Digital Radiology: an Opportunity for Quantitative Measurement

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Abstract
A digital detector provides numerical information at each pixel. This value may be difficult to be interpreted quantitatively. In this paper, the main factors to be considered during physical interpretation are reviewed: beam-hardening effect, scattering diffusion, type of detector. Some of them induce degradation on the digital radiograph while others modify the nature of available information. Signal-to-noise ratio should be taken into account, and compared to the accuracy required by the inspection process. Different existing methods are discussed for scatter correction. Then we analyse different techniques of digital radiography based on the quantitative aspect – thus assuming good accuracy of radiographs values: tomography and 3D techniques, and dual-energy approaches. Finally we evoke emergent detectors based on semi-conductors, which are energy selective photon-counters, thus offer new opportunities in terms of information processing.
Keywords: Radiography, X-ray imaging, Quantitative, Tomography, Dual-energy, Scattering, Detectors.

1. Introduction

For over half a century, film radiography has been very useful to industrial control. This NDT technique has proven to be efficient for material inspection as well as defect detection. Film characteristics and acquisition protocols have been optimized for the visual control by a human operator, leading to the specification of inspection acceptance standards. Nevertheless, digital detectors have progressively emerged. Amorphous silicon plates optically coupled with CCD cameras have been implemented in many systems, and they remain the only possible solution when speed is required, for process flow control or real-time radioscopy. Phosphor screens, used by the “computer radiography” technique, can be classified as digital. Although they require successive steps, they are irreplaceable for some configurations, curved geometries for instance. The recent development of flat panels, easily integrated, enlarges the applications field. More recently, a new technology of detectors emerged. Designated by “direct conversion” because absorbed photons are directly transformed into electric charges that can be collected thanks to semi-conductor physics, they can be energetically selective.
The advantages of digital radiography compared to the traditional one based on film are well known: free of chemistry, linearity, dynamic, reproducibility, fast reading. Recent reviews can be found [1]. It is clear that to benefit totally from this new technique, an evolution is also required in terms of specification of protocols and inspection standards [2]. The purpose of this paper is to focus on the processing aspect. One of the benefits of digital radiography is to provide a digital image – a map of quantitative values. One can expect to interpret these values in terms of physical quantity, at least relatively. Furthermore it should be possible to combine two or more radiographs, within dual-energy X-ray techniques (energetic combination) or tomographic reconstruction (geometrical combination). All these digital processes assume some properties of the measured values. In fact, the underlying physical models used for interpretation are often simplified (neglecting scattered radiation for instance). Furthermore, noise can not

be ignored – at least the photonic Poisson noise. Finally, a sensor is *never* perfect. For all these reasons, the exact relationship between the measured value and the expected one is not perfectly known. Nevertheless, some industrial applications using digital radiography have been developed without considering these aspects – this is acceptable as long as the measurement uncertainty and degradation are small compared to the inspection process constraints.

In this paper, we analyse the nature of the radiographic measurement and the associated noise, we identify the main factors, especially the poly-chromaticity of the source spectrum and the scattered radiation. Different methods for scattering correction are reviewed. Then we consider different techniques of digital radiography assuming good accuracy of radiographs values: tomographic reconstruction, and dual-energy techniques. Finally the emergent use of spectrometric-type detector is addressed. Illustrating examples are presented using the simulation software tool Sindbad [3] developed in our laboratory, as well as experiments on several test benches.

2. Measurement in radiography

2.1 The theoretical perfect case

Let us first consider the perfect case of a monochromatic source and a linear detector. If the number of emitted photons is N_0, then the number of photons N imaging on a collimated detector of one pixel after attenuation by a thickness T (cm) of an object of homogeneous attenuation μ (cm^{-1}), is given by: $N = N_0 \exp(-\mu \cdot T)$ (Beer-Lambert).

The coefficient μ depends on the density of the material ρ, on its chemical composition (atomic number Z), and on the energy E of the photons: $\mu = \rho \cdot \tau(E, Z)$ where τ is the mass attenuation of the material (cm2/g). For an inhomogeneous object, the product $\mu \cdot T$ should be replaced by its integral along one ray $\int \mu(l)\, dl$.

If we compute the log-measurement, we get a value that is proportional to the thickness crossed by the x-ray: $m_E = -Log(N/N_0) = \mu \cdot T$. This can be generalized to an object composed of several materials: $m_E = \sum_{material\ l} \mu_l \cdot T_l$. The photon number N can be considered as a random variable having a Poisson distribution of parameter (thus variance) N. The variance of the log-measurement of the attenuation is $\sigma^2(m_E) = 1/N$.

2.2 Polychromatic Energy Spectrum

In fact, the spectrum of an X-ray tube is polychromatic. Let us call $S_0(E)$ the spectral density of the source flux, $S(E)$ the attenuated one. We analyze successively the different possible signals provided by a digital detector, depending on its type.

A detector in *integration mode* provides a signal that is proportional to the deposited energy. This is the most frequent case for digital detectors. For a spectrum in the energy range $[E_1, E_2]$, the signal without attenuation is ($D(E)$ being the detector efficiency): $I_0(E) = \int_{E1}^{E2} D(E) \cdot S_0(E) \cdot E\, dE$, and $I(E) = \int_{E1}^{E2} D(E) \cdot S_0(E) \cdot e^{-\sum_{mat\, l} T_l \cdot \mu_l(E)} \cdot E\, dE$ after attenuation by T_l thicknesses of materials l.

For a detector in *photon-counting mode*, the provided signal corresponds to the number of photons. So we get, with the same notation as previously:

$$I_0(E) = N_0(E) = \int_{E1}^{E2} D(E) \cdot S_0(E)\, dE \text{ and } I(E) = N(E) = \int_{E1}^{E2} D(E) \cdot S_0(E) \cdot e^{-\sum_{mat\,l} T_l \cdot \mu_l(E)} dE$$

For both cases, the log-measurement of attenuation is: $m_{[E1,E2]} = -Log(I(E)/I_0(E))$.

Without loss of generality, we can neglect *D(E)* and by using a discrete notation, the spectral density can be written $S(E)\, dE = N(E_i)$, and we get simpler formula:

	Integration mode	*Photon-Counter mode*
Polychromatic measurement	$m_{[E1,E2]} = -Log\left(\frac{\sum_{i=1}^{K} N(E_i) \cdot E_i}{\sum_{i=1}^{K} N_0(E_i) \cdot E_i}\right)$	$m_{[E1,E2]} = -Log\left(\frac{\sum_{i=1}^{K} N(E_i)}{\sum_{i=1}^{K} N_0(E_i)}\right)$
Associated variance	$Var(m_{[E1,E2]}) = \frac{\sum_{i=1}^{K} N(E_i) \cdot E_i^2}{\left(\sum_{i=1}^{K} N(E_i) \cdot E_i\right)^2}$	$Var(m_{[E1,E2]}) = \frac{1}{\sum_{i=1}^{K} N(E_i)}$

where $N(E_i) = N_0(E_i) e^{\left(-\sum_{material\ l} T_l \cdot \mu_l(E_i)\right)}$.

Notice the difference between the two modes: for integration one, equations are more strongly weighted by high energies, leading to a lower measure and a higher variance, thus a worse signal-to-noise ratio than for counting-photons mode. Mind that this conclusion is based on the photonic aspect only. For both integration and photon-counting modes, the relationship between measurement and material thickness is no more linear. This non-linearity, and the fact that low energetic photons are more attenuated than high energetic one, induce the “beam-hardening” effect, discussed in §3.1. The information provided by the detector for each pixel is $m_{[E1,E2]}$, though the physical quantities are thickness T_l and attenuation μ_l for all materials *l*.

2.3 Scattered radiation

The above models consider only the photo-electric effect, for which a photon interacts with an atomic electron by transferring totally its energy. Other types of photon-matter interaction can occur. At the energies considered in NDT domain, the main one is the Compton scattering, when the incident x-ray photon is deflected from its original path by a coherent interaction with an electron. The x-ray photon looses a significant part of its energy but continues to travel through the material along an altered path. This interaction is preponderant in the range domain 100KeV-1MeV. Scattering can be modelled by Klein-Nishina formulae, which provides an accurate prediction of the angular and energetic distribution of the scattered x-rays [4]. Multiple scattering is difficult to be modelled and can be simulated using a Monte Carlo code.

