High Accuracy X-Ray Dual-Energy Experiments and Non-Rotational Tomography Algorithm for Explosives Detection Technique in Luggage Control

Mihai Iovea [1], Marian Neagu [1], Octavian G. Duliu [2], Gabriela Mateiasi [3]

[1] Accent Pro 2000, Ltd (www.accent.ro), 1 Nerva Traian Str., K6, 031041 Bucharest, Romania, phone: +4074 518 2660, e-mail: office@accent.ro
[2] University of Bucharest, Department of Atomic and Nuclear Physics, P.O. Box MG-11, 077125 Bucharest, Romania, e-mail: duliu@b.astral.ro
[3] The Politehnica University, Bucharest, 313, Splaiul Independentei, 060032, Bucharest, Romania, e-mail: miovea@pcnet.ro

Abstract
The experiments using our laboratory dual-energy X-Ray Radioscopy/Tomography equipment reveals an accuracy better than 2% in measuring $Z_{effective}$ and around 5% in the weight measurement. In "dual-energy" X-ray tomography (CT) accuracy better than 3% in measuring $Z_{effective}$ and Density of scanned objects and less than 2% accuracy in materials identification (using also the attenuation coefficients comparison) has been obtained. Due too the high accuracy of both methods is it feasible to discriminate between water (or other typical standard organic materials found in baggage) and the liquid explosives. Also, by applying both methods successively, a much lower false positive alarm rate could be reached. Both techniques have been successfully checked using simulated explosives samples (manufactured by *X-ray NESTT* Co.- USA) having known values of $Z_{effective}$ and Density. Further, we present the simulated encouraging results of a new iterative reconstruction algorithm intended for replacing the actual rotational-based CT scanning method with a linear movement scan. The new algorithm is a combination of a classical ART with a fast ray-tracing algorithm for evaluation of rays' pixels contribution. The main goal of the algorithm is to develop a new X-Ray CT machine for luggage control within the size and the cost of the actual standard X-Ray screening devices.

Keywords: Dual-energy, CT, radioscopy, Effective Atomic number, luggage, screening, explosive detection

1. Introduction

Fig. 1 – The X-Ray dual-energy Radioscopy and Tomography laboratory equipment

The X-ray Digital Radiography (**DR**) and Computed Tomography (**CT**) domains destined for luggage threats detections has been substantially developed within the last years due to the increase of the security measures after the events from 9/11 and after the series of terrorist attacks in Europe. The equipments have become more faster, offering a better resolution images, are now largely using the dual-energy technique for identifying the main class of materials (organic, non-organic and metallic) but only a few of the manufacturers have been approached directly the matter of accurate identification of the materials. Many of equipments are using a "simplified" dual-energy method for presenting coloured images of the scanned objects, the all organic substances being represented with a distinctive colour and the final decision still is strongly based on the operator's experience. Also, the CT for luggage control, that is widely manufactured and used in USA, despite its good ability in automatically measurement of the Atomic Effective Number (**Z_{eff}**) and the **Density** for the scanned materials, still has a big size, is very expensive and has a throughput relatively small.

Table 1 - Non-Hazardous Explosives Simulants for Security Training and Testing (NESTT) used in DR and CT tests

X-Ray Simulants Compared to Explosives and Powders

Explosive	Major Ingredients	Approximate Density (g/cc)	Approximate Average Effective Atomic Number (Z)
XM-08-X	OUO	0.7	7.5
Smokeless Powders	nitrocellulose	0.5 to 1.0	7.4 to 7.8
ANFO	ammonium nitrate	0.9	7.4
XM-07-X	OUO	1.03	13.8
XM-09GE-X	OUO	1.12	7.2
Black Powder	potassium nitrate	1.2	14.2
Commercial Slurries and Emulsions	ammonium nitrate (*higher Z nitrates*)	1.1 to 1.5	7.3 to 10.0
XM-10GE-X	OUO	1.32	8.3
XM-06-X	OUO	1.37	9.2
XM-11GE-X	OUO	1.44	9.8
Dynamites	nitroglycerine sodium nitrate (*higher Z nitrates*)	1.3 to 1.6	7.3 to 9.0
XM-05-X	OUO	1.45	7.3
Detasheet	PETN	1.47	7.2
SEMTEX H	RDX	1.47	7.1
SEMTEX 1A	PETN	1.47	7.2
XM-04-X1	OUO	1.47	7.3
TNT	TNT	1.51	7.1
XM-02-X1	OUO	1.50	7.1
Comp C-4	RDX	1.58	7.1
XM-01AL-X	OUO	1.60	9.3
Tritonal	TNT	1.65	9.1
XM-03-X	OUO	1.68	7.2
XM-15-X	OUO	1.70	7.2
Comp B	RDX	1.71	7.2
Octol	HMX	1.80	7.2

Like an attempt for improving the above drawbacks, in the last years we made some investigations for increasing the accuracy in **Z_{eff}** and **Density** measurement by dual-energy **DR** and **CT** (1-6) and we made preliminary investigation for developing a non-rotational scanning algorithm for tomography, by translating the object between X-ray tube and the line detectors. The new algorithm has been preliminary tested only by computer simulation (7) and now we are presenting the first laboratory experiments. Both new techniques have been developed and checked using our dual-energy X-ray laboratory equipment, destined for Radioscopy and Tomography experiments, presented in **Fig. 1**.

2. Dual-energy DR and CT experiments

Luggage control for explosives detection, from the point of view of dual-energy **DR** investigation, requires to have enough accuracy in measuring **Zeff** for separating explosives from other domestic materials that has almost the same **Zeff,** as presented in **Table 1**. Most of the luggage **DR** screening devices that are now in use are only "colouring" the baggage content or poorly measuring **Zeff**. This is the reason why they cannot distinguish between two very closed **Zeff** materials, reaching in this way high rate of false positive alarms. For dual-energy **CT** investigation, the explosives detection is in a much better situation because both parameters **Zeff** and **Density** could be measured**,** reducing in this way substantially the false positive alarms rate. But, even in this advantageous situation, is not so simple to do it without having a good accuracy in measurement of **Zeff** and **Density**, still being so many domestic materials that almost overlaps with explosives **Zeff** and **Density** values, as seen in **Figure 2**.

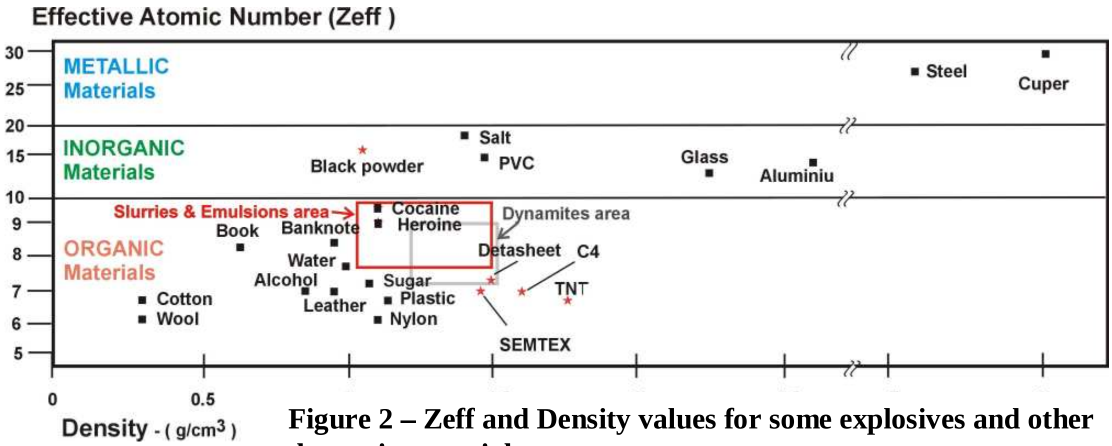

Figure 2 – Zeff and Density values for some explosives and other domestic materials

Therefore, the improvement of **Zeff** and **Density** measurement is a must for improving the explosives detection by X-Ray **DR** and **CT** and we made the further developments in this direction. We canalize our efforts in improving the dual-energy **DR** and **CT** techniques and in implementing them for testing in our 2x480 detectors and 160keV/3mA X-Ray laboratory equipment (**Fig.1**). For checking the accuracy in materials measurement of developed algorithms we used the Non-Hazardous Explosives Simulