

## **SINDBAD : a realistic multi-purpose and scalable X-ray simulation tool for NDT applications**

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### **Abstract**

The X-ray radiographic simulation software SINDBAD, 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. This software can model any radiographic set-up, including the X-ray source, the beam interaction inside the object represented by its Computed Aided Design (CAD) model, and the imaging process in the detector. For each step of the virtual experimental bench, SINDBAD combines different modelling modules, accessed via Graphical User Interfaces (GUI), to provide realistic synthetic images. In this paper, we present an overview of all the functionalities which are available in SINDBAD, with a complete description of all the physics taken into account in models as well as the CAD and GUI facilities available in many computing platforms. We underline the different modules usable for different applications which make SINDBAD a multi-purposed and scalable X-ray simulation tool.

**Keywords:** simulation, radiography, CAD, source modelling, detector modelling, scatter image, direct image.

### **1. Introduction**

In NDT studies, the availability of a radiographic devices simulation is of primary interest to design the most suitable system and to predict the future device performance. Numerical simulation of radiographs and CT scans makes inspections more reliable and efficient by providing realistic quantitative answers to non-trivial non-destructive evaluations of complex components. Designers of digital processing techniques, such as tomography, tomosynthesis and automated defect detection can also take advantage of realistic simulated images. The necessity to have fast and convenient software tools at disposal lead, during the last decade, to the development of software based on Computer Aided Design (CAD) model of the examined part and Graphical User Interface (GUI) [1-5]. In this context, the X-ray radiographic simulation software, SINDBAD, has been developed in our laboratory.

This paper first presents an overview of the general model characteristics used by SINDBAD v6 in order to compute the radiographic image of a complete radiographic system. In a second part, it focuses on the different computing models SINDBAD offers, depending on the needs of the user (1D computing, 3D computing with or without scatter modeling). SINDBAD can run now upon different computing environments, with specific GUI facilities. Finally, the paper presents some applications based on SINDBAD extensions, as scanner option, optimization of acquisition parameters and gamma-camera simulation.

## 2. General model characteristics

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 transmitted photon flux and transformation into a measured signal) as shown on Figure 1.

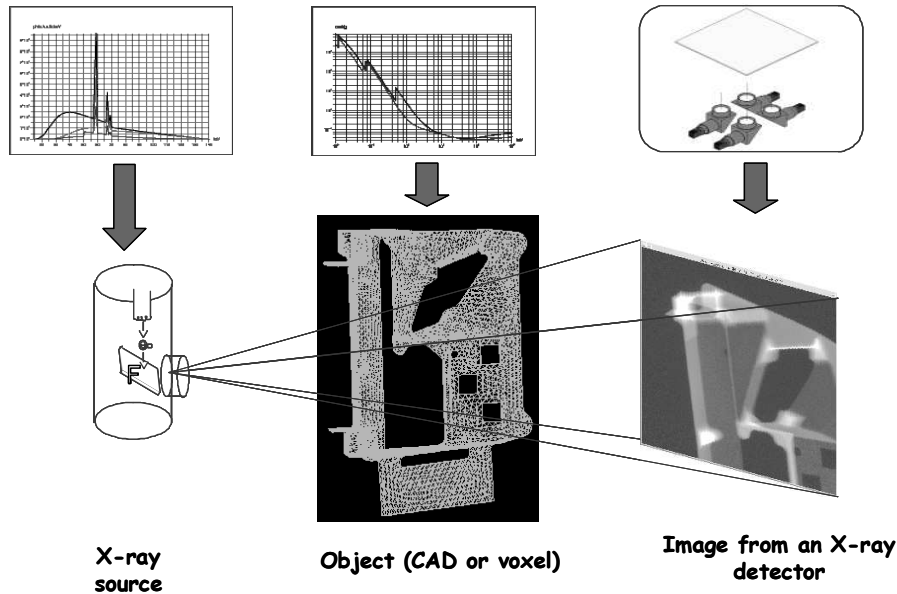


Figure 1 : SINDBAD architecture.

