams involved in X-ray NDE simulation [4, 5, 6, 7] have developed their own software, based on analytical or Monte Carlo models and using ray tracing techniques, computer aided design (CAD) of the examined sample, and a graphical user interface (GUI).

The X-ray radiographic simulation software, Sindbad [8, 10, 12, 13], has been developed to help the design stage of radiographic systems or to evaluate the efficiency of image processing techniques, in both medical imaging and Non-Destructive Evaluation (NDE) industrial fields. In this paper we give an overview of Sindbad and present the most recent evolutions for scattered radiation computation : simulation of complex geometries and speed up techniques based on a CAD model simplification.

Results:

Overview of Sindbad:

The physics of the radiographic inspection process can be divided into three separate parts, namely the X-ray beam generation in the source, the beam interaction with the examined sample, and the imaging process (detection of the remaining photon flux and transformation into a measured signal) as shown on Figure 1.

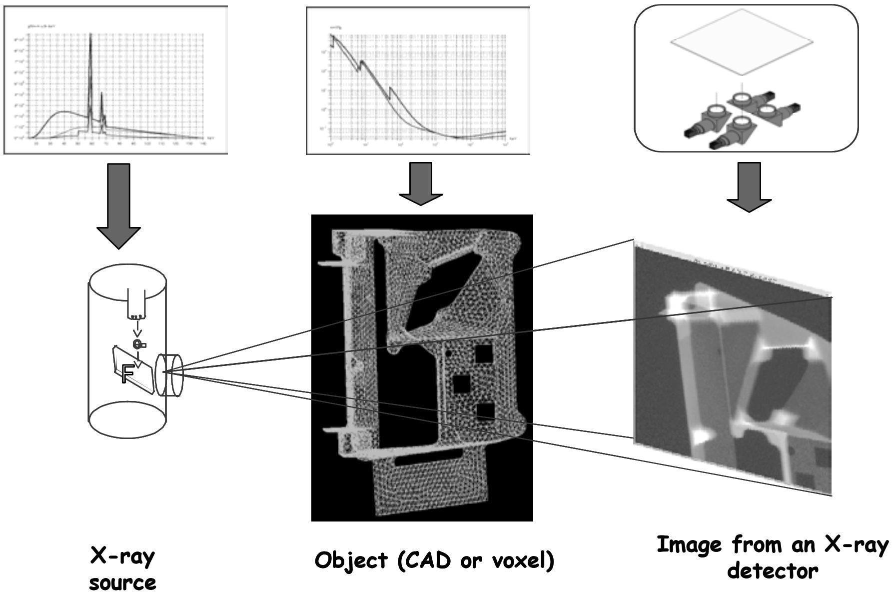


Figure 1 : Sindbad architecture.

The implemented X-ray tube model, which can be used between 30 and 450 kV, simulates the physical phenomena involved in bremsstrahlung and characteristic photon production with a semi-empiric model. It takes into account the anode angle and composition, the inherent and additional filtration and the photon exit angle. Experiments performed at LETI show that the calculated and measured doses usually agree to within 20%.

Detectors are modeled in two successive steps. The first step which is common to all types of detectors computes the energy deposition in the sensing part of the detector using the energy absorption attenuation coefficients. The second step, specific to each type of detector, simulates the successive physical phenomena involved in the energy to signal transformation. For instance, in the case of a scintillating screen viewed by a CCD camera, it accounts for the energy to light photon transformation, the light photon absorption in the screen and optical coupling system, and the photon to electron conversion in the CCD device. Noise and resolution effect (MTF) can be added on the resulting image.

Concerning the interaction in the object, the first approach adopted was an analytical one which combines ray tracing techniques and the attenuation law (Beer Lambert) by calculating the energy dependent attenuation due to the crossed materials. The 3D analytical simulation computes an image of the uncollided flux simulation which relies on the computation of the attenuation of the incident flux, binned in narrow energy channels, by the examined sample. This is performed by tracing rays from the source point to every pixel of the detector through the sample, either a CAD model built with BRL-CAD [9] or a 3D data volume segmented in materials. This computing model shows very efficient results concerning the uncollided photon flux but fails to evaluate the scattered photon flux correctly.

