A SOFTWARE SIMULATION TOOL DEDICATED TO THE DESIGN AND EVALUATION OF X-RAY BACKSCATTER SYSTEMS

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Abstract

Backscatter X-ray technique is particularly convenient for the inspection of single-sided access objects, in order to detect subsurface defects or control subsurface layers thickness. This well known technique can benefit today from recent developments in detectors technology. Backscatter technique requires many parameters: relative geometry of source, detector and object, and associated collimation. In order to help the design of backscatter systems, we have developed a software simulation tool, able to predict the backscatter signals for given systems and objects. Theoretically, such a simulation should be performed based on Monte Carlo code to manage multiple scatter interactions. We propose a version based on analytical computation, allowing fast simulation, and a modified one using partially a Monte Carlo code, if more accuracy is required. Experimental measurements are compared to simulation. The proposed tool can also help the interpretation and analysis of backscatter signal for complex objects.

Key-words: X-ray imaging, backscatter, Compton scattering, simulation, inspection, single-sided access objects, subsurface defects.

1. Introduction

Backscatter X-ray technique is a suitable technology for the inspection of single-sided access objects, or of large or dense parts that are too attenuating to be imaged by conventional radiography techniques. For both, backscatter technique could allow the detection of subsurface defects or non-homogeneities, or the measurement of subsurface layers thickness. The principle is based on scattering effect: X-rays are emitted from a collimated source, most of the photons are attenuated by the sample, but part of them are scattered, within any angles, and may be measured by one or several detectors that are located in the same half-space than the source (Figure 1). This scattered radiation depends on the object structure and on the chemical properties of the constituting materials, thus contains information about the sample inside.

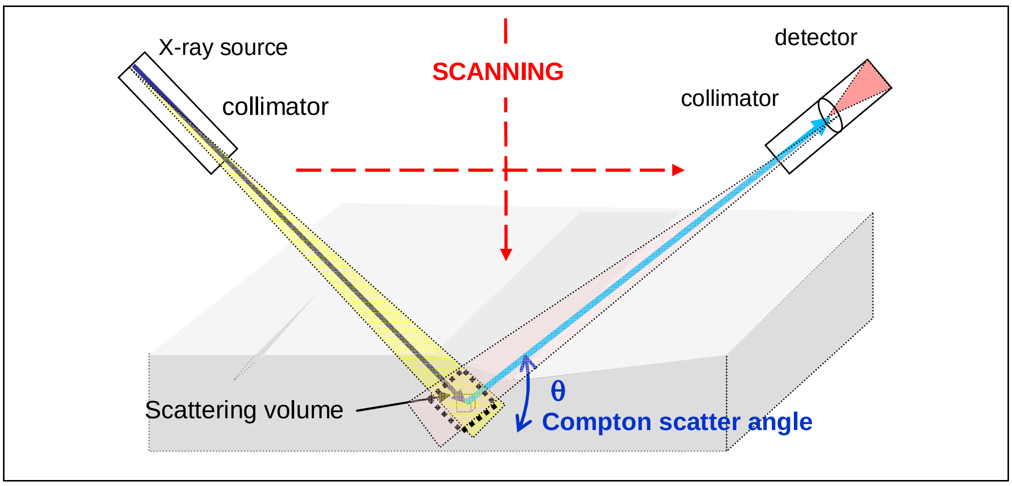

Figure 1: Functional principle of X-ray backscatter technique.

By applying a suitable collimation to both source and detector, an elementary inspection volume is defined, at a given focal depth. A scanning is accomplished by moving the system relative to the sample. This scanning can be performed parallel to the local surface, in order to inspect large parts, or perpendicular to it, to inspect different depths. This scanning technique, often called “flying spot”, requires long time for the inspection of large volumes. By using a number of detectors arranged side by side, one can obtain a higher speed. A slightly different technique, namely “imaging” technique, consists in using a collimation system such as a pin-hole to image directly an intermediate volume on a 2D detector.

In fact, backscatter techniques have existed for a long time (for instance [1], [2]). But the availability of new types of detectors is offering new functionalities and performances. Notice that the photons flux to be measured is low in backscatter geometry. Replacing standard detectors measuring the total deposited energy, counting mode detectors provide the total number of photons. Generally based on semi-conductor technology, they are highly sensitive and particularly convenient for subsurface defect detection. Spectral mode detectors, able to give the actual spectrum of the scattered photons, may allow the discrimination between different material layers.

A backscatter system presents a lot of parameters: source characteristics and collimation, detector characteristics and collimation, relative angles and geometry, scanning protocol. These parameters have to be optimized depending on the sample (shape and material) and the inspection task (potential defects). For that objective, we have developed a simulation software tool that models the signal provided by a backscatter system. The present paper focuses on this tool. It is organized as follows: first we remind some fundamentals on backscatter physics, then we describe the proposed simulation tool, insisting on computational aspects. Different examples illustrate the behavior of the technique. Finally, validations are presenting both using Monte Carlo code and experimental benches. Discussion on the potential interest of this software concludes the paper.

