Improving the quality of radiographic images acquired with conical radiation beams through divergence correction and filtering

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Abstract. Earlier works have shown the feasibility to correct the deformation of the attenuation map in radiographs acquired with conical radiation beams provided that the inspected object could be expressed into analytical geometry terms. This correction reduces the contribution of the main object in the radiograph, allowing thus the visualization of its otherwise concealed heterogeneities. However, the non-punctual character of the source demanded a cumbersome trial-and-error approach in order to determine the proper correction parameters for the algorithm. Within this frame, this work addresses the improvement of radiographs of specially tailored test-objects acquired with a conical beam through correction of its divergence by using the information contained in the image itself. The corrected images have afterwards undergone a filtration in the frequency domain aiming at the reduction of statistical fluctuation and noise by using a 2D Fourier transform. All radiographs have been acquired using ¹⁶⁵Dy and ¹⁹⁸Au gamma-ray sources produced at the Argonauta research reactor in Instituto de Engenharia Nuclear - CNEN, and an X-ray sensitive imaging plate as detector. The processed images exhibit features otherwise invisible in the original ones. Their processing by conventional histogram equalization carried out for comparison purposes did not succeed to detect those features.

1. Introduction
The well-known historic radiograph Hand mit Ringen (Hand with rings) reproduced in figure 1, taken with the newly discovered X-rays caused a high impact in Science because for the first time it was possible to visualize the bones of an alive creature without any intrusive procedure. However, the very 1st radiograph made by Röntgen and shown to his colleagues was a set of weights in a box [1], i.e., a potential industrial application rather than a medical one. In both cases, the new radiation made visible high attenuating materials enclosed inside low attenuating ones. If Röntgen had taken samples with an inverse configuration - a creature with an exoskeleton, instead of his wife’s hand for instance - then the application of X-rays in Medicine could most likely be delayed. Indeed, the favorable ratio
between the attenuation coefficients for bones and flesh - surpassing 5 for soft X-rays [2] - allowed Röntgen to exhibit a dramatic picture at the Physik Institut of the University of Freiburg on 1 January, 1896. As for the industrial application, its spreading as a non-destructive assay had to wait until the advent of high voltage tubes - 100 kV in 1913, 200 kV in 1922 and 1000 kV in 1931 - and of radioisotopes in 1946. Further details can be found elsewhere [3].

An inverse situation, i.e., the visualization of a low attenuating stuff enclosed within a high attenuating one, is a much more difficult task due to the feeble achievable contrast resolution, an essential parameter, as it rules the capability of the human eye to differentiate neighbor pixels as individual ones. This constraint is even strengthened when a broad angle conical beam is employed, for the apparent thickness increases with the distance between the point where the radiation hits the detector and that one directly beneath the source. This variable thickness not only deforms the attenuation map, but concomitantly increases the dynamic range of the image, limiting its further stretching, precluding thus the improvement of the contrast.

Some techniques have been developed [4-9] to overcome this hindrance but they work based upon a blind approach, i.e., using the information provided solely by the image itself. Recent works [10-11] perform their tasks by entering some physical properties of the object being radiographed and their related geometrical arrangements. Due to these utterly different approaches, [10-11] would perform better than [4-9] but the proper information should be provided as above mentioned, otherwise they couldn’t work at all.

Figure 1. X-ray radiograph made by Wilhelm Röntgen in 1895.

The ratio of some linear attenuation coefficients are shown for reference.

This work proposes an algorithm to unveil feeble attenuating structures or heterogeneities enclosed inside high attenuating objects inspected by radiography employing conical beams. Unlike [10-11] which require a detailed description of the object, its attenuation properties, and geometrical arrangement, the proposed algorithm extracts the necessary information from the image itself. But, unlike the blind techniques, it is assumed that the image has been acquired with a conical beam and that the main object is a plate or a pipe. Besides the correction of beam attenuation and divergence, the radiographs in this work, acquired with \(^{165}\text{Dy}\) and \(^{198}\text{Au}\) have undergone a filtering in the frequency domain by using a Fourier transform aiming at the reduction of noise and statistical fluctuation. The grounds for this expectation are the fine results obtained in [10] for images generated without noise.
2. Methodology
Since this work addresses the detection of feeble attenuating structures concealed into high attenuating ones, two test-objects matching this condition, as sketched in figure 2, which have been earlier manufactured [11] have been radiographed with 95 and 412 keV gamma-rays from the reactor-produced $^{165}$Dy and $^{198}$Au respectively.

The test-object Aluminum Plate comprised of thin aluminum strips sandwiched between 3 mm thick aluminum plates has been exposed to a 3.89x10$^8$ Bq $^{165}$Dy source. In this object, the thinnest 0.1 mm strips add circa 0.46% to the total attenuation factor. As for the Iron Pipe exposed to a 6.38 x10$^7$ Bq $^{198}$Au source, the thinnest 1 mm-thick strip adds 2.53% to that factor.

Since it is expected that thinner and farther strips from the source would be hardly detectable due to the higher attenuation factors caused by the main object, the strips have been distributed in such a way to cover a fair range of thicknesses of Al strips along the plate.

![Figure 2](image_url)

**Figure 2.** Geometrical arrangement used to acquire the radiographs of the specially designed test-objects with gamma-ray sources and an X-ray sensitive imaging plate.

All radiographs have been taken with an X-ray sensitive Imaging Plate - IP, and developed with a 0.050 mm resolution reader. Typical exposure times - ranging from a couple of hours or days for the Aluminum Plate and Iron Pipe respectively - have to be lengthened due to the limited achievable source activity produced under a 2.23x10$^5$ n.cm$^{-2}$.s$^{-1}$ neutron flux. The expected lower efficiency of an X-ray IP when operating with higher energies certainly contributes as well to a longer exposure time, which has been chosen after some trials.

After the approach adopted in this work, the radiographs undergo a correction of divergence and attenuation with an algorithm specifically developed to perform this task, followed by a filtering in frequency domain. Both procedures have been embedded into a program written in Fortran 90 language capable to plot the images as well.

2.1. Beam divergence and attenuation correction
Unlike a parallel beam, which casts an undisturbed attenuation map of the inspected object on a 2D detector, a divergent beam not only changes this map, but also causes a secondary effect, namely an increase in the dynamic range of the acquired image. This increase precludes a further stretching of the dynamic range, making thus impossible to visualize low attenuating features, for they would be overwhelmed by the abnormally high - and wrong - attenuating factors of the main object. Indeed, the farther an object region from the source, the higher its apparent attenuation factor, since the beam would have to travel a greater distance both across the object and the air. Earlier works [10-11] suggested techniques to correct those phenomena, but they required a tedious and cumbersome trial-and-error procedure to determine the proper algorithm parameters.

This work proposes a novel algorithm which performs an automatic correction of the disturbed image by using the existent, although concealed, information contained in the image itself. It’s based
on the flattening of the longitudinal and transversal pixel intensity profiles, simulating thus, that one which would be exhibited by a radiograph taken with a parallel beam.

A longitudinal profile, as shown in figure 3, comprised by a sequence of transversal ones, has a convex shape with a maximum occurring at the point beneath the source. In the scheme showing the construction of the longitudinal profile as a sequence of transversal ones, they are depicted as smooth curves, but actually they are modulated by the heterogeneities eventually present in the main object. The baseline of the each transversal profile raises as it get closer to the source due to the higher flux causing a bending in the longitudinal profile. Due to the same reason this profile is broader at the central region.

In order to simulate a radiograph acquired with a parallel beam, both profiles should be corrected until they become flat, preserving however the modulation. This flattening requires a different approach for each profile type, but both demand that the source should be positioned in the vertical line passing through the center of the object to assure the symmetry required by the correction algorithm. The flattening of the longitudinal profile is carried out in two steps: first, the baseline of each transversal profile - the line connecting the pixel intensities occurring at its extremes - is raised to the same level of the baseline of the central profile, carrying with it all pixel intensities mounted on it, preserving thus the net pixel intensities with regard to the base line.