A Monte Carlo simulation module [10] has also been implemented in Sindbad in order to compute the radiation scattered in the examined object. It relies on a coupling of the BRL-CAD CAD and ray-tracing package [9] with EGS-NOVA [11], a program dedicated to Monte Carlo radiation transport simulation. Once incident particles are emitted from the source, their tracking and interaction in the object are managed by the EGS Nova shower simulation. The geometry interrogation function, whose goal is to compute the distance from the current particle position to the next boundary that will be crossed, uses the ray tracing functions provided by BRL-CAD. History flags are used in order to finally provide the uncollided, once scattered and several times scattered photon images. This Monte Carlo method gives good quality results either for uncollided or scattered photon flux images [12] but its use is largely limited by the execution time drawback.

An original model was developed after, combining the advantages of both analytical and Monte Carlo techniques [13]. The purpose of this computing model is to provide a total synthetic radiograph by combining images obtained from two simulations, one performed with the analytical model for the uncollided photon flux and the other one with the Monte Carlo model for the scattered radiation. As presented in the scheme in Figure 2, the absorbed energy Monte Carlo scattered flux image estimated for a low dose is scaled up to the analytical dose level, and then combined to the uncollided flux image. This scaling is independently performed for both the mean scattered image and the scattered image noise. The main advantage of the combination is that it becomes possible to obtain detailed simulated images, taking into account various interaction effects such as scatter, in a feasible computation time (a few minutes when a pure Monte Carlo simulation would take a few months).

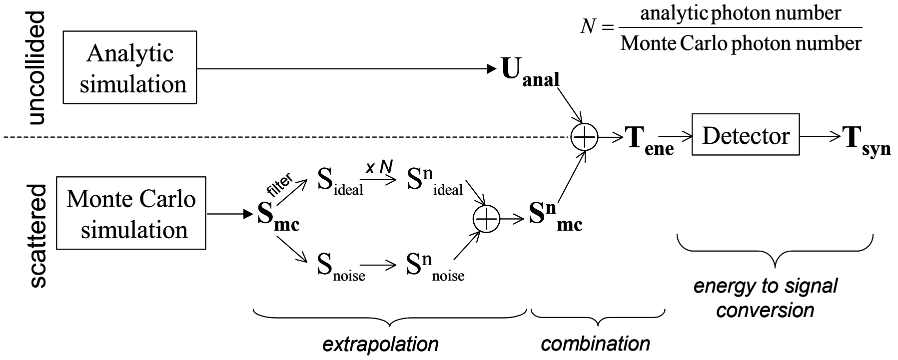


Figure 2 : Analytical and Monte Carlo images combination scheme.

<u>Geometrical improvements in Sindbad:</u>

Recent developments in Sindbad have consisted of improving the geometric simulation configurations. In Monte Carlo simulations, scattering effects are taken into account only in the object under evaluation but not in the detector and an important restriction in the previous version was that the raytracing algorithm assumed that the detector was outside the system “source-object”. When a particle was launched, the coupling between EGS-NOVA routines and the BRLCAD raytracing routine first managed the interactions of the particle inside the object. Next, once the object was entirely crossed, detection routines developed in Sindbad were called to manage detection in the sensitive part of the detector. Consequently, in configurations where the detector was not separated from the system “source-object”, back scattering was not taken into account, nor were the particles which could cross the object after having crossed the detector.