2. Scattering phenomenon and models

2.1 Single and multiple scattering

The physics involved in the system concerns X-ray/matter interactions. Different processes occur: scattering phenomena, and also attenuation in material (before and after scattering events). The most part of scattered photons in backscattering inspection comes from Compton scattering. Single Compton scattering (one interaction) can be modelled in an analytical way, thanks to Klein-Nishina formula. Multiple Compton scattering (successive interactions) also intervenes and contributes to the final scan profile. The simulation of multiple Compton scattering is very difficult in an analytical mode, and generally requires Monte Carlo code. We have evaluated the relative contribution of first and multiple Compton scattering. An example is presented in Figure 2. We can notice that the multiple scatter level is low, but not negligible; in fact it is all the lower that the system is highly collimated. Furthermore, the multiple scatter signal does not contain additional information on local internal structure.

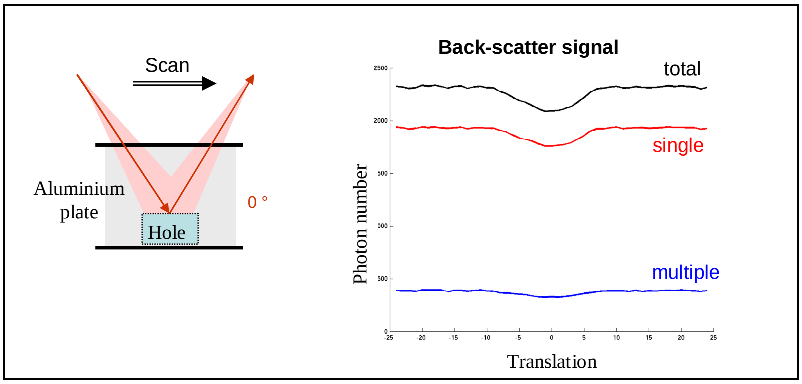

Figure 2: Relative contribution of single and multiple Compton scattering (example).

2.2 Klein-Nishina model for single scatter

Compton scattering occurs when the incident x-ray photon is deflected from its original path by an interaction with an electron (Figure 3). The electron is ejected from its orbital position and the x-ray photon looses energy because of the interaction but continues to travel through the material along an altered path. Energy and momentum are conserved in this process.

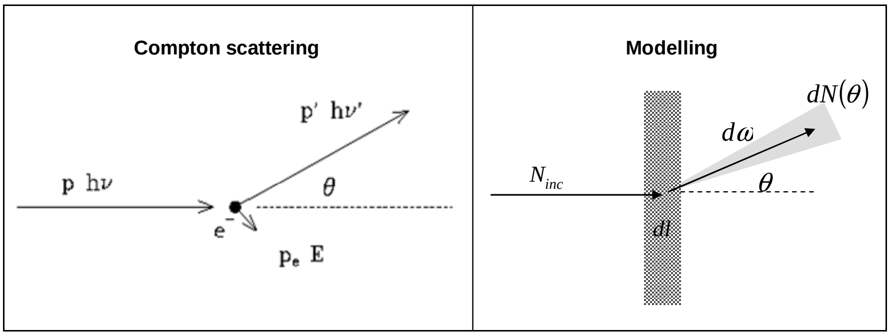

Figure 3: Single Compton scattering interaction (left), model for Klein-Nishina formula (right).

The Klein-Nishina formula [3] provides an accurate prediction of the angular and energetic distribution of scattered x-rays with respect to solid angle of scattering. More precisely, the number of photons of initial energy E_0, scattering in a target of thickness *dl* toward a solid angle $d\omega$, for a given scattering angle θ is:

$$dN(\theta) = N_{inc}.\frac{d\sigma_{KN}(E_0,\theta)}{d\Omega}d\omega.n_e.dl$$

where N_{inc} is the number of incident photons, n_e the volumic density of electrons in the material ($n_e = N_a Z\rho / M$ with N_a the Avogadro's number, Z the number of electrons per nuclide, ρ the density and M the molar mass). The differential cross section for Compton scattering, $d\sigma_{KN}/d\Omega$, is the probability that a photon will scatter into the solid angle defined by $d\Omega$, and is given by:

$$\frac{d\sigma_{KN}(E_0,\theta)}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E_\theta}{E_0}\right)^2\left(\frac{E_\theta}{E_0}+\frac{E_0}{E_\theta}-\sin^2\theta\right)$$

where r_e the classical electron radius, E_θ the energy of the scattered photons.

