X-RAY BACKSCATTER IMAGING WITH A NOVEL TWISTED SLIT COLLIMATOR

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Introduction

No one less than Wilhelm Conrad Röntgen himself discovered X-ray backscatter radiation first when exploring the properties of the new kind of radiation he had discovered [1]. However, the predominant application of X-rays remained with the common radiology. To a lesser extend, X-rays have found their way into spectroscopic methods such as fluorescence or diffraction analysis, but within a considerable low energy range that is of limited use in the radiological field. From an energy level of some 100 keV on, the Compton Effect increasingly contributes to the absorption of X-ray. Concomitantly, the associated scatter radiation also increases which is regarded as a nuisance since it decreases the object contrast and may even blur sharp contours. Due to the lower capability to absorb X-rays lighter material consisting of low-Z-elements such material is preferentially prone to the Compton scatter effect. This also means that, if the scattered radiation would be visualised, the image would be dominated by the light materials, quite vice versa to the radiograph itself. Since this kind of view would be desirable in some applications, there should be a way to make a virtue out of necessity, i.e. utilising the X-ray backscatter effect for imaging. By any means, such an approach has to take into account that the scattered radiation is not directed, i.e. distributed into any spatial direction. This leaves an insurmountable problem in the beginning, there are no optical devices available as with the visible light, at least in the energy range relevant for Compton scattering. As a matter of fact, this is the reason why radiology only is handling shadow images in the first place.

This problem has been resolved by two different approaches as indicated in **Figure 1**. Both show the advantage of having the source and the detecting system on the same side of the specimen, in difference to all other radiological methods. This allows interrogating large objects not allowing any access to the rear side. The first one is a scanning method that controls a highly collimated X-ray beam, collects all occurring backscatter radiation with highly sensitive large area detectors and compiles successively an image based on the beam direction and the detector responses [2]. This kind of backscatter imaging is commercially available [3]. In a more industrial environment when e.g. monitoring a production line, the backscatter technology has been introduced to scan either a constant stream of products [4] or large areas [5], but by scarifying the compilation of an image and replacing it by plain monitor signal. However, an image remains indispensable when assessing the overall integrity of an interrogated specimen. Alternatively, the whole image of an irradiated object might be viewed “at a glance” with some kind of camera. This reminds of a quasi-optical setup where the X-ray tube “illuminates” the sample. However, the lack of any optical device for X-rays leaves a pinhole camera like approach only (see [6] for further references). But the penetration property of X-rays requires sufficient shielding, that means several centimetres of heavy metal to achieve at least a contrast ratio better than 100. But this is contradicting to the requirements of an ideal pinhole camera where the diaphragm has to be as thin as possible. A solution of this problem is provided by the twisted slit collimator shown here that opens a sliding hole at different positions along a slit in a thick-walled diaphragm depending on the incident direction [7]. The advantage of an unilateral approach to the specimen and the property of showing preferentially low-Z-materials makes X-ray backscatter imaging also interesting for security applications [8].

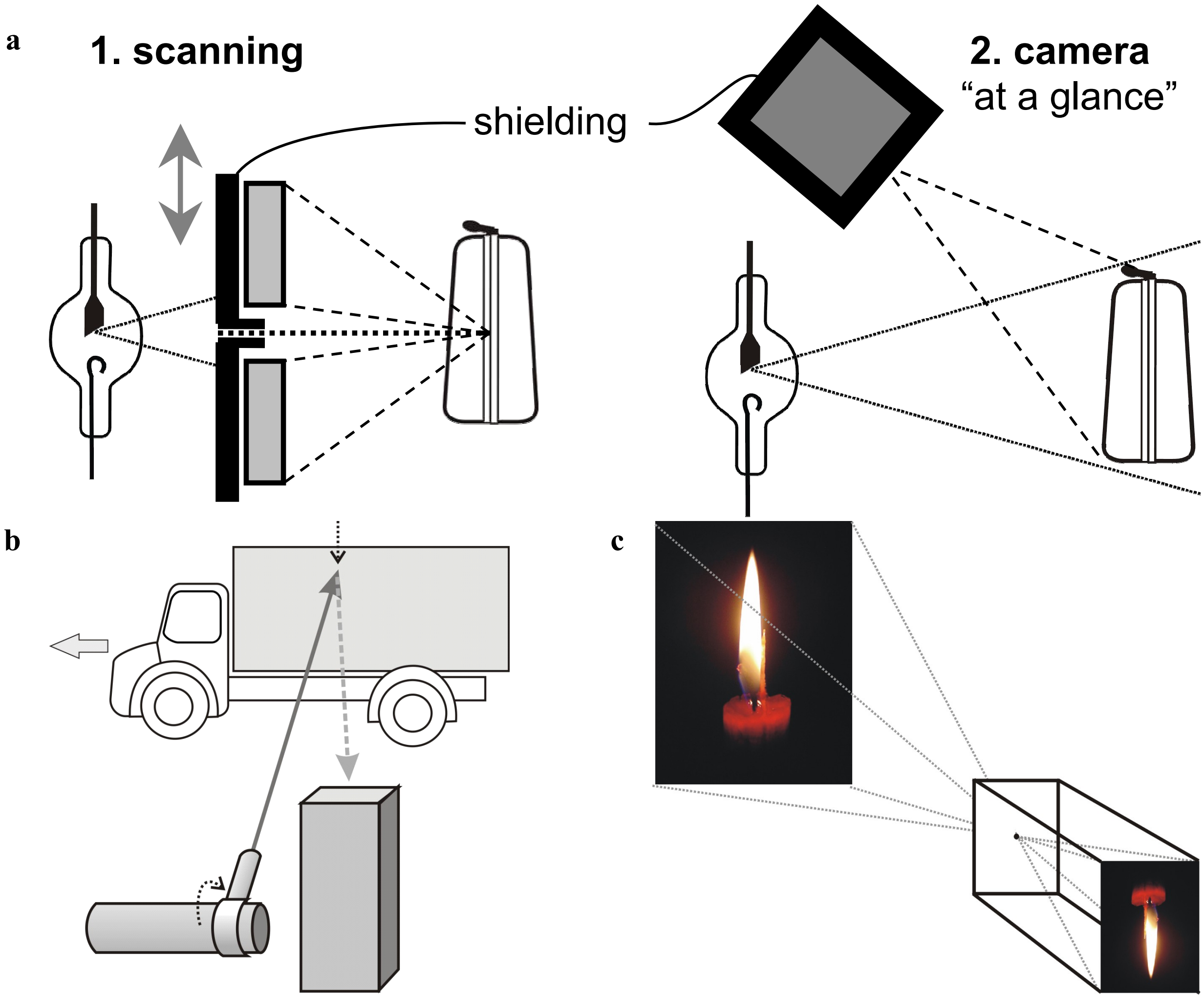


Figure 1: Principles of backscatter imaging: **a)** different approaches of scanning (left) and viewing per camera (right), **b)** vehicle scanning, **c)** pinhole camera principle

Results

The experimental setup is shown in **Figure 2** with the very preliminary version of the camera, the twisted slit collimator, the high energy X-ray tube used in many of the experiments and the functional principle of the twisted slit. A much smaller version of the camera made of tungsten and weighing significantly less than 50 kg is currently in development. The inside of the twisted slit lined with ruled surfaces (panel 2 **d**) allowing to passing only one selected beam at each position depending on the incident angle (panels 2 **e** and **f**). A cassette with a phosphor imaging plate as seen in the open camera of panel 2 **b** served as the image detector in all experiments up to now. It should be emphasised that this is an experimental version only.