To be able to solve such configurations where the detector is inside the system “source-object”, the ray tracing algorithm was adapted, with additional calls to the detector intersection routines during the crossing of the object. More precisely, now, each time a particle is located in an air or vacuum region, a test is performed to check if the particle can touch and be absorbed in the detector. If the particle touches the detector and is absorbed, it is scored; otherwise, EGS NOVA routines continue to follow its course in the object. The detection process in Sindbad simply consists of assigning a probability that each photon will interact in the sensing part of the detector. In the old version of Sindbad, this probability depended only on the detector thickness, on its material and on the energy of the photon. For more accuracy, Sindbad now also takes into account the direction in which the photon hits the detector. Note that in spite of the permanent inter code calls, this new algorithm is not much more time consuming than the old one.

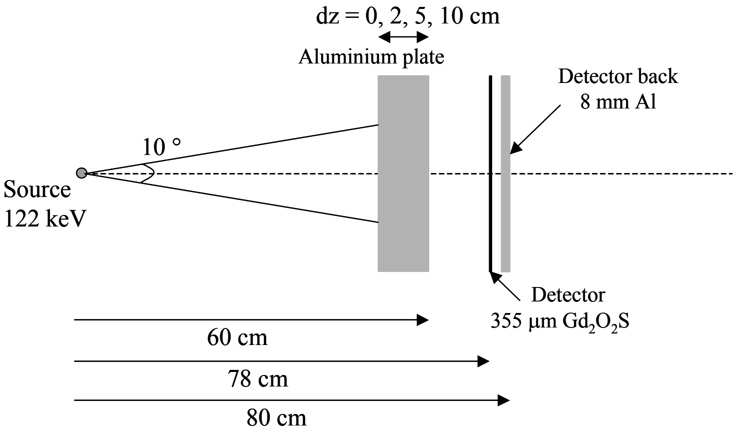


Figure 3 : Experimental bench principle.

A first set of verification studies was carried out by comparing the variation of the number of detected scattered, backscattered and uncollided photons with Al plate thickness in a typical radiography setup (see Figure 3). The acquisition system is composed of a virtual monoenergetic source ^{57}Co, assumed ponctual, irradiating a flat Al plate whose thickness varies from 0 to 10 cm. The Lanex scintillator detector is simply modeled by an equivalent thickness of 0.355 mm Gd_2O_2S and by an Al plate (8 mm) set behind the Gd_2O_2S part, to simulate the back protection of the detector. Although the thickness of the first Al plate were varied, the other dimensions of both the plate and detector parts were kept fixed at 10 cm x 10 cm. To validate the backscattered estimation of Sindbad, two Monte Carlo simulations of 10^6 showers were performed with both the PENELOPE code [14] and the new version of Sindbad. For Sindbad simulations, both Al plates before and after the Gd_2O_2S thickness are drawn in BRL-CAD.

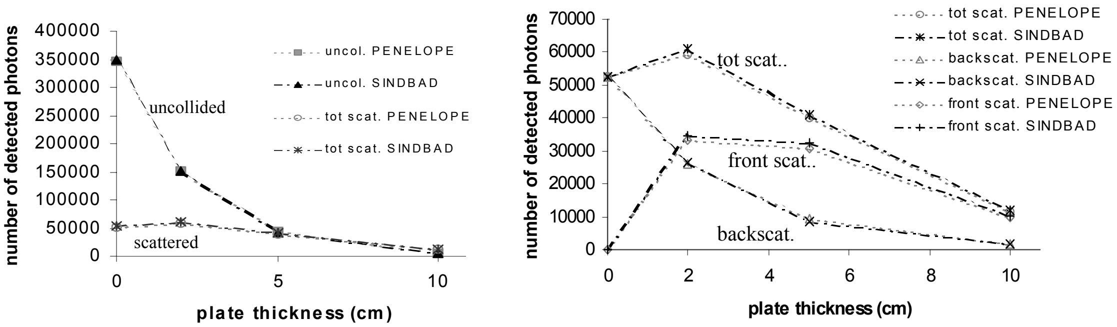


Figure 4 : Comparison of Sindbad and PENELOPE simulations for uncollided/scattered radiation with a simple object.