It is well known that the Klein-Nishina equation makes the assumption of a free electron model. This model is not sufficient because of electron binding [4]. The commonly used correction is via the ISF approximation, where the atomic Compton differential cross section is the product of the Klein–Nishina differential cross section by the incoherent scattering function. Various tabulations of this function are available, among which the compilation by Hubbell et al. is certainly the most widely used [5]. At low energies, the incoherent scattering function can play an important role in suppressing forward scattering. At higher energies, it plays a less important role, except at very small scattering angles. The influence depends also on the material, with effects almost negligible in case of very light atoms (with a weak Z). For backscatter technique, the scattering angles are rather high and the examined materials light, so the standard Klein-Nishina model is sufficient.

3. Description of the developed simulation software

3.1 Principle of SinCompton, a simulation tool for single Compton scattering

Several simulation tools have been developed for backscatter technique, but with important limitations such as consideration of a mono-energetic source instead of a realistic generator (energy distribution) or ignorance of energy shift due to Compton. In terms of geometry, the approach is sometimes restricted to 2D model, or the object shape supposed to be a plate, and the defect shape

restricted to a rectangle. On the opposite, other authors have developed time consuming complete Monte Carlo software. An interesting because hybrid approach is presented in [6]. In [7], the author demonstrates the interest of backscatter simulation to adjust system parameters.
Or objective being to optimize realistic backscatter system, aiming at inspecting various objects containing different defect types, we require a simulation tool able to consider any source, any part, any defect of any material, any detector and any geometry configuration. We have previously developed a software tool to simulate realistic radiographs. This tool, called Sindbad [8], allows the user to describe any X-ray system (polychromatic source and various detectors, energy resolving or not) and any geometry. Objects are defined using CAD format. Radiographs are then simulated in various modes: analytical mode for attenuation simulation, additional single Compton scatter mode, Monte Carlo mode, and combined mode [9]. Based on Sindbad, we have implemented a new software called SinCompton considering only first Compton scattered photons, in order to get a fast estimation of backscatter measured signal. From Sindbad we re-used the analytical simulation of both attenuation process (Beer Lambert law) and first scattering phenomena (Klein-Nishina equation). The code uses a ray-tracing algorithm and can deal with large scale, complex and multi-material objects.

3.2 Collimation models

Analytical model allows fast computation. Nevertheless, to be more efficient while assuming a good accuracy, we developed a precise collimation model. The source can be considered as punctual, so that its collimator simply defines an emission cone, and the intensity of the emission cone is homogeneous (figure 4, a). Collimation on detector is more complicated, as the detecting surface is not punctual (figure 4, b). The detection cone will be defined by a top located in the middle of the collimator and an aperture angle φ_{ape}. Each ray outside this cone cannot reach the detector surface without hitting the collimator [10].

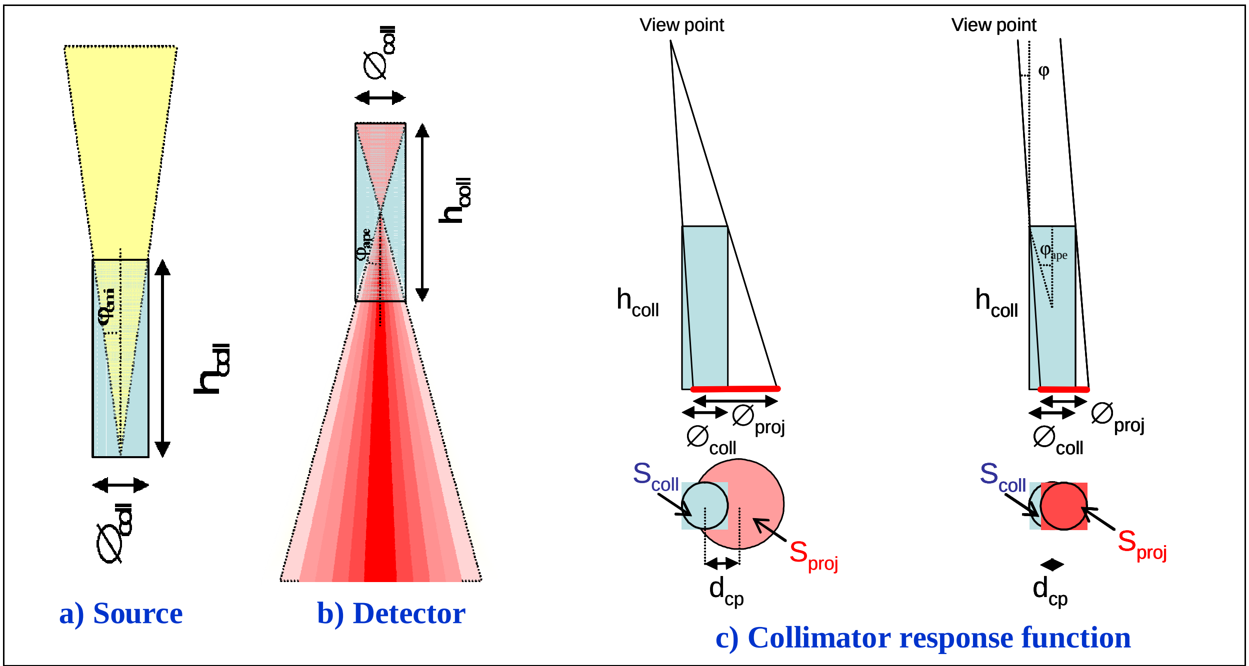

Figure 4: Collimation of the source (a) and the collimator (b), collimator response function (c).

The probability for a ray to reach the detector depends directly on its incident angle φ. For each point of the inspection volume, the ratio of rays which can be seen by the detector, after having crossed the collimator is defined by the “lightened” surface S_{ligh} resulting from the intersection of the projected surface S_{proj} with the surface S_{coll} of the collimator hole (figure 4, c).
We assume that the view point is far from the detector and that the distance between the inspection volume and the detector is large, compared to the height of the collimator ($D \gg h_{coll}$). The lightened

surface then consists of the intersection of two circles of the same radius. After development, we obtain the ratio of the lightened surface S_{ligh} on the collimator surface S_{coll}:

$$F(\varphi)=\frac{S_{ligh}}{S_{coll}}=\frac{2}{\pi}\left[\arccos\left(\frac{\tan\varphi}{\tan\varphi_{ape}}\right)-\frac{\tan\varphi}{\tan\varphi_{ape}}\sqrt{1-\left(\frac{\tan\varphi}{\tan\varphi_{ape}}\right)^2}\right]$$

This collimation model has been used in our software. Finally, the inspected volume is the intersection of the emission cone and the detection cone.

3.3 Algorithmic and computational aspects

An elementary calculation consists in considering a source point (with a energy E_0), an elementary volume in the part and then calculating the number of photons arriving on a given detector surface, coming from the point source and having submitted one Compton scattering in the elementary volume.

Let us call N_0 the number of photons emitted in the direction and in the solid angle of the elementary volume V. The calculation will be performed in three successive steps:

- Calculation of the number N_1 of photons arriving on the volume, based on attenuation law:

$$N_1 = N_0.\sum_{mat} e^{-\mu_{att}(E_0).l_{mat}}$$

- Calculation of the number N_2 of photons submitting a Compton scattering in the volume towards the direction of the detector, that is to say with an angle of θ, following Klein-Nishina equation (notations previously introduced, §2.2):

$$N_2 = N_1.\frac{d\sigma_{KN}(E_0,\theta)}{d\Omega}d\omega.n_e.dl$$

- Calculation of the number N_3 of photons coming from the volume and arriving on the surface detector (attenuation law)

$$N_3 = N_2.\sum_{mat} e^{-\mu_{att}(E_\theta).l_{mat}} \quad \text{with} \quad E_\theta = E_0\frac{1}{1+\varepsilon(1-\cos\theta)}$$

Integrating the collimator model, the final number of photons coming on the surface detector without hits on the collimator is given by: $N_{fin} = F(\varphi).N_3$.

The global algorithm performs a loop according to three parameters: the energies of the spectrum, the number of elementary volumes, and the number of position scans.

The algorithm provides for each position scan the total number of scattered photons that are detected (without and with photonic noise modelling), corresponding to the measurement obtained with a photon counting mode detector. But other information is available, such as the distribution of detected photons in energy, or the relative contribution of the different steps: photon attenuated by each collimator, by the object before and after scattering, and scattered in the volume.

3.4 Modification of SinCompton for multiple scattering

The SinCompton software presented before only simulates first Compton scattered photons. We have implemented a modified version integrating multiple scattering. The algorithm is largely inspired from the hybrid method developed by N.Freud [6], using conjointly deterministic and probabilistic simulation methods.

The algorithm consists of two stages:

- Firstly, a set of scattering events occurring in the inspected object is determined by Monte Carlo simulation. Source collimation is taken into account. As the emission cone is reduced by the

source collimation, this Monte Carlo simulation is rather efficient as it gives a large number of information (historic of scattering events) with a reasonable number of particle showers.
- Secondly, this set of scattering events is used as starting points to compute the particles which achieved their tracks on the detector, with a deterministic algorithm based on a “forced detection”. Each scattering event is now considered as an elementary secondary source toward the detector. If the scattering event is included in the detector cone we compute the ratio of particles which will be diffused in the solid angle of the detector, then the ratio of scattered photons which will cross without attenuation the material between the secondary source and the detector. Then we add the response function of the collimator.

The second step is similar to SinCompton. The first one is an additional step, obviously increasing computational time, but still reasonable due to efficiency brought by the collimation. Depending on the required simulation, the user may choose one version or the other one.

3.5 Example of results using SinCompton

To illustrate the behavior of the software, backscatter signals for a simple configuration are presented in figure 5: a 5mm thick Aluminum plate, containing one defect (3mm sized hole). The source is a generator 60kV collimated at 5.2°, detector collimation is a tube ϕ=5mm and h=55mm. The corresponding inspection volume intersects the surface of the plate on a length ~14mm.

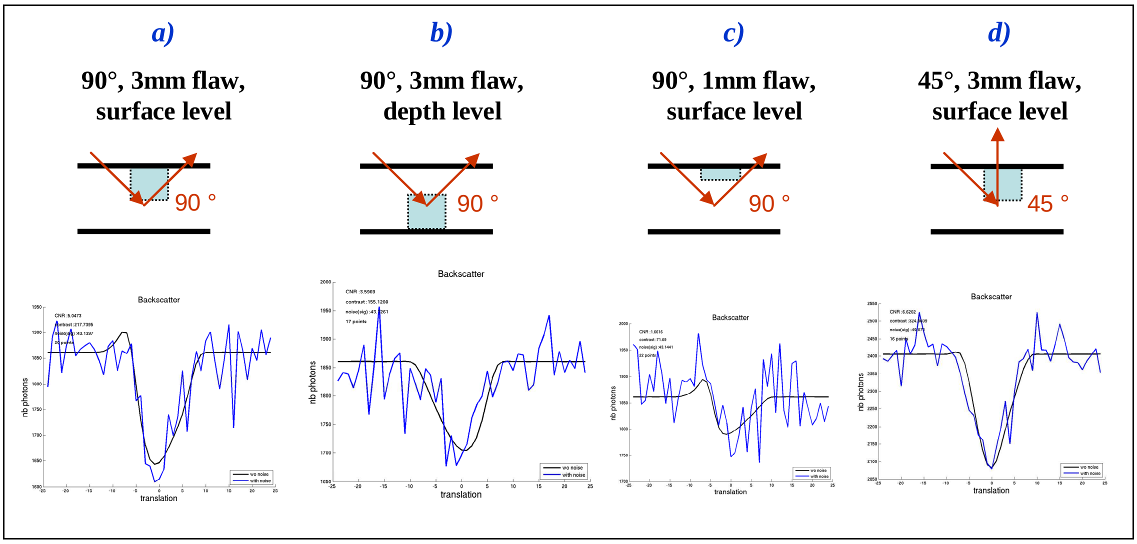

Figure 5: Backscatter signals obtained for various simple configurations (blue: noisy / black: noise-free).

The different curves illustrate variations of defect location depth, defect size and system geometry. Black signal has been obtained without noise, and blue one with Poisson noise corresponding to realistic photons flux. Even with this rather simple configuration, we can notice that the defect characterization in terms of thickness and depth from these scans is not obvious.

4. Validation of the developed simulation software

4.1 Validation using a Monte Carlo code

For quantitative validation, we first simulated similar configurations both with SinCompton code and a Monte Carlo code, called PENELOPE [11]. The adequacy between both signals was very good for various geometries. Slight differences have been observed at low small scattering angles – the reason is that the basic Klein-Nishina formula used in SinCompton becomes false for small scatter angles.

We have also compared the analytical version of SinCompton with the modified one, which first step is based on a Monte Carlo code optimized using collimation priors (presented in §3.4). A PVC wedge presenting calibrated holes has been modelled (figure 6, left), and backscatter signals simulated using SinCompton, with (in blue) and without (in black) noise, and with Monte Carlo based version. In the latest, of course only the first scatter signal is drawn (in red) to be compared with the others. Results of both codes are in very good agreement.