### 2.1 Source modelling

Regarding the X-ray beam generation in the source, SINDBAD proposes a X-ray tube model, which can be used between 30 and 450 kV. This implemented X-ray tube model, simulates the physical phenomena involved in bremsstrahlung and characteristic photon production with semi-empiric model. It takes into account the anode angle and composition, the inherent and additional filtration and the photons exit angle. Experiments performed at LETI with well known experimental conditions and tubes working under nominal conditions show a good agreement from 10 to 20%, respectively for low and intermediate high voltage values, between calculated and measured doses [6]. Spectra can also be described as user-defined data, which is convenient for high-energy (a few MeV) spectra, or gamma sources. Concerning source geometry, SINDBAD is able to manage both conic and panoramic sources.

### 2.2 Interaction in the object

Concerning the interaction of particles within the sample, SINDBAD simulation is based on a coupling of raytracing techniques to access the thicknesses of the crossed materials with the physical laws of the different interactions phenomena. The geometry description of the inspected part can be voxelised or in a CAD format. Voxelised objects can be modelled only in the analytical computing, with raytracing routines self developed, based on the Joseph algorithm. In case of CAD description of the inspected

part, 3D objects must be described or converted in formats compatible with the BRL-CAD package [7], as the raytracing routines used by SINDBAD are directly those of BRL-CAD. The paragraph §3.1 explains in detail how objects can be described in BRL-CAD.

The materials cross sections used in SINDBAD are those described in Storm and Israël tables [8] for the total attenuation coefficients (used for direct radiation computing) and those of PEGS4, the EGS4 preprocessor, for the scattering phenomena. All types of materials are available thanks to a mixture module.

### ***2.3 Detector modelling***

Detectors are modelled in two successive steps. The first one, common to all types of detectors computes the energy deposition in the sensitive part of the detector using the energy absorption attenuation coefficients. The second one, specific to each type of detector, simulates the successive physical phenomena involved in the energy to signal transformation. Different models have been integrated, such as a scintillating screen viewed by a CCD camera, a photomultiplier and a film.

Recently, a new detector model, called cascaded linear system model [9], has been developed to enable the user to model any kind of detector in a more general way. In this model, the user builds its own detector by cumulating several linear processes such as amplification process, blurring process, noise process for each physical phenomenon involved in the detection. It appears very powerful, especially for flat panel detectors, but requires either a very good knowledge of the detector or a set of calibration measurements (MTF, electronic noise, etc.).

Concerning detector geometry, SINDBAD can manage both plane and curved detectors.

## **3. The scalable simulation approach**

Within a unique framework, it is possible to adapt the accuracy (and the computation time) of the simulation to the user needs, from a 1D simulation to give a first global approach to a problem, up to 3D Monte Carlo to get accurate simulations with scatter effect.

### ***3.1. 1D simulation***

During the initial design stage, a simplified one-dimensional simulation can be performed, in which a single ray is shot through the examined part, defined as a plate of given thickness, to a single pixel detector. This simulation gives the possibility to display the X-ray spectra computed along the beam path (source spectrum, spectrum after object attenuation, spectrum absorbed in the detector) and to access some important figures such as the expected signal and noise values. This facility is quite useful for studying beam hardening effect.

### ***3.2. 3D analytical simulation***

The 3D analytical simulation computes an image of the uncollided flux simulation that 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 [7] or a 3D data volume segmented into materials.

The finite size of a source can be simulated through convolution of the image with a X-ray spot size dependent kernel, assumed to be Gaussian. The standard deviation of the kernel is obtained by considering a mean geometrical magnification factor, which can be calculated automatically or tuned by the user to fit with the plane of the flaw [10].

When the objects have fine structures with characteristic sizes identical or smaller than the width of the pixels, an automatic over-sampling of the detector is carried out to assure a good projection of details. This over-sampling is followed by a gathering of pixels to recover the real resolution [9].