Figure 4 shows that the agreement between PENELOPE and Sindbad results is good. The very small discrepancy, noted for front scattered estimations, is probably caused by differences in the Gd_2O_2S cross sections used by Sindbad and PENELOPE. These results confirm that backscattering is important, especially for thin Al plates.

Other geometric improvements recently integrated in Sindbad are the modelling of panoramic sources and of the curved detector in the Monte Carlo module. Figure 5 presents a realistic and complex radiographic set-up which has been simulated in order to demonstrate the capabilities of the new version of Sindbad . The examined sample is an assembly of two metal parts which are welded one with the other. As these parts are hollow, the welding is inspected thanks to a panoramic source set in the center of the piece and with a cylindrical film detector stuck to the piece. The source is an X-ray tube with a voltage of 150 kV which emits towards a panoramic beam whose aperture angle is 20°. This geometry was unsolvable by the old version of Sindbad which was only able to simulate conic sources and planar detectors.

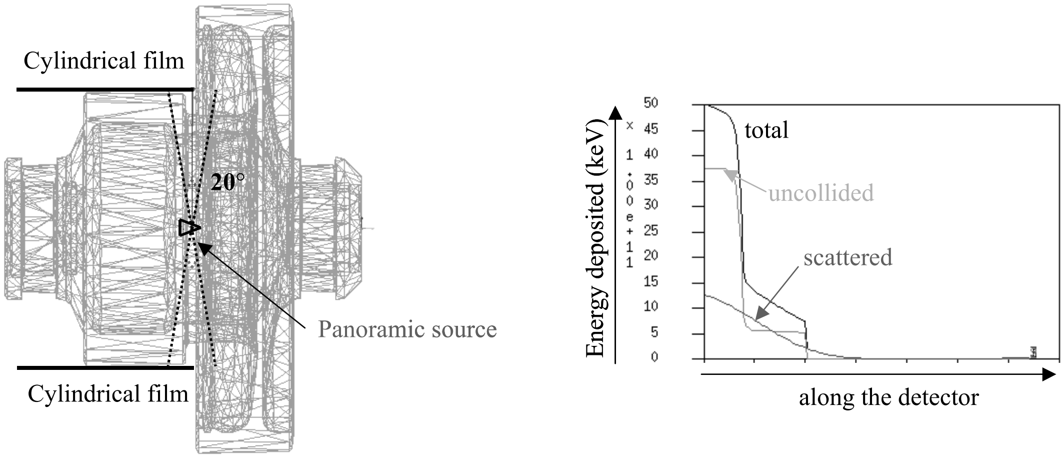


Figure 5 : Application example. Test part geometry (left) and simulated flux profiles (right). The origin of profiles corresponds to the detector point in front of the source.

Profiles in Figure 5 show that the scattered radiation is quite large at the edge of the film. This is partly due to the backscattering radiation coming from the external part of the biggest pinion, which is behind the film.

<u>Acceleration of the scattered simulation by object simplification:</u>

Another improvement speeds up the algorithm for scattered simulation in Sindbad. Scattering is a low frequency phenomenon and is not sensitive to the fine structures of the irradiated objects, if the object is not in contact with detector. Moreover, it has been noticed that Monte Carlo computation time depends a lot on the complexity of the CAO description of the object, knowing that a large number of facets increases both the memory usage for each raytracing routine call and also the number of these calls. Consequently, an idea to speed up the computation is to simplify the object.

For that, we adapted a pre existing simplification algorithm developed by M Garland [15,16] for our specific application. The Garland algorithm has been developed to control processing time for many applications in computer graphics, where it is desirable to use approximations in place of excessively detailed models. This algorithm is a surface simplification algorithm which uses iterative contractions of vertex pairs. The principle of pair contraction is to move two vertices v_1 and v_2 to a new position $\bar{\mathbf{v}}$, connecting all their incident edges to v_1 and deleting the vertex v_2 (see Figure 6). In the original algorithm, the selection of contractions to perform during the iterative process depends on a contraction cost, defined and computed considering the sum of squared distances between a given vertex to the planes of the triangles that meet at that vertex.