The scattered photons absorbed in the detector may come from the inspected object, from the environment and from the detector itself. A scattering model should integrate all these components, thus can not be deduced from the radiograph only without prior knowledge. A collimated system selects only the geometrical rays coming directly from the source toward the detector, allowing to eliminate the scattered ones. For a linear array being correctly collimated, the scattered radiation may generally be neglected. In case of non collimated geometries, the scattered radiation induces a *scattered* image that is physically added to the primary flux image to provide the *acquired* image (figure 1). If the scattered image is ignored, the attenuation values are underestimated.

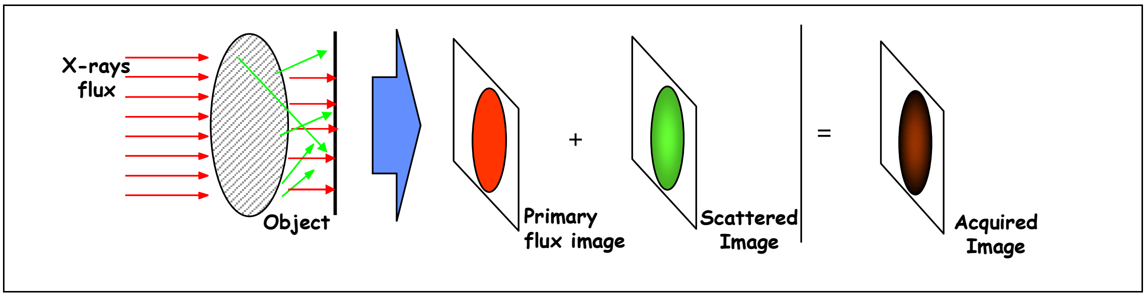


Figure 1: The acquired image is the sum of the primary flux and the scattered radiation images.

Let us evaluate the order of magnitude of the scattering effect. A simulation software tool including Monte-Carlo code as Sindbad can be used to quantify the various factors influencing scattering effect for a 2D detector, mainly the distance between the examined object and the detector, and the shape of the object. The object-detector distance, often called *air-gap*, has a strong influence on scattering level. X-rays scattering being a diffusive phenomenon, its intensity decreases with the distance from its creation point, while the primary flux remains in the direction defined by the X-rays source. For a 2D detector and an object close to the detector, the scattering level may reach 3 times the primary flux one. The above table gives ratio of scattered/primary flux for an object of constant thickness (aluminium plate 8 cm thick), standard X-ray generator 140KV and 2D detector, and a source-detector distance 100cm:

Air Gap	0 cm	5 cm	10 cm
Scattered / Primary flux	1.94	1.05	0.58

The severity of disturbances induced by scattering depends on its level, but also on its shape. The more the object shape is complex, the more the scattered image will present high frequencies in the radiograph. This effect is all the stronger that the inspected object is close to the detector (figure 2). On the opposite, for an object of approximately constant thickness and important magnification geometry, the scattered image may be approximated by an offset.

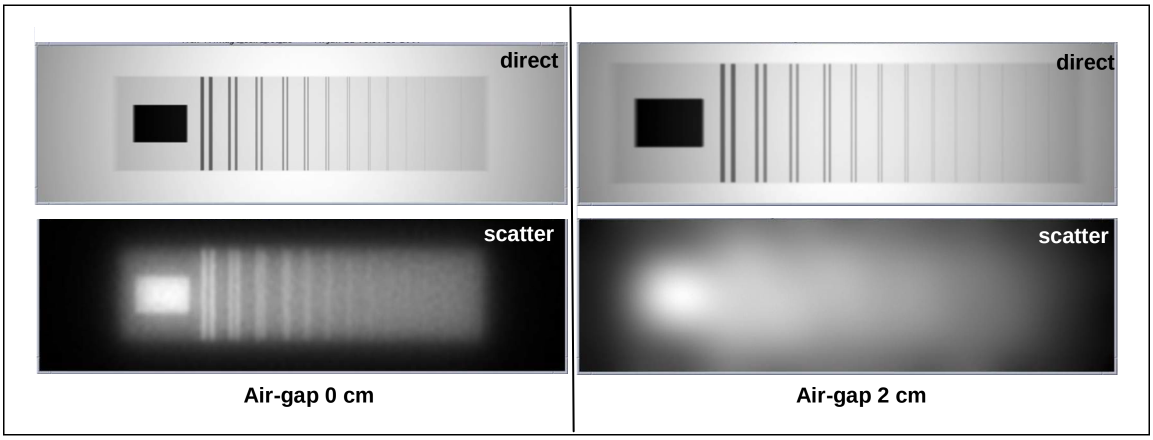


Figure 2: Spatial frequencies of scattering for an IQI, for two air-gap values: 0 & 2 cm. Simulation study.

3. Preprocessing the radiograph

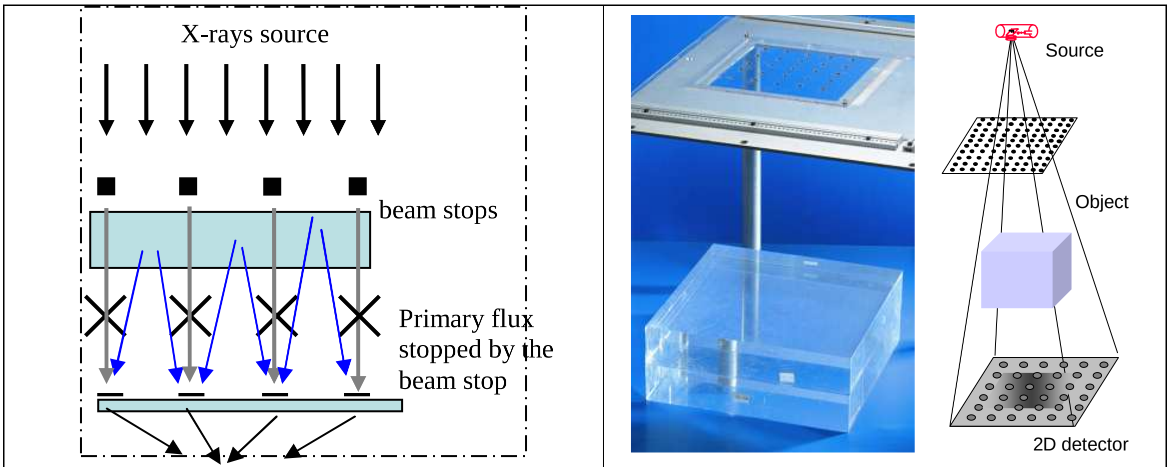
3.1 Sensor correction

In order to access to quantitative information, digital detectors acquisitions require specific calibration and correction processes. A digital detector may contain some defective pixels, i.e pixels that do not respond to the incident flux or pixels that present a significant variation to linearity. These pixels locations have to be determined and then a correction based on the interpolation of valid nearby pixels can be used. Acquisitions can also be altered by non uniformities of pixels response. A gain correction, i.e normalization by a full flux acquisition, globally corrects this point. When the detector presents spatial or flux level variations of non linearities, this correction has to be refined spatially or in regard to the flux level.
Moreover, a digital acquisition may be degraded by different sources of scattering inside the detector (X-rays scattering, light scattering). A correction approach for digital flat panels based on modelling and estimating the sources of scattering, has been proposed in [5]. The *beam-hardening* effect, introduced in §2.2, is induced by the fact that low energetic photons are more attenuated than high energetic ones, thus hardening the spectra when crossing increasing thicknesses of material. To get free from this, the usual method is to perform a calibration: measurements based on step wedges of known thicknesses are acquired, then the parametric model of the relationship giving thickness as a function of measurement is estimated, in order to be applicable further. An example is presented within tomography technique in §4.1. Generally performed thanks to experiments, this calibration is sometimes done by simulation, but this second way does not allow to integrate the detector non-linearities. Notice that being performed using one material, such calibration is not strictly applicable to multi-material objects.

3.2 Scattered radiation correction method for radiography and tomography

There are two main classes of scattered X-rays correction methods. The *mechanical* approaches prevent scattered X-rays to reach the detector. The *numerical* ones estimate the mean value of scattered radiation in order to subtract it from the acquired flux.
At first, let us mention scattered radiation reduction by air gap technique (introduced in §2.3). This approach consists in increasing the object-detector distance as much as possible. One of its main drawbacks, is that magnification of X-rays imaging implies larger surface of detector.
Anti-scatter grids are another way for *mechanically* reducing scattered radiation level. It consists in a device composed of thin lead plates regularly spaced, focalized in the direction of X-rays emission. Between these lead plates a significant part of primary flux is transmitted while the defocalized scattered x-rays are stopped. The proportion between X-rays scattering suppression and primary flux transmission is driven by the ratio of the inter-space between lead plates to their height. When the inter-space between lead plates is lower than the pixel size, a grid vibration mechanism has to be used in order to avoid grid structure artifacts. Main constraint for the use of anti-scatter grids is the efforts needed for their implementation: accurate focalization, vibration…
The beam-stop approaches estimates a mean value of the scattered flux image by interpolating measures at some points of scattered flux acquired after interposition of high attenuating lead balls between the source and the examined object (figure 3). The

number of beam stops has to be limited in order to limit perturbation of X-rays scattering generation. In order to get an adequate sampling of the scattered flux image, it may be necessary to carry out several acquisitions at different positions of beam stops balls. As the beam stop approach requires the acquisition of additional images with beam stops, it increases acquisition time and dose transmitted to the examined object.
Some authors [6] propose an analytical model of scattered flux image formation expressing its estimation as a convolution of a function of the primary flux. These approaches lead to fast algorithms, their main limitation is the accuracy of scattering estimation due to the complexity of the X-Rays scattering phenomenon and the difficulty to model it accurately. In order to improve this accuracy, some authors [7] propose to model X-rays scattering image formation through a Monte-Carlo estimation code. The price of such an approach is a significant increase of computation time.



Sampling values of scattering + interpolation → estimation of scattered flux image (only the scattered flux is acquired behind the beamstop)

Beam stops radiograph acquisition.

Figure 3. Principle of scattered X-rays image estimation (left) and experimental set up (right).

In order to deal with this computation time problem, we have proposed [8] the API (Analytical Plus Indexation) approach based on an off-line calibration of scattered flux level and global shape combined to an analytical model adapting the scattered flux shape to the current acquisitions. The off-line calibration objects are chosen in order to represent the main materials composing the examined objects and to cover the full range of potential thicknesses. The analytical model is derived from the model describing first order Compton interaction within the examined object. This approach requires a significant off-line calibration step, however online acquisitions can be processed in real time. An example of scattering correction using the API method is shown in figure 4.
Mechanical and *numerical* approaches present a main difference in regards to the way to process the noise of scattered radiation. *Mechanical* approaches, by stopping the scattered photons, reduce the scattered radiation level as well as its noise. *Numerical* approaches enable to remove an image estimating scattered flux mean values while providing a corrected image with the total flux noise level. Therefore, it is sometimes advantageous to combine a light *mechanical* approach (large inter-space anti-scatter grid for instance), enabling to significantly reduce scattered radiation level without inducing heavy experimental constraints, to a complementary *numerical* correction approach.

At the price of some adaptations the above presented scattering correction approaches can be extended to the tomographic context. In order to ensure the focalization of the anti-scatter grid with the X-rays source during tomographic acquisition process, it is essential to make them interdependent. Due to the low frequency content of scattered images it is possible to limit the beam stops estimation to a few rotational angle and to interpolate between angles [9]. As for *numerical* approaches they can take profit of information provided by a first tomographic reconstruction by making the model of scattered radiation formation more representative. This is of special interest for the Monte-Carlo or the API approaches.

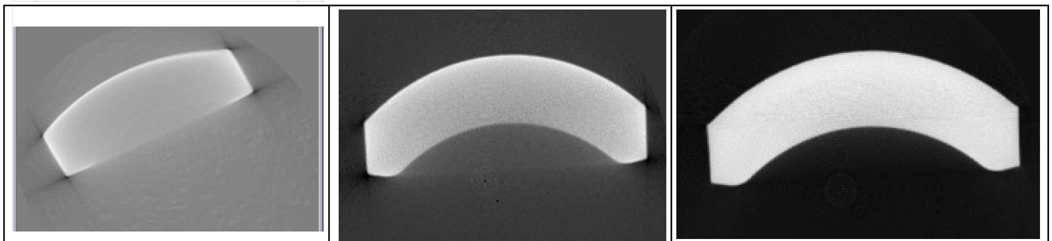
total flux acquisition	scattered flux estimation (API correction)	primary flux image

Figure 4. Example of API scattered radiation correction approach (Chest radiography).

4. Processing toward a quantitative value

4.1 Tomography and other 3D reconstruction techniques

The use of a digital detector allows successively acquired radiographs to be combined geometrically, as long as their relative positions are known. This corresponds to the tomographic technique, for a sufficient number of angles of acquisition view, or variants such as limited angle tomography, limited number of views tomography, and tomosynthesis (sometimes called planar tomography) [10].



Slice of a 3D tomographic reconstruction, without any correction	2D tomographic reconstruction of a mechanically collimated slice (lead collimator)	2D tomographic reconstruction of a collimated slice, after beam-hardening correction

Figure 5. Influence of scattering and beam-hardening on tomographic reconstruction.

All these techniques, in addition to require accurate geometrical calibration, need to correct the acquired values before the reconstruction process itself. As a mater of fact, radiographs values are assumed to be proportional to thickness in case of an homogeneous material (and to $\int \mu(l)\rho(l)dl$ otherwise). Thus corrections have to be applied, to get free from sensor non-linearities and beam-hardening effect. In case of 2D detector, scattered radiation should also be corrected (§3.2). If it is not, induced disturbances may be so strong in some configurations that the voxel distribution between object and background is no more possible, prohibiting reverse engineering for instance. Figures 5 and 6 present two experimental examples, illustrating the influence of beam-hardening and scattering in tomography, and the importance of their correction.

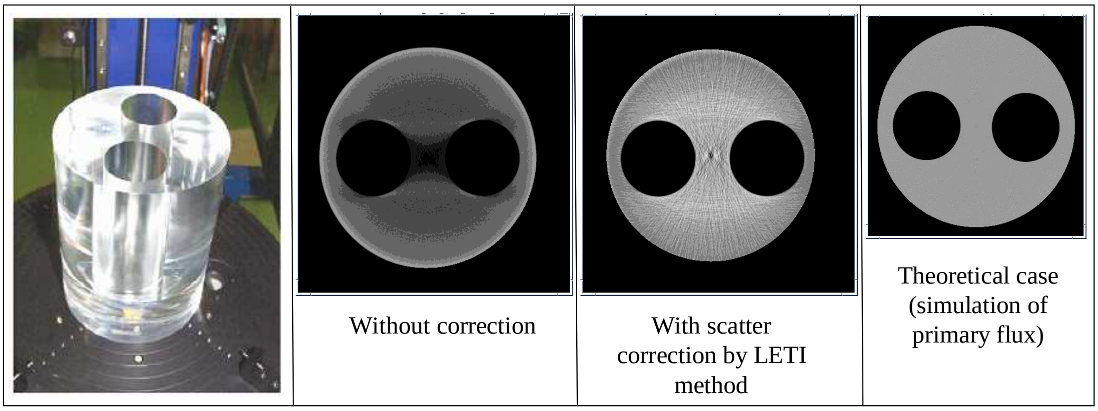


Figure 6. Influence of scattering and Scattering correction for tomographic reconstruction.