### 3.3. 3D Monte Carlo simulation

A Monte Carlo simulation module [11] has also been integrated 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 with EGS-NOVA [12], a Monte Carlo radiation transport simulation code. Once incident particles are emitted from the source, the EGS Nova shower simulation manages their tracking and interaction in the object. 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 multiple scattered photons images. The coupling between BRL-CAD and EGS-NOVA authorizes the detector to be inside the object, so that backscatter can always be simulated.

Monte Carlo simulations, which are very time consuming, are often only performed for the estimation of scattered radiation. Thus, as scatter 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. On complex industrial objects, the computations can be twenty times faster [13].

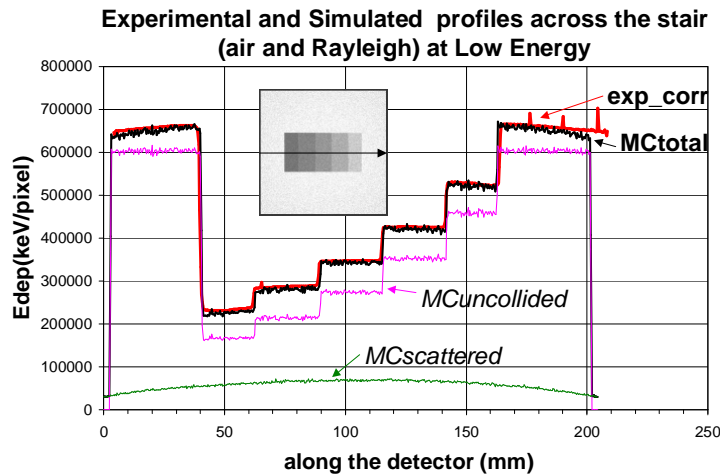


Figure 2 : Experimental validation on stair phantom at 70 kV.

This Monte Carlo module has been validated with respect to experimental acquisitions at low [14] and high energies. Experimental validation at low energy is illustrated on Figure 2 with profiles along experimental and simulated images of a

PolyVinylChloride stair. Figure 3 shows an absolute validation at high energy, with a Cobalt 60 source on steel slabs and two kinds of dosimeters, an ionisation chamber and a thermoluminescent dosimeter. Again, a partial comparison was done for a 50 mm slab with PENELOPE [15], another Monte Carlo code. SINDBAD gives good but slightly underestimated results for a large thickness range.

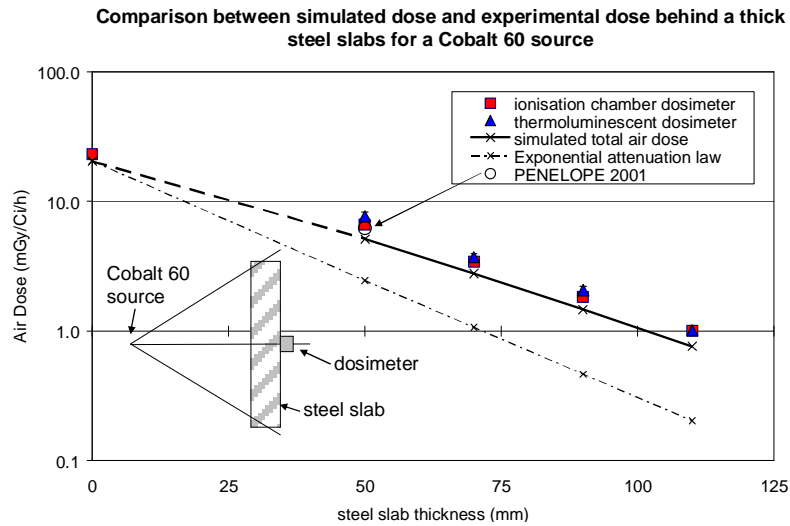


Figure 3 : Comparison between simulated dose (SINDBAD V4) and experimental dose in air behind a thick steel slab for a Cobalt 60 source. Check at 50 mm with PENELOPE 2001.