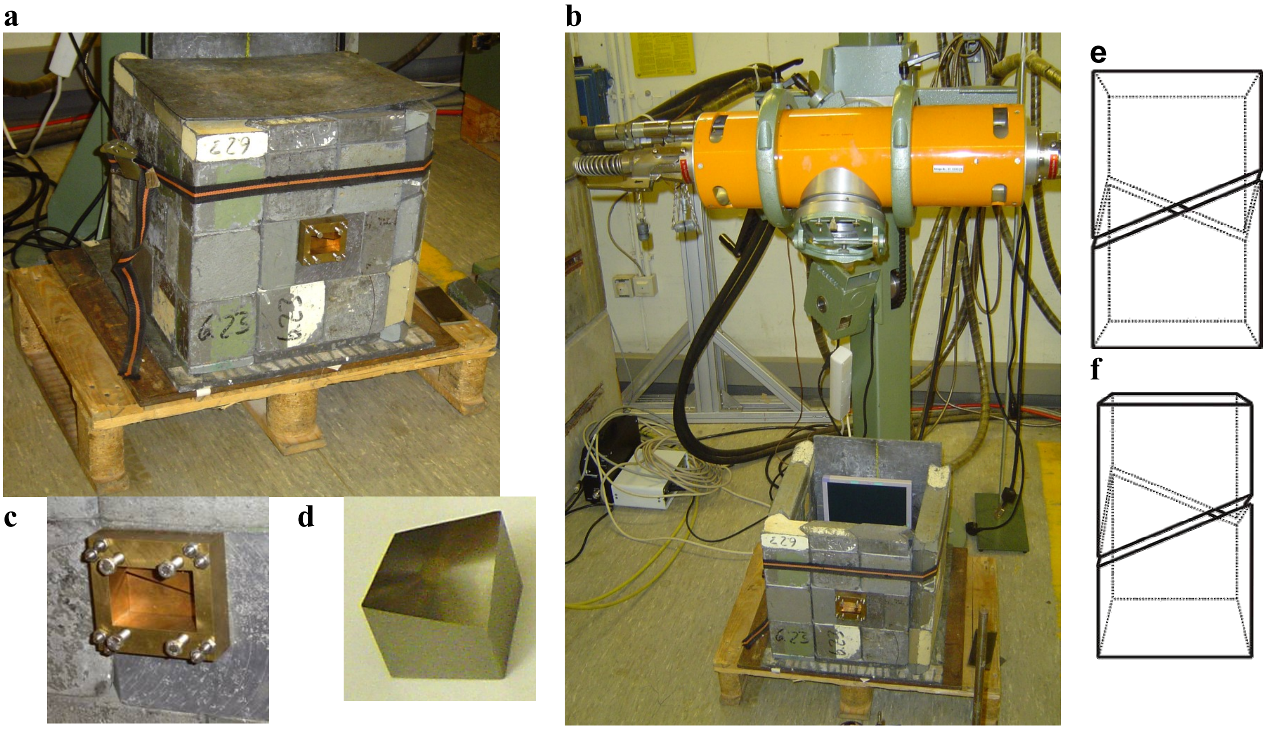


Figure 2: Experimental realisation of a camera for high energy radiation, **a)** camera made of lead bricks with twisted slit diaphragm in the front wall, **b)** whole setup with high energy X-ray tube, camera lid removed, cassette with a phosphor imaging plate inside, **c)** twisted slit collimator, **d)** inner surface of the collimator [7], **e)** beam passage through the collimator in perpendicular direction, **f)** beam passage from top.

The first step was the proof of principle with an efficiently backscattering object. For this purpose, a 100 ml Erlenmeyer flask was filled with water and sealed with a rubber bung (**Figure 3**). The specimens were placed in front of the camera shown in **Figure 2** so they were illuminated by the X-ray tube sloped from the top. As a first experiment, the minimum radiation energy was determined together with a second backscattering sample, a piece of marble (**Figure 3 a**). At a setting of 150 kV, the water phase and the rubber bung were clearly visible, the marble was less apparent (**b**). At a higher voltage of 200 kV, not only the marble was better visible but also the glass of the Erlenmeyer flask (**c**). As a consequence, this voltage was taken as a minimum for the following experiments. Any further increase of the voltage did not show any advantage in this kind of experimental setup. In a fast experiment, the specimen, in this case the Erlenmeyer flask with water only, was moved away from the camera from 45 cm to 67 cm (**d**). At the same time, the incident angle between the X-ray beam and the central axis of the camera inevitably became smaller. As a result, the glass of the flask disappeared in the image and the shape of the rubber bung was narrowed (**f**). This could mean that the incident angle of the radiation may have an influence on the backscatter radiation with this kind of samples, i.e. different materials and a round shape. At least, the position of the radiation source requires further investigation. A simple, but instructive experiment was designed to demonstrate the influence of absorbing parts within the specimen by attaching a lead character ("W") to the front of the flask (**g**). The silhouette of the character in the radiograph clearly indicated that the backscatter radiation from behind was absorbed by the lead.