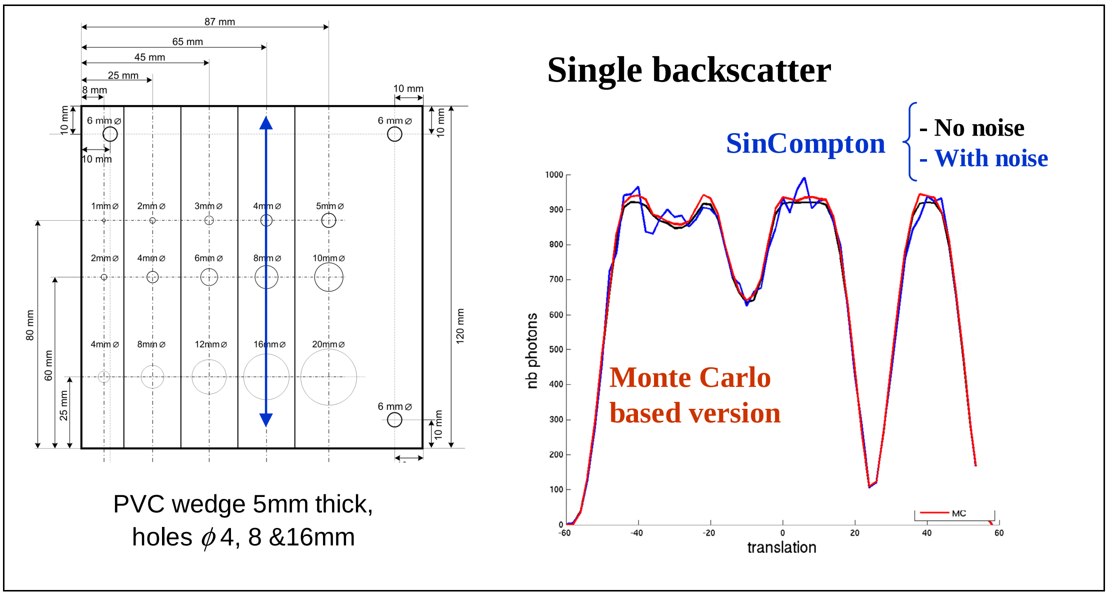

Figure 6: Comparison of analytical version of SinCompton and modified one based on Monte Carlo.

4.2 Comparison with experiments

For experimental validation, we used different test benches and devices developed by Innospexion [12]. The source is a 10-70 kVp 0-4 mA cooled metal ceramic tube of a relatively compact design. The detector has been provided from AJAT, MGC detector with single photon counting ability. Scionix NaI(Th) detector connected to a Multi Channel Analyser can alternatively be used for spectral analysis.

The first example (figure 7) concerns a GRFP sample (40 mm thick) with several defects of diameter 20 mm, located at depth 20 mm. The technique applied is “flying spot” one, the generator is tuned to 50kV, 0.35mA. Collimators are stainless steel tubes (length=55mm; diameter=5mm). The scan is performed horizontally, with accumulation time of 1s. For simulation (left), we present two independently simulated scans crossing the holes (red and blue) and one outside the holes (black). Inspection is performed at 15.5 mm depth. Experimental backscatter scans are presented in the exactly same conditions (right): red & blue through defects, and yellow (instead of black) outside defects. Another sequence of scans is presented (dotted curves) at a slightly different depth (15.8mm). Corresponding signals are slightly higher but present the same features.

The second example (figure 8) concerns the study of the interface between two close materials layers (namely water and oil). The technique is also flying spot, here at 30 kV, but the scan is performed vertically. A counter mode detector is used both for simulation and experiments. For simulation, different voltages have been tested, the best one being 30keV. At that energy, scans in oil (black) and water (red) are clearly different, scan in mixture oil-water is close to water one. The accurate location of the interface is hardly possible, even for noise-free simulation, unless a dedicated algorithm for backscatter signal analysis is developed. Experiments (the three curves are three independently acquired vertical scans), the interface is not visible. Other experiments with more contrasted materials have been performed with obtained interface being visible and coherent with simulation results. But it is clear that the interface between so close materials is out of the limit of the current system. An open question is the potentiality of a spectral detector for such configurations.