Concerning backscatter estimation [13], SINDBAD has been compared to PENELOPE in case of aluminium plate thickness of various thicknesses. The Lanex scintillator detector was simply modeled by an equivalent thickness of 0.355 mm  $Gd_2O_2S$  and by an aluminium plate (8 mm) set behind the  $Gd_2O_2S$  part, to simulate the back protection of the detector (see scheme in Figure 4). The agreement of PENELOPE and SINDBAD results is good.

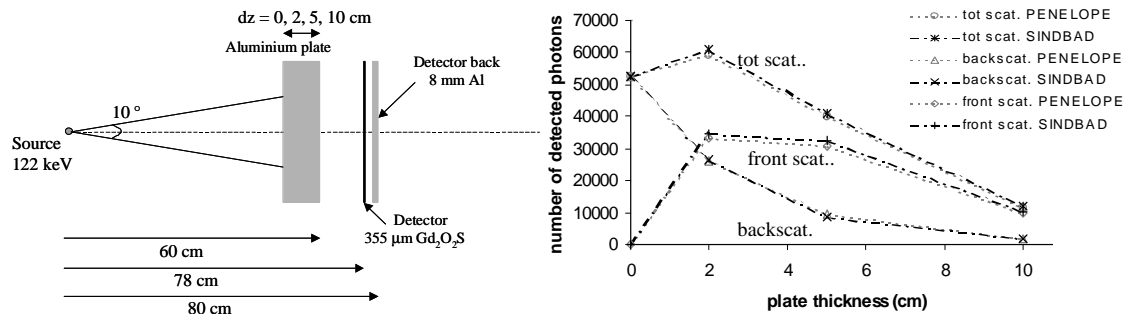


Figure 4 : Comparison of SINDBAD and PENELOPE simulations for scattered radiation.

### 3.4. 3D analytical and Monte-Carlo simulation

The Monte Carlo method gives good quality results either for uncollided or scattered photon flux images but its use is largely limited by the execution time drawback. An original hybrid model was developed then, combining the advantages of both analytical and Monte Carlo techniques [16]. 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 5, 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 noise image. The main advantage of this combination mode is that it becomes possible to obtain detailed simulated images, taking into account various interaction effects such as scattered, in a feasible computation time. The scaling of the mean component of the scatter image is carried out thanks to a low pass filter, which frequency can be computed automatically, or tuned manually by the user afterwards.

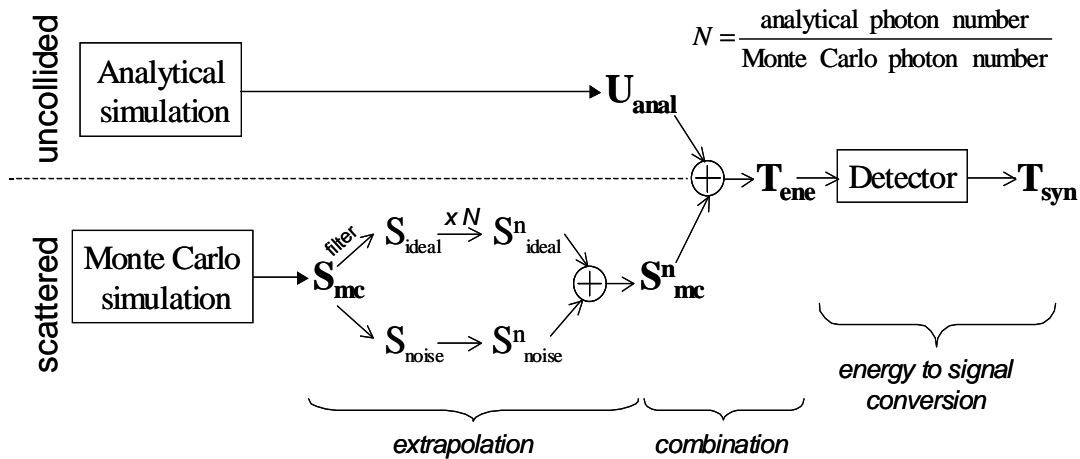


Figure 5 : Analytical and Monte Carlo images combination scheme.