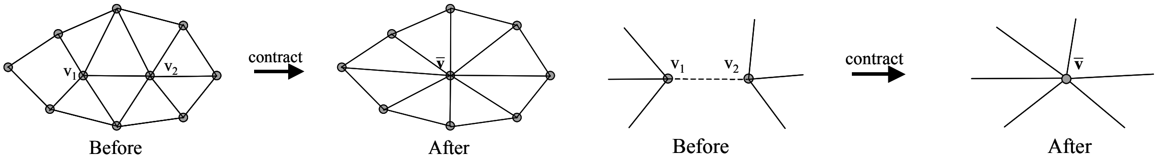
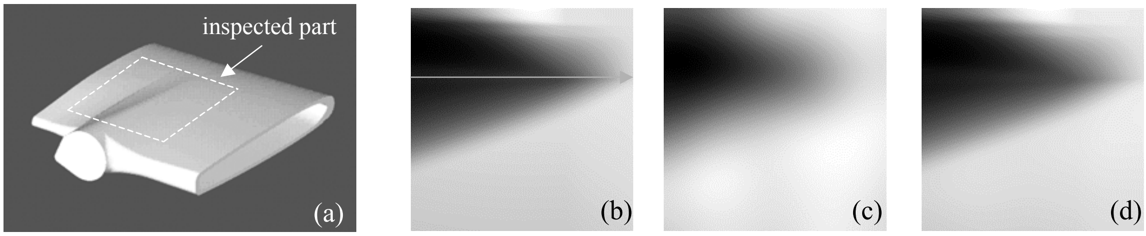


Figure 6 : Pair contraction scheme. Case of edge contraction (left) and of non-edge contraction (right).

In its original version, this program accepts as input data the initial object in Wavefront format (format similar to "stl" format used in Sindbad) and the final number of facets. For our specific application of scattering estimation, it is difficult for the user to choose a good number of facets for the simplified object. Consequently, we added a new option to simplify the object automatically with an appropriate number of facets. To keep the automatic simplification from deteriorating the simulation accuracy too drastically, it takes into account the modification of scattered estimation caused by a pair contraction.

For that, we assumed that only first Rayleigh or Compton scattered photons keep the memory of the geometry of the object, considering that other scattered effects or multi scattered photons can be considered as inducing a simple offset on scattered images. Thus, the modification induced by a pair contraction is estimated by considering The Klein Nishina formula [17]. More precisely, as the Klein Nishina formula gives the angle distribution of Compton scattered photons, a projection of this formula on the detector can estimate the spatial dispersion of all photons having submitted one Compton scattering at a particular point. Finally, the criterion to stop the iterative simplification for this automatic option is based on the comparison of the spatial dispersion of photons before and after the pair contraction. If we consider the first order of the Klein Nishina formula, only two parameters intervene in the scatter modification estimation : the initial energy of the incident photon and the distance between a given vertex and the detector. Actually, we assume a mean energy rather than the whole incident spectrum, which is not a dramatic approximation since the dependence of the angle distribution with the energy is quite weak.

This simplification program has been validated with respect to an experimental set-up with a complex industrial item (see Figure 7a). The source is a 140 kV X-ray tube and the detector is modelled with a equivalent thickness of 0.2 mm CsI and a Beryllium filter for protection in front of the sensitive layer. The item is composed of Nickel based alloy and is set on the detector to inspect the critical part. Two simulations are performed with the original model (114300 facets) and the simplified model (798 facets). The number of showers for the Monte Carlo simulation is 10^8, and the computation time gain thanks to the model simplification is equal to 12.25 changing from 20h 7mn to 1h 39mn on a SUN workstation (1280 MHz). Profiles of scatter images (after scaling) presented in Figure 7 show that the discrepancy caused by the simplification is negligible (<5%). This example confirms that in several conditions, scattered flux exceeds the uncollided flux and presents some low frequencies which can dramatically disturb the radiograph.



uncollided scattered total

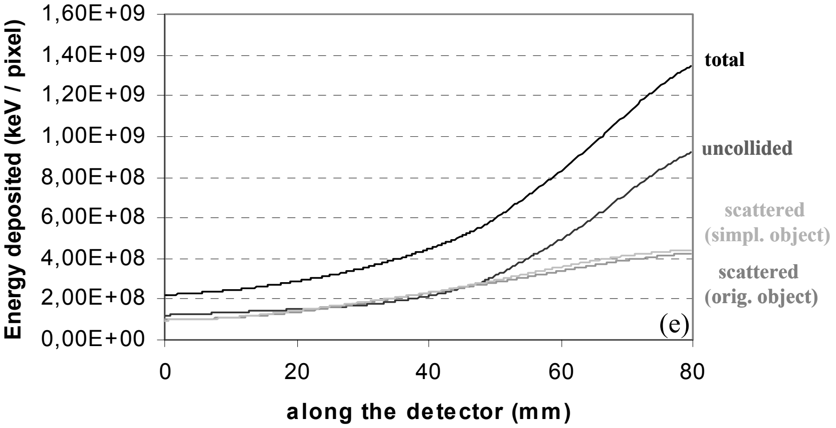


Figure 7 : Application example. Test part geometry (a), simulated uncollided (b), scattered (c) and total flux images (d) and profiles along a horizontal axis (e) of all images, included scattered images computed with the original complex object (114 300 facets) and the simplified object (798 facets).

Discussion: Thanks to the recent improvements concerning the geometry of simulated radiographic systems, Sindbad is now able to estimate the scattered radiation in a large number of experimental configurations, including the contribution of backscattered particles. The Monte Carlo computation of scattering is still performed only in the object and not in the detector, so that the detection modelling can be performed independently and consequently more accurately, by taking into account the specificity of each kind of detectors (film, CCD, photomultiplier, numerical flat panel…).

With the scaling process of Monte Carlo computed scattered image, the object simplification method significantly accelerates the calculation of a scattered image. Note that the computation time gain due to the object simplification is only worthwhile for complex objects. However, this simplification algorithm is available for items made up of one structure and in particular of one material. Each structure of a multi-structured object can be separately simplified but recombination of these simplified structures may after induce some interface problems. The generalization of this simplification program to multi-structured objects could be developed in the future.

Finally, another planned extension of the scattered simulation is to compute the detected scattered spectra in order to better evaluate the effects of the scattering and to develop suitable detection systems or correction methods.

Conclusions: In a unified framework, Sindbad is a multipurpose X-ray simulation software suite which provides a scalable approach of computation and very efficient results by combining two methods : an analytical computation for the uncollided radiation image and a Monte Carlo simulation followed by a scaling process for the scattered image estimation. Recent developments have improved the performances of Sindbad to simulate the scattered flux radiation. There were two types of developments : integration of new geometric models to manage more complicated configurations (panoramic source, curved detector, detector set in the object model..) and also an algorithm acceleration using an object simplification program. Validations on simple and realistic cases have been performed to check the accuracy and the reliability of these developments.

Thanks to these improvements, Sindbad can now provide synthetic radiographs with a good estimation of the scattered flux, including both backscattering and scattering from the environment. Simulations can be performed within complex set-up geometries and in reasonable computing times.

Acknowledgments: This work is supported by the European Commission under grant GED1-2001-40151, associated with the Verdict project. The authors would like to thank the Verdict partners and specially Snecma and Turbomeca for providing their industrial part models.