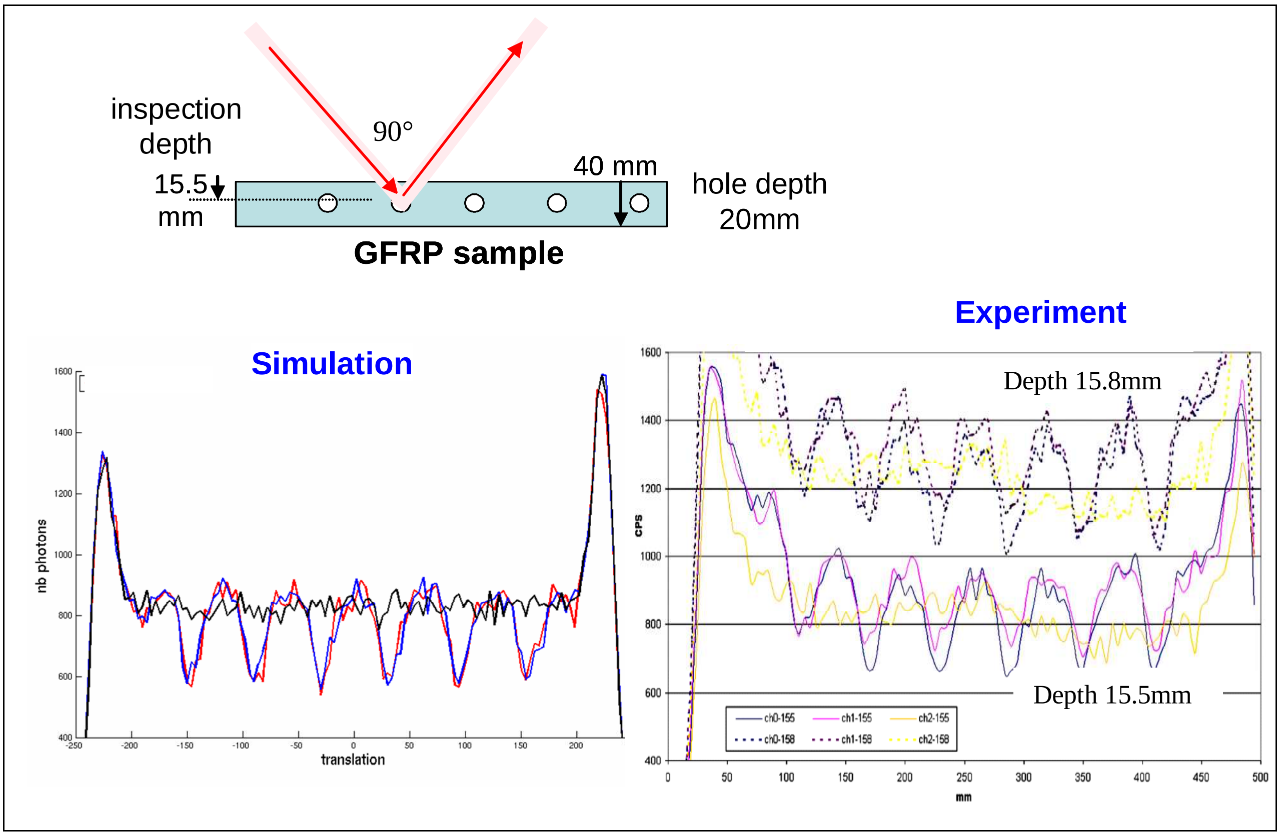

Figure 7: Simulated and experimentally measured backscatter signals on a GFRP sample.

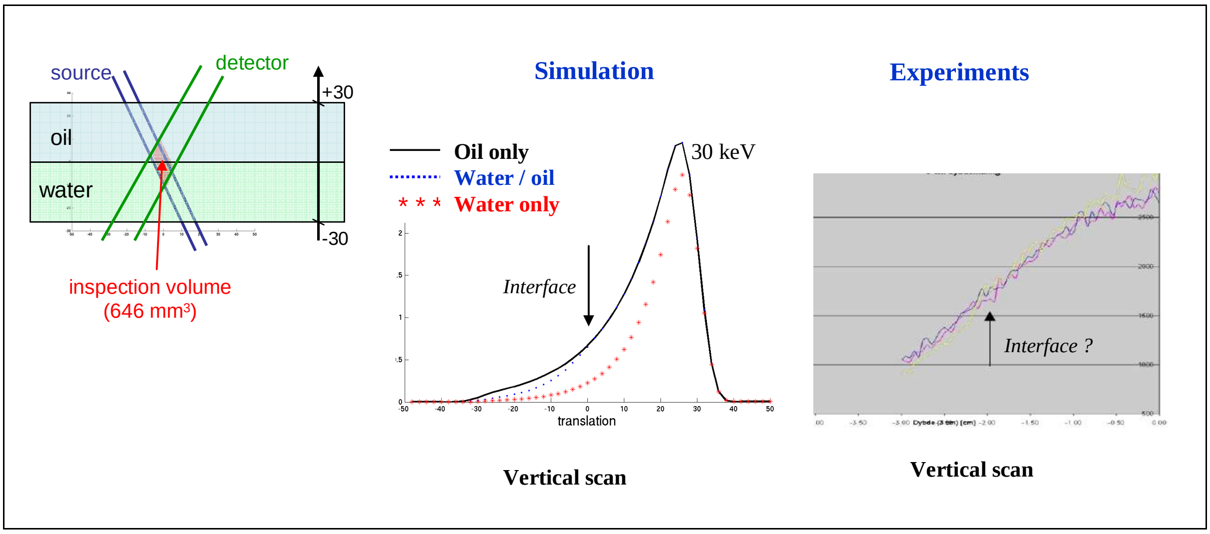

Figure 8: Simulated and experimentally measured backscatter signals on oil/water interface.

Other experiments have been performed and shown a good agreement with simulation. More quantification has still to be performed, using calibrated defects, but the developed software has proved to be accurate enough to predict realistic backscatter signals. In particular, in most cases, the assumption that the multiple scatter level is negligible in terms of signal shape has shown to be acceptable, even it induces a slight underestimation of the total scatter signal level.

5. Discussion

The developed simulation tool is able to provide accurate backscatter scans for any system geometry, any object and defect. It is a useful tool to optimize backscatter system and inspection protocol. Parameters to be tuned are: geometry (angles between source, detector and sample surface), collimators, scanning parameters. Choice of appropriate generator and detector has also to be done. Finally, the software permits to predict the performance of a backscatter system.

As we have seen, multiple scattering can not be completely ignored in backscatter technique, especially if one wants to estimate the absolute backscatter level. In fact, this level depends on many factors, including the acquisition geometry and the examined object itself. Thus it is all the more interesting to be provided with two versions of the software: one based on Monte-Carlo code, which can be used to evaluate the multiple backscatter level, and a second one, purely analytical and fast, to perform numerous simulations in the purpose of system optimization. Additional works are planned for the partially based Monte Carlo version of SinCompton to be more efficient while keeping the probabilistic aspect. Improvements on scattering model using Klein-Nishina equation could also be done on Sincompton if required.

Other works in progress concern backscatter imaging. This technique differs from “flying spot” one, and consists in using a non-collimated source, and illuminating a significant part of the object to be inspected. In that case a collimation system such as a pinhole is placed between the object and the detector. An adapted version of SinCompton has been developed to integrate that functionality. The volume is under-sampled in many small voxels, and a procedure similar to SinCompton is applied with a modified collimation. In this technology, the detector used is necessary a 2D one. The sensitivity of defect detection in terms of location and depth in the sample is lower that for the “flying sport” technique, but the speed is of course highly increased. Simulated images of calibrated objects have been obtained with this version of the software. Experimental measurements for comparison and validation are currently under study.

Another undergoing development concerns the use of recently emerged energy resolving detectors. These detectors, generally based on semi-conductor technology, provide the actual energy spectrum of detected photons. To be used for backscatter inspection, they should be optimized (obviously, the flux of photons is far lower than in radiographic system). Notice that our software could be helpful for that detector design. The information provided is potentially much richer than with standard detectors, but the amount of data is important. Algorithms able to manage the backscattered photons spectra and to extract useful information have to be developed. Few authors have undergone some preliminary works [13]. With such detectors, one can hope to improve defect detection or interface characterization, but also to perform material identification.

Figure 9 presents some spectra of backscattered photons, acquired at different depths (20, 30 and 40 mm) in successively Water, Teflon, and Plexiglas samples. The detector used is a prototype of CdZnTe detector developed at CEA-LETI (energy resolution 2% at 122 keV, [14]). The differences that can be noticed between the spectra are in favour of spectral acquisition and analysis of backscatter signal.

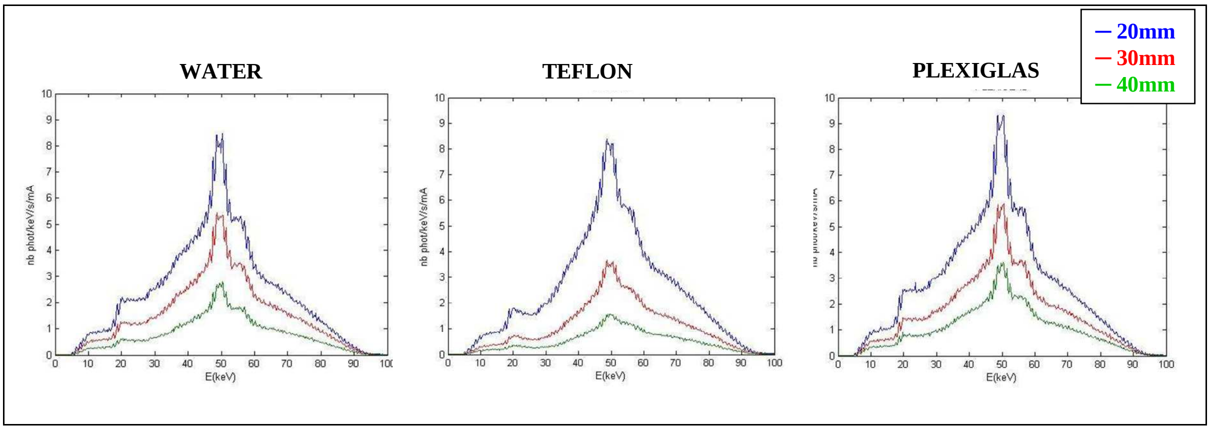

Figure 9: Backscattered photons spectra for different materials and depths.

6. Conclusion

We have developed a software tool providing realistic simulation of backscatter scans in any configuration. Two versions of the software are available, a purely analytical and fast one, and a more time consuming one partially based on Monte Carlo code. This software has been validated by comparison with other codes and with experiments performed by Innospexion. The interest of this software is multiple. First, it is a useful tool for backscatter system design and parameters optimization. It allows predicting performance of a backscatter system. Moreover, by changing samples and defects, with different materials, shape, dimensions, and positions, the tool could help the interpretation of the obtained backscatter scans which is clearly not obvious, especially for complex objects. Simulation could also be used for the development of dedicated processing for backscatter scans analysis: from de-convolution to signal inversion, a lot of methods could be investigated for the quantification of defects or layers thickness.

Flying spot technique requires long time for the inspection of large volumes, but it can be accelerated by using a number of detectors arranged side by side. An alternative technique, namely "imaging" technique, exists and has also been simulated.

Counting mode detectors are highly sensitive and particularly convenient for subsurface defect detection. Emergent spectral mode detectors, able to provide scattered photons spectra, may allow the discrimination between different material layers. Our software allows to model these different detection modes.

Acknowledgment

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