In case of low stopping detector, a speed up option [9] has been integrated, which relies on performing the extrapolation on the incident scatter image rather than on the absorbed energy one. A mean absorption coefficient is finally applied to get the good detected scatter radiation.

### 3. SINDBAD on different platforms

#### 3.1 On Unix and Linux workstations

SINDBAD is developed in ANSI C language. At the beginning, it was only running under UNIX on SUN workstations. The code has been recently transferred with success on LINUX environment, with the same Guide User Interface. In these environments, User's interaction with non computing intensive modules is performed through a Motif Graphic User Interface, where all parameters of source, geometry, material, detector pages can be easily reached and modified.

However, on Unix and Linux environment, the description of the object has to be performed independently within the BRL CAD software. To be simulated in SINDBAD, 3D objects must be described or converted in formats compatible with the BRL-CAD package [7]. Two formats are available: the constructive solid geometrical (CSG) format of BRL-CAD, consisting in combinations (union, subtraction, intersection) of simple geometric shapes (sphere, box, cone) and the faceted format, resulted from conversion of standard stereolithography (STL) format. BRL-CAD is very

flexible as the user can easily add, subtract or modify any item in a given object, even if it is not in the same format. Such modification or creation can be carried out thanks to an interactive GUI interface proposed by BRL-CAD, which enable the user to easily insert one defect, move it, turn it, scale it or even distort it by playing on its control points (Figure 6).

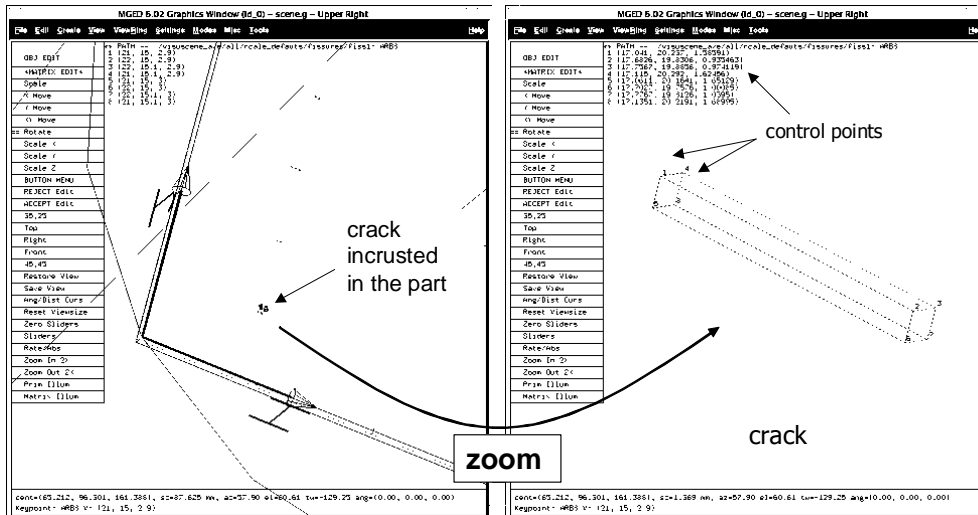


Figure 6 : BRL-CAD interface used to insert defects in CAD models. Many buttons (scale, rotation, translation) enable the user to modify the crack which is inserted in the object.

### 3.2 On PC Windows

SINDBAD, as well as MODERATO [1], is being integrated in the CIVA software platform.