4.2. Dual-energies x-rays techniques

We have seen that even in the perfect case, a conventional radiograph provides a representation of the object in terms of attenuation coefficient μ (in tomographic mode), and of product of μ by material thickness (radiographic mode). This information is not sufficient to characterize precisely the object in terms of constituting materials. In the usual inspection energy range, the attenuation of X-ray radiation is a combination of two photon-matter interactions: photo-electric effect and Compton scattering one. The two interactions and their relative contribution to the total attenuation μ are energy dependant. Thus, measurements at two distinct energies should permit the separation of the attenuation into its basic components, which can be used to identify material, and finally to produce material-specific image. Another goal in dual-energies radiography could be to determine material thickness, or to produce more contrasted images.
Systems have been successively implemented with different modalities of dual-energy data acquisition. In dual exposure technique, two acquisitions are performed successively, the energy being switched by voltage tuning associated with the use of filters placed behind the generator. Single exposure technique permits to acquire the two radiographs simultaneously, with adapted detectors consisting in two receptor layers separated by an intermediate filter (sandwich-type detectors).
We do not detail here the dual-energy methods. They usually perform a decomposition onto a material basis, or provide a representation in (ρ, Z) (refer for instance to [11][12]). The design of a dual-energy system being multi-parametrical, its optimization has to be analyzed carefully [13]. Our purpose here is to stress on the degradations to take into account, in order to benefit effectively from dual-energy approach. Let us consider the method using a decomposition on a basis of two materials, well-adapted for a few of known-material object constituents (composite material for instance). The calibration is performed experimentally with step wedges of basis materials. A polynomial transform is estimated, it is then applicable to any pair of measurements at low and high energy (respectively m_{LE} and m_{HE}), providing equivalent thicknesses in basis materials (example of basis material decomposition in given in figure 7).

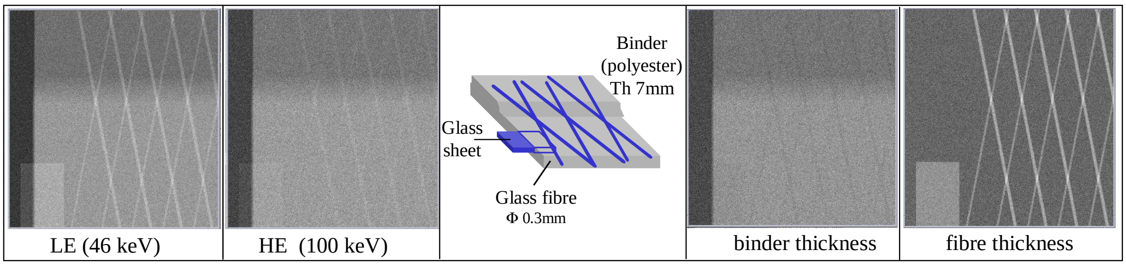


Figure 7. Decomposition of a composite material in binder and fibre image. Simulation study.

Let us consider the accuracy on the final result - thus the basis material equivalent thickness in case of the dual-material basis approach. It can be written in a simplified way: $\sigma^2 \propto \sigma^2(m_{LE}) + R^2\sigma^2(m_{HE})$, and depends on:

- the uncertainty on both low and high energy measurements (m_{LE}, m_{HE}),
- the separability of the basis, through R coefficient, which depends on the basis materials chosen, the type of detector, and the two energetic spectra.

For accurate values of the measurements m_{LE} and m_{HE} , noise (mainly the Poisson noise) should be reduced as far as possible. Additionally, to assume exact values, physical disturbances should be corrected. In fact, beam-hardening effect is corrected thanks to the experimental calibration. The main disturbance then comes from scattering, if a 2D detector is used. Such degradation has to be corrected for each acquisition, both during calibration and on-line process, especially if the studied materials are chemically close.

4.3 Energy selective process

Recent development in technologies of semiconductors as CdTe or CdZnTe have permitted the emergence of direct-conversion detectors. They can be energy selective, providing a classification of absorbed photons depending on their energy – and that for each pixel [14]. Narrow energy resolution is available today, allowing spectrometric quality. High speed electronics is required. Many problems still need to be improved, for instance charge sharing between neighbouring pixels. Even with an optimized detector, remaining imperfections should be modelled or at least understood to be corrected. The energy resolution can reach a few KeV, but the Point Spread Function is energy dependant and non symmetric, thus should be modelled carefully. If we shortly come back to the formalism of §2.2 of this paper, the measurement is composed of a values set: $\{N_i\}$, and $\{N^0{}_i\}$ for the full flux (with $N_i = N(E_i)$). The log-measurement defined previously could be computed for each energy channel i: $m_i = -Log(N_i / N^0{}_i)$, but it is too noisy and altered to be directly usable, and requires the inversion of the corresponding complex model. Such a detector can of course be used in dual-energy mode, by cumulating the spectral values in two wide channels, but this approach does not benefit totally of the capabilities of a multi-energy approach. Optimized methods should emerge soon, driven by the needs of the explosive detection application.