References:

[1] F Inanc, "Analysis of X-Ray and Gamma Ray Scattering through computational experiments", *Journal of Nondestructive Evaluation, Vol. 18, No. 2, pp 73-82*, 1999.
[2] G-R. Tillack, V. M. Artemiev and J. N. Gray, " The effect of scattered radiation in X-ray techniques – Experiments and theoretical considerations ", *Review of Progress in Quantitative Nondestructive Evaluation, Vol. 18, pp 631-638*, 1999.
[3] C. J. Leliveld, J. G. Maas, C. W. E. van Eijk and V. R. Bom, " On the significance of scattered radiation in industrial X-ray computerized tomographic imaging ", *IEEE Transactions on Nuclear Science, Vol. 41, No. 1, pp 290-294*, Feb 1994.
[4] G-R. Tillack, C. Nockemann and C. Bellon, "X Ray Modelling of Projection For Industrial Applications", *NDT &E International 33, pp 481-488,* 2000.
[5] M. Mangard, P. Hammersberg and M. Sandborg "Modelling of an X-ray Image Intensifier Based Radiography System", *J. X-ray Sci and Tech 8, pp 31-50,* 1998.
[6] P. Duvauchelle, N. Freud, V. Kaftandjian, G. Peix, D. Babot, "Development of a simulation tool for X-ray imaging techniques", Workshop on the application of X-ray tomography in materials science, Villeurbanne, Oct. 28-29, 1999, ed. by J. Baruchel et al., Hermes, Paris, 2000.
[7] Bonin, B. Lavayssiere and B. Chalmond, "Moderato : A Monte-Carlo Radiographic Simulation", *Review of Progress in QNDE, Vol 19A , pp 651-656,* 1999.
[8] R. Guillemaud, J. Tabary, P. Hugonnard, F. Mathy, A. Koenig, A. Glière, "Sindbad : a multi-purpose and scalable X-ray simulation tool for NDE and medical imaging", PSIP 2003, Grenoble, France, 2003.
[9] P.C. Dykstra, M.J. Muus, "The BRL-CAD package: An overview," in *Proc. 4th Computer Graphics Workshop--USENIX*, Phoenix, Arizona, U.S., pp 73-80, Oct. 1987.
[10] J. Tabary and A. Glière, "Coupling photon Monte Carlo simulation and CAD Software. Application to X-ray nondestructive evaluation," in *Proc. Monte Carlo 2000,* pp 461-466, Lisbon, Portugal, Oct. 23-26, 2000.
[11] J.C. Satterthwaite, "EGSNova : An adaptation of EGS in C/C++," May 1998. [Online]. Available : **http://www.nemc.org/nova**.
[12] F. Mathy, R. Guillemaud, "Experimental validation of a coupled photon Monte Carlo and CAD software," *The e-journal of Nondestructive Testing*, Vol.7, no. 12*,* Dec 2002. [Online]. Available : http://www.ndt.net/article/ecndt02/206/206.htm
[13] J. Tabary, A. Glière, R. Guillemaud, P. Hugonnard, F. Mathy, « Combination of high resolution analytically computed uncollided flux images with low resolution Monte Carlo computed scattered flux images", *IEEE Transactions on Nuclear Science, Vol. 51, No. 1, pp 212-217*, Feb 2004.
[14] J. Sempau, E. Acosta, J. Baro, J.M. Fernandez-Varea and F. Salvat, "An algorithm for Monte Carlo simulation of the coupled electron-photon transport", *Nucl. Instr. and Meth. B* 132, pp.377-390, 1997.
[15] Michael Garland & Paul S. Heckbert, "Surface simplification using quadric error metrics", *Computer Graphics, Vol.31 (SIGGRAPH'97 Proceedings),* 1997.
[16] Michael Garland, "QSlim 1.0," Oct. 1997. [Online].
Available : http://graphics.cs.uiuc.edu/~garland/software/qslim10.html
[17] H. E. Johns and J. R. Cunnigham, *The Physics of Radiology (3^{rd} Ed.),* Charles C. Thomas, Publisher, USA, p175, 1974.