The CIVA simulation software [17] has been developed at the CEA-LIST, with other partners, since more than one decade. Until its last release (v8), CIVA dealt with ultrasonic testing and eddy current techniques, by offering within the same framework several simulation modules suitable to research and industrial needs. The CIVA package brings together imaging, processing and simulation tools in the same environment, thus enabling a direct comparison to be made between experimental and theoretical data. The imaging system associated with the signal and image processing tools enables the interpretation and expertise of simulation and experimental results. The next release CIVA 9.0 of CIVA will integrate a X-ray and gamma-ray module, based on the two pre-existing codes MODERATO and SINDBAD. CIVA is a marketed code which runs on PC windows.

In this new platform, most of the functionalities of SINDBAD will be present, including 3D analytical, Monte Carlo and combination computing modes. The main difference with the Unix release of SINDBAD will be the Guide User Interface, very interactive and user-friendly, and identical for all NDT techniques. The description and positioning of the component inside the radiographic scene is performed interactively. Whereas the geometrical parameters in Unix release of SINDBAD was convenient for tomography, the way of positioning the source and detector in regard to the object in the CIVA framework is more appropriate for radiology. Flaw insertion will be also possible.

## **4. Extended applications of SINDBAD**

### ***4.1. Scanner simulation with animated volume***

Above the radiograph simulation process, it is also possible to build new applications such as scanner simulation.

A virtual scanner based on SINDBAD has been developed to produce a series of acquisitions. The simulation software generates 2D projections of a phantom, which can be animated (to simulate breathing for example), during the rotation of the X-ray source and 2D detector system [18]. The three main steps are phantoms animation (in order to get a realistic scanner acquisition mode), ray-tracing through the object and projection computation.

### ***4.2 Optimization of acquisition parameters***

An optimisation process has also been developed to find the optimal acquisition parameters to detect a specific defect in a well known industrial part [19]. Indeed, the radiograph quality is highly dependant of a large number of inspection parameters: generator settings, object geometrical parameters and detector characteristics.

The program consists in a main loop scanning the whole parameters space to find the optimal parameters set, using a defect detectability criterion as cost function. Precisely, for every particular set of acquisition parameters, some radiographs with and without defect and noise are simulated, followed by an image processing determining the level of detectability for the corresponding configuration. Different versions of the detectability criteria are proposed, depending on whether detection is performed by numerical processing or human inspection. Experimental validation of our approach has been performed using components from aeronautics.

### ***4.3. Simulation of a gamma-camera***

SINDBAD has also been used as a help to design gamma-cameras in medical or molecular imaging. In a previous version, the collimator could be described analytically as a filter for the detector (multi square hole collimator) [20], it is now described as a CAD object to take the septal transparency into account. The attenuation phantom, if any, is also described as a CAD object, where the emission phantom is described as a voxelized phantom. In an external loop, for each active voxel of the emissive phantom, the relative position of source-object-detector is updated, only the useful part of the detector is considered in order to speed up the computation and the intermediate result is summed into the final image [21].

This kind of loop can also be considered if the source is really volumic, compared to the details one wants to examine. In this case, the source will be split into several elementary sources and the simulation will be carried out using a similar loop.

## **5. Conclusion**

In a unified framework, SINDBAD is a multipurpose X-ray simulation software which provides a scalable approach of computation and very efficient results by combining analytical and Monte Carlo simulations. The software has been validated



experimentally. It is also an “easy to use” software with a strong emphasis on user friendly GUI, simple description of object (CAD or volume) and visualization tools. The future integration of SINDBAD and MODERATO in the next release of CIVA will make available its functionalities on PC window platform, in a simulation package joining together all NDT control techniques.

## Acknowledgements

The authors would like to acknowledge all persons who have closely or not participated to the development of SINDBAD for the last fifteen years, with special thanks to the initial author Alain Glière (CEA/LETI). They also would like to acknowledge all persons at the CEA-LIST involved in the integration of SINDBAD in CIVA, especially Arnaud Levêque and Stephane Leberre (CEA/LIST).

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