![Figure 3](image3.png)

**Figure 3.** Typical sketch of a 2D pixel intensity profile and the procedure employed to correct its longitudinal component, comprised by a sequence of transversal ones side by side.

In the second step, all net pixel intensities measured from the henceforth common baseline are normalized with regard to the maximum occurring at the point beneath the source. After this process all transversal profiles would be enclosed between the common baseline and the upper line defined by the maximum pixel intensity, and the image should exhibit a homogeneous background along the longitudinal direction. It should be stressed that this homogeneity doesn’t mean a loss of information of the eventual fine inner structure of the object, since it remains as irregularities modulating each transversal profile.

After this flattening, the image would still exhibit shadows at the bottom and upper regions, due to the convex shape of the transversal profiles which should be as well flattened without loss of information. This task is accomplished by rectification of the profile in such a way that it becomes a horizontal straight line. As each profile is unique - and unknown - a polynomial is fitted to each of them in order to obtain their individual approximate shape. The gap between the polynomial and the upper line at each point along the transversal profile is added to the pixel intensity at that point rectifying thus its value. In this rectification process the net pixel intensities mounted on the polynomial are raised to the upper line, flattening hence the profiles but keeping the information.

The original radiograph of the test-object Iron Pipe has a longitudinal profile with a large dynamic range \( D \) reaching 30k as shown in figure 4. Both graphs refer to the same image, but different domains for the sake of illustration. The zoomed graph on the right shows the rectification of 5 transversal profiles conducted by a \( 3^{rd} \) degree polynomial.
As a tiff-type image, the pixel intensity is enclosed within the range 0 - 65,535. Hence, the high $D$ value steals almost 50% of the potential to improve the image through stretching of the dynamic range.

A longitudinal correction yields a profile with the narrower - and better - value $D_1$, where the dynamic range has been reduced to about 20k. A further rectification of the transversal profiles produces an even narrower dynamic range $D_2$ limited to 5k, or about 8% of the total dynamic range for a tiff image. When this shallow profile undergoes a stretching of its dynamic range, the feeble attenuating features emerges from a - now diminished - low background.

2.2. Filtration of high frequencies

As shown in the scheme of figure 5, the 2nd step carried out in this work to improve the quality of the radiographic images involves the filtering in the frequency domain of their Fourier transforms, aiming at the reduction of high frequencies related to statistical fluctuation and noise. Since the Fourier transform is a widely known technique and the scheme is fairly self-explaining no further details are given.

For this purpose, a Butterworth low-pass filter, $B(u,v)$, is applied to the discrete Fourier transform $F(u,v)$, yielding the filtered transform $C(u,v)$. Examples of Fourier spectra for both transforms, as well as a map of the filter are shown for reference. The parameter $L_0$ - distance of a point to the center of the plane of frequencies defined as a fraction $\alpha$ of the semi-height of this plane - rules the frequency cutoff, while $n$ specifies the abruptness of this cut.

High $n$-values would make the Butterworth filter to perform more like an ideal low-pass filter. Both parameters should be adequately chosen by the customer, a known matter of concern in the field of frequency filtering. A value $n=1$ has been chosen in this work because for higher values some artifacts arise as white shadows at the borders of the image. Hence, filters with a steeper roll-off, such as Chebyshev for instance have not been tested. The value of $\alpha$ has been chosen by applying a Butterworth high-pass filter to the filtering procedure and watching its impact on the final image. As edges - due to their steep contrast change - contain high frequency components, they have been chosen as an indicator of the point where high frequencies do not contribute to their formation anymore, but only would add noise to the image. The results in figure 6 show that beyond about 0.7 no insert is visible any more. This means that the edges of the inserts have no significant frequency component above this point, and thus, all of them may be discarded. It may also be noticed that, as expected, the granulometry becomes finer as $\alpha$ increases. The visually estimated minimum $\alpha$-value of 0.7 has been
cross-checked by carrying out filtrations around this value with a Butterworth low-pass filter as later shown in the section Results.

\[
F(u, v) = \frac{1}{MN} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) e^{-j2\pi \left(\frac{ux}{M} + \frac{vy}{N}\right)}
\]

Once the minimum $\alpha$-value is evaluated, it is used in the Butterworth low-pass-filter, and the final image is obtained after the Fourier inverse transform $I(x, y)$.