Conclusion

Digital radiography and tomography provide digital images or volumes that can be interpreted or combined numerically. But such interpretation or process generally assume some model of the relationship between the measurements and the physical quantitative parameters (linear attenuation, thickness, density, atomic number - for each constituent). The model is often simplified too much (extensive use of linear relationship between log-measurement and material thickness) and neglects a lot of disturbing phenomena. One solution consists of being closer to the model (for instance mechanical scattering elimination, or uniformity correction of the detector pixels). Another approach is to integrate explicitly the degradation or physical effect in the model, which becomes more complex, and to inverse it using prior information on the examined object and the acquisition device (case of numerical scattering correction or dual-energy decomposition). Once these precautions are taken, one can hope to get exact values of measurement. Additionally, if noise is acceptable compared to the accuracy required by the application, trustful quantitative imaging has been reached.

References

1. U.Zscherpel, U.Ewert, K.Bavendiek, “Possibilities and Limits of Digital Industrial Radiology”, Int. Symp. on Digital Industrial Radiology and CT, Lyon, June 2007.
2. U.Ewert, U.Zscherpel, K.Bavendiek, U.Heike, W.Meade, “New Digital Radiography Procedure Exceeds Film Sensitivity Considerably in Aerospace Applications”, Proc. 9th ECNDT, Berlin, September 2006.
3. J.Tabary, P.Hugonnard, F.Mathy, “SINDBAD: a realistic multi-purpose and scalable X-ray simulation tool for NDT applications”, Int. Symp. on DIR and CT, Lyon, June 2007.
4. N.Freud, P.Duvauchelle, S.Pistrui, JM.Letang, D.Babot, “Deterministic simulation of first-order scattering in virtual X-ray imaging”, Nucl.Inst.&Methods in Physics Research B, Vol 222, PP 285-300, july 2004.
5. J.Rinkel, L.Gerfault, F.Estève, J.M.Dinten, “Data pre-processing for quantification in tomography and radiography with a digital flat panel detector”, Proceedings of SPIE Medical Imaging 2006, Physics of Medical Imaging.
6. B.Ohnesorge, T.Flohr and K.Klingenbeck, "Efficient object scatter correction algorithm for third and fourth generation CT scanners", European Radiology, 9:563-569, 1999.
7. A.Colijn, W.Zbijewski and F.Beekman, "Monte Carlo based scatter correction for cone beam micro CT", Proceedings of the 7th Int.Conf. on Fully 3D Reconstruction in Radiology and Nuclear Medicine. Saint Malo, France, June 2003.
8. J.Rinkel, L.Gerfault, F.Estève and J-M.Dinten, "A new method for X-ray scatter correction: first assessment on a cone-beam CT experimental setup", accepted for publication in Physics in Medicine and Biology, 2007
9. R.Ning, X.Tang, and D.Conover, “X-ray scatter correction algorithm for cone beam CT imaging,” Medical Physics 31, pp. 1195–1202, 2004.
10. Journal of X-ray Science and Technology, Special Issue “Recent Development of X-ray CT”, Vol 12, No 4, 2004.
11. JM.Letang, N.Freud, G.Peix, “Optimal calibration via virtual X-ray imaging for dual-energy techniques: application to glass wool”, Proc.SPIE vol.5132, pp 422-32, 2003.
12. B.Heismann, J.Leppert, K.Stierstorfer, “Density and atomic number measurements with spectral x-ray attenuation method”, J.Applied Physics, Vol 94, No 3, 2073-79, aug.2003.
13. V.Rebuffel, JM.Dinten, “Dual-Energy X-Ray Imaging: Benefits and Limits”, Proc. 9th ECNDT, Berlin, September 2006.
14. T.Schulman, K.Spartiotis and All, “A photon counting CdTe gamma- and X-ray camera”, Nucl.Inst.&Methods in Physics Research A, Vol 550, PP 267-77, 2005.