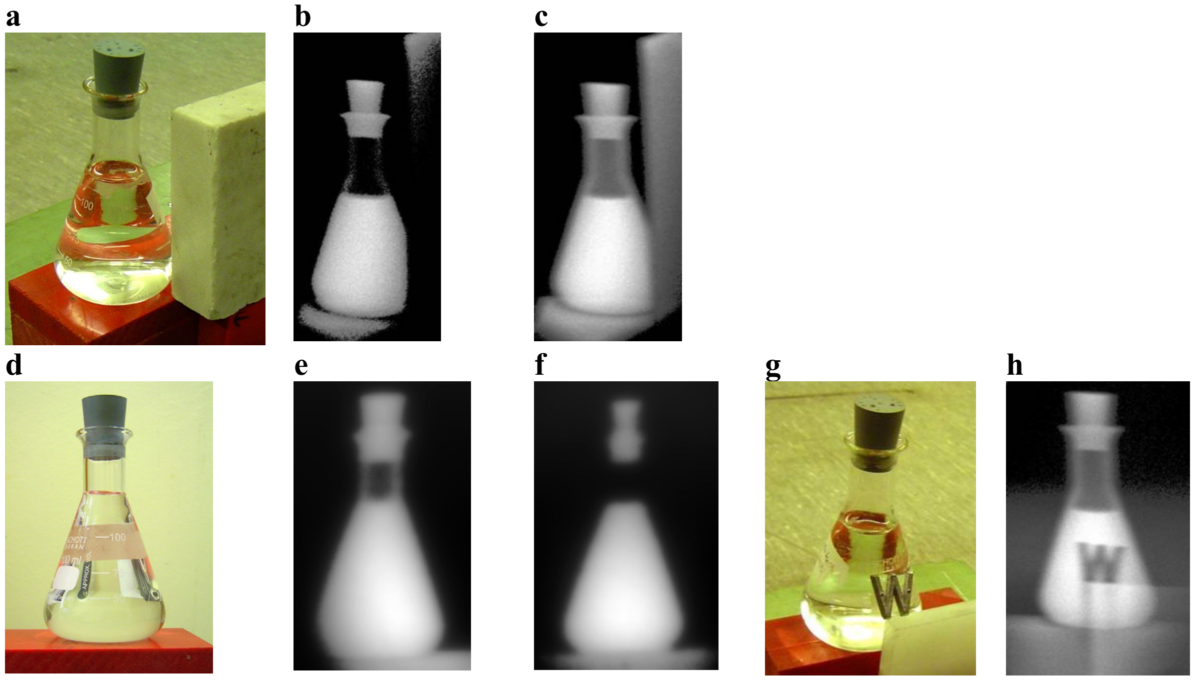


Figure 3: Backscatter studies with a simple object containing water and rubber, **a)** Erlenmeyer flask with water and rubber bung, **b)** backscatter image with 150 kV exposure, **c)** same with 200 kV exposure, **d)** specimen without surroundings, **e)** 45 cm distance from camera, irradiation from top, **f)** distance increased to 67 cm paralleled by lower incident angle of the X-ray beam, **g)** lead character attached to the front of the specimen, **h)** image with the silhouette of the absorbing lead character "W".

As a demonstration that this technology principally is applicable to security problems, this Erlenmeyer flask was hidden in a suitcase stuffed with all odds and ends (**Figure 4**). The panel **b** clearly showed that the flask was clearly visible within the packed suitcase. Some of the surrounding was also backscattering leaving some traces in the image.

Figure 4: Erlenmeyer flask filled with water and sealed with a rubber bung hidden in a packed suitcase, a) experimental setup, **b)** backscatter image of the hidden object encased by odds and ends.

In order to determine the contrast between different backscattering materials, a plate with a thick honeycomb structure was illuminated as before (**Figure 5**). This plate left a homogeneous plane covering the whole window of the slit collimator currently in use (**b**). In addition a vial with water and a rubber bung were attached to the plate from behind (**c**) and another vial to the front (**d**). All three attached objects were visible in the backscatter image (**e**), i.e. giving contrast to the overall backscattering plane, no matter if the additional part was affixed to the front or to the rear of the plate.

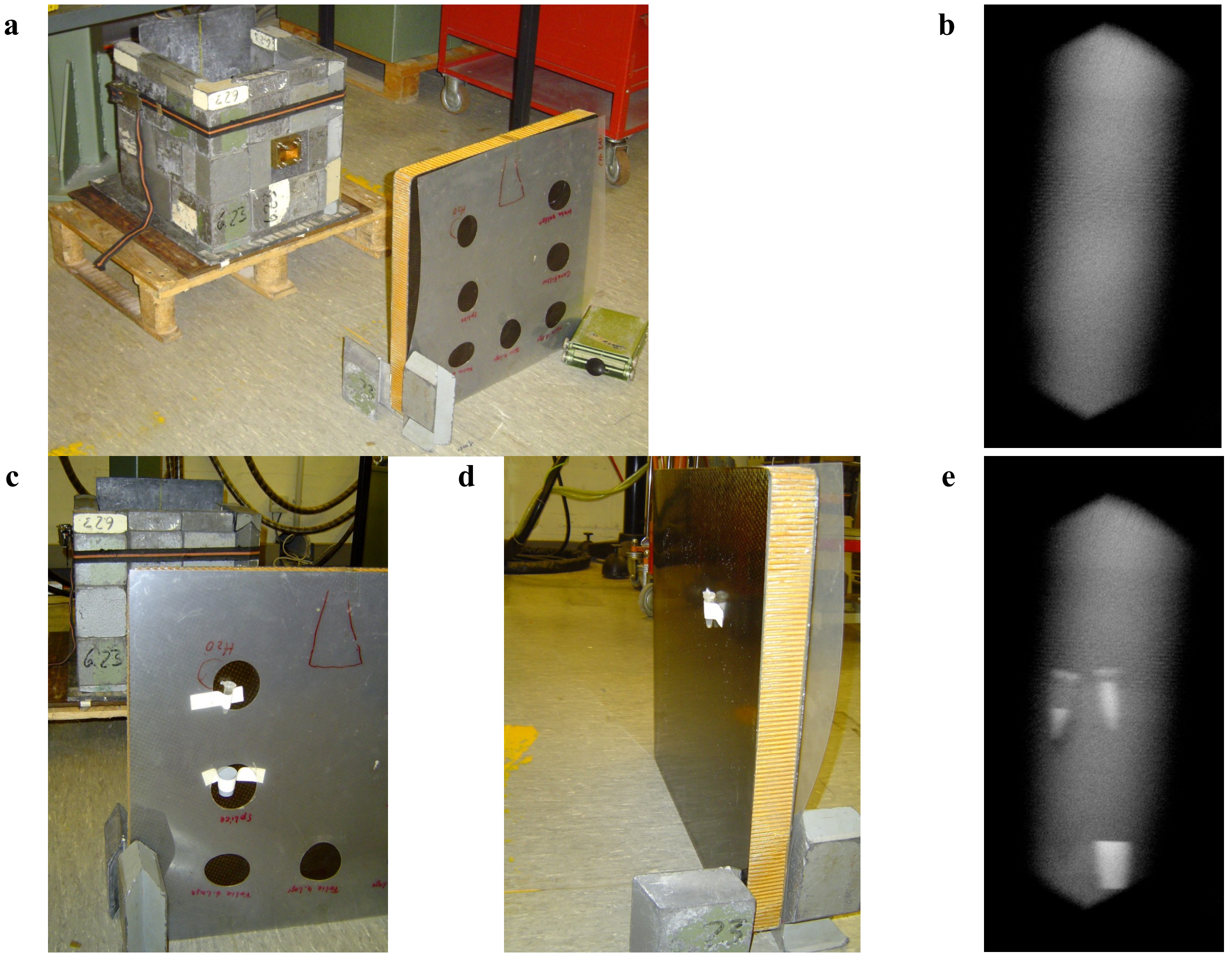


Figure 5: Objects on a backscattering matrix, **a)** honeycomb structured plate in front of the backscatter camera, **b)** backscatter image of the plate, **c)** further objects with backscattering properties attached behind the plate, **d)** another one to the font, **e)** backscatter image including all attachments.

Since the intrusion of water into honeycomb structures exhibits a serious problem particularly in the field of aviation, tiny water droplets were injected into such a structure with a syringe (**Figure 6**). These droplets were well visible in the backscatter image (**b**) and later confirmed by a conventional X-ray radiograph (**c**). In this context, the big advantage of the backscatter technology is the unilateral access to the object while any conventional radiological technology needs placing the image detector on the opposite side of the specimen. By this way, construction elements could be inspected in place if there is no chance to gain access to the rear.

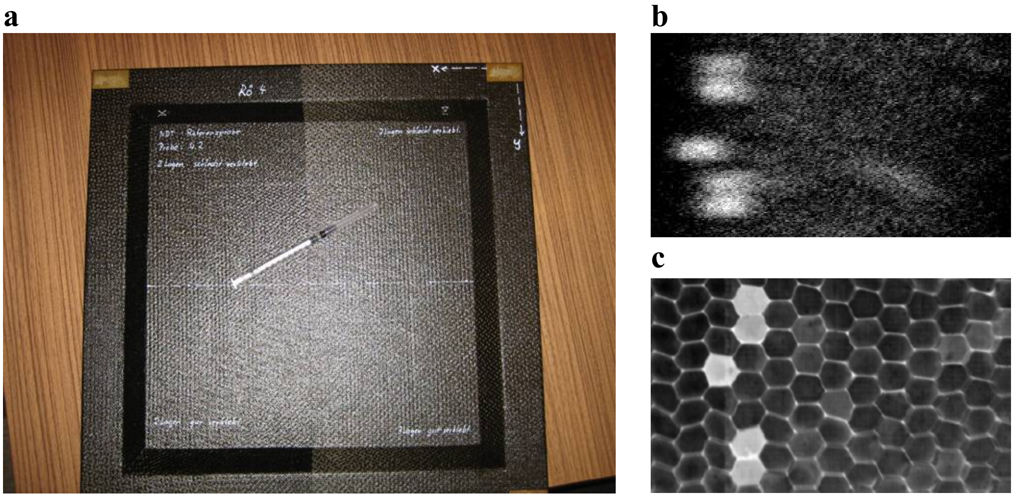


Figure 6: Water inclusion inside of a honeycomb structure, **a)** plate and syringe for injecting water droplets into the honeycomb cells beyond the surface, **b)** backscatter image showing the injected water droplets, **c)** confirmation by conventional X-ray.

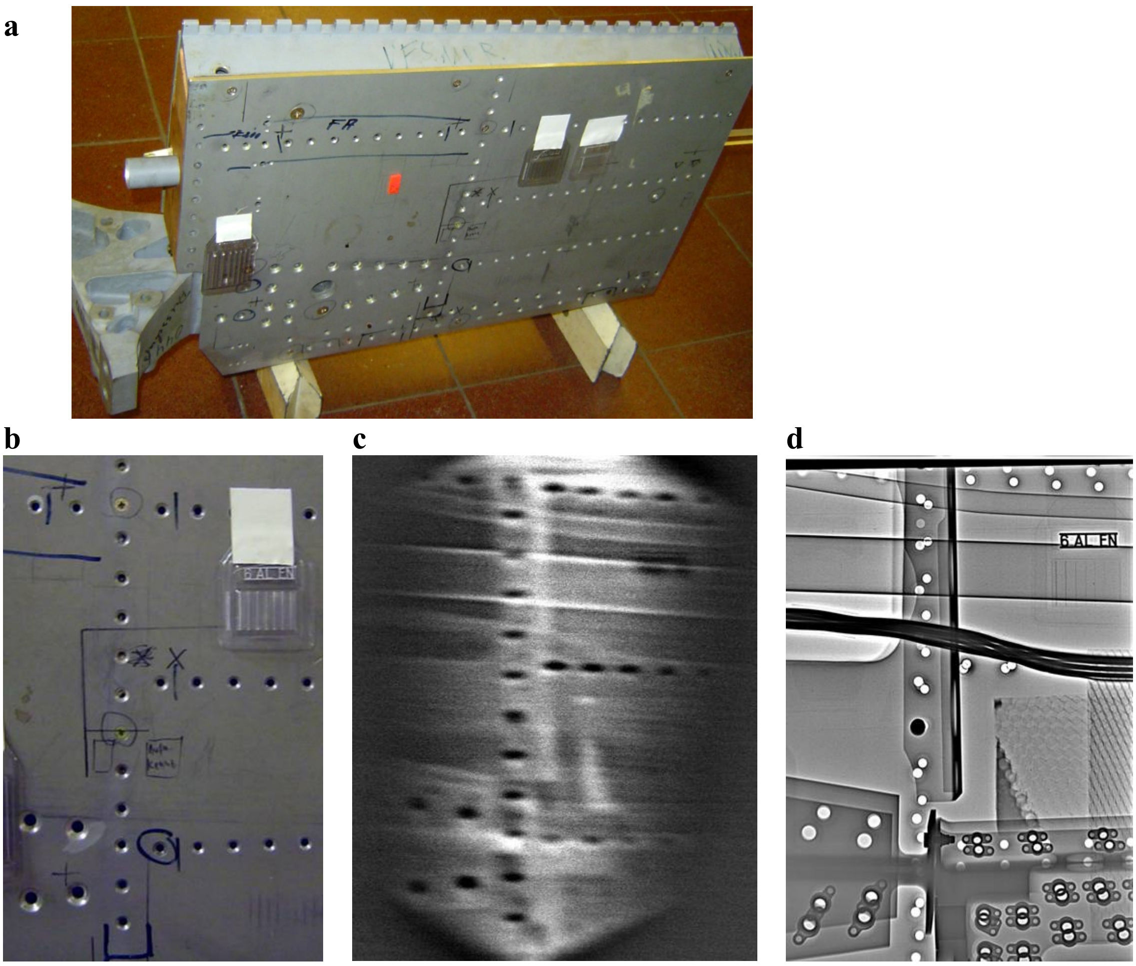


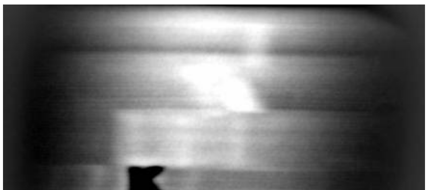
Figure 7: Inspection of an aeronautic component (flap model), **a)** whole model, **b)** view onto the surface, **c)** backscatter image showing details underneath the surface, **d)** conventional X-ray as a reference.

A more complex sample exhibits a part from the aircraft industry, a flap model of an airplane wing with components in the inside symbolising certain testing situations (**Figure 7**). The area to be viewed is magnified in the panel **b**. All major details appearing in the reference X-ray radiograph (**d**) can be seen in the backscatter image (**c**), but in a different way. The absorbing inclusion in the piece of a honeycomb plate in the centre clearly showed a backscattering property, as well as the tubes in the upper part. The cable in the centre makes a difference, the backscatter technology only shows the insulation, but not the metallic core which predominates in the conventional image. Remarkably, the lead characters of the image quality indicator in the upper right appeared as a shadow in the backscatter image.

a

b

c



d

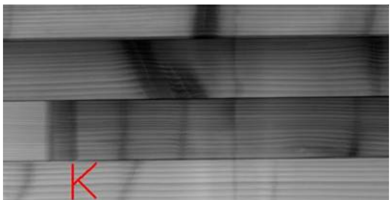


Figure 8: Internal structures of timber, **a)** experimental setup with camera (lid removed) and X-ray tube in close vicinity, **b)** surface with attached lead marks, **c)** backscatter image, **d)** conventional X-ray, the position of the previously affixed lead mark is indicated in red.

Backscatter technologies could be also of benefit in other areas as shown with a voluminous glulam girder (**Figure 8**). In this setup, the X-ray source was brought closer to the object as shown in panel **a**. It was directed towards the lead character "K" in the centre of the image (**b**). The backscatter image (**c**) shows all the internal structures not necessarily visible on the surface but present in a conventional X-ray radiograph (**d**) where the position of the lead character is marked in red. This example should demonstrate again the capability of a radiological approach with unilateral access only if the part to be inspected is firmly built into a larger construction.

Discussion

The twisted slit collimator efficiently resolved the problem of providing a pinhole like camera system for high energy radiation. In a proof of principle, the capability was demonstrated to produce real X-ray backscatter images. Since this technology requires large radiation dosages, it certainly may remain restricted to technical applications. It further could be shown that even complex parts could be inspected needing an unilateral access only. By this way, components firmly built into larger constructions could be interrogated on site. The property of backscattering highlighting light materials makes this technology also applicable for security purposes. In brief, X-ray backscatter imaging works with the novel twisted slit collimator.

Currently, the practical developments promise a significantly smaller device capable for mobile applications. The biggest advantage over existing scanning systems with a fixed geometry is the free choice of the angle of the incident radiation that may open numerous variations to visualise selected parts or areas of an interrogated object.

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