**Figure 5.** Scheme of the applied filtration procedure in the frequency domain by using a 2D Fourier transform and a low-pass Butterworth filter.
Filtered radiographs, acquired with 95 keV gamma-rays from $^{165}$Dy, of the plate used as test-object. Labels refer to the different $\alpha$-values employed to define the high-pass Butterworth filter for $n=1$.

### 3. Results

The final images for the test-objects, after they have undergone beam divergence correction and filtration, are summarized in figure 7. Combined effects of beam divergence and the related increased thickness emerge as a diffuse brighter spot at the center of the radiographs, i.e., directly beneath the source used to acquire them, surrounded by a darker region.

**Figure 6.** Filtered radiographs, acquired with 95 keV gamma-rays from $^{165}$Dy, of the plate used as test-object. Labels refer to the different $\alpha$-values employed to define the high-pass Butterworth filter for $n=1$.

**Figure 7.** Original and processed radiographs. The *correction* process changes substantially the images, but a further *filtration* only slightly improves them. A value $n=1$ has been used for the low-pass Butterworth filter. Images from [11] and an equalized histogram are shown for comparison.
The consequent wide dynamic range makes difficult or even impossible to detect feeble differences between close attenuation factors. This drawback has been reversed by the correction algorithm allowing the retrieving of the image that would be obtained if the beam were parallel.

A substantial improvement can be observed between original and corrected the images. Indeed, the thin aluminium strips in both test-objects - hardly observable in the original image - can be readily identified in the corrected ones, except for the thinnest 0.1 mm-thick located near the edge of the Aluminium Plate. For this test-object, when exposed to the 95 keV gamma-rays from $^{165}$Dy this strip adds 0.46% to the total attenuation factor. As for the Iron Pipe exposed to 412 keV gamma-rays from $^{198}$Au, the thinnest aluminum strip, 1 mm thick, adds 2.53% to the maximum attenuation factor.

It can be observed that a filtration of the previously corrected images only causes a slight improvement of their qualities, even so, for $\alpha$-values greater than 0.5. Such an outcome is consistent with the results shown in figure 6 where values below 0.7 should be discarded in order to avoid the elimination of frequencies having significant amplitude. Indeed, the design of both test-objects incorporates inserts with sharp edges, which require high frequencies for their proper representation in the frequency domain. Therefore, a low $\alpha$-value eliminates them causing an image blurring.

The original images have also undergone a treatment with the conventional histogram equalization - a technique for contrast enhancement - for the sake of comparison with the developed algorithm. It can be observed that the achieved improvement is very poor.

4. Conclusion
An algorithm to correct the attenuation map of radiographs acquired with conical beams has been developed and its soundness and performance evaluated. It is based on the fact that for radiographs taken with conical beams, parameters such as geometrical arrangement and attenuation coefficients are concealed and embedded in the attenuation map of the final images themselves. Hence, although they cannot be easily retrieved, their overall impact can be reversed in order to emulate an image obtained with a parallel beam.

For this purpose gamma-ray radiographs of two specially tailored test-objects have been obtained with 95 and 412 keV gamma-rays from the reactor-produced isotopes $^{165}$Dy and $^{198}$Au respectively. The corrected images have undergone a filtration in the frequency domain after the 2D Fourier transform approach aiming at their further improvement. The corrected images were remarkably improved exhibiting features otherwise concealed in the original ones. A filtration nevertheless solely improved their quality very slightly, which emerges as a reduction of the granulometry. Both processes have been embedded into a Fortran 90 program specially written to deal with the images and to plot them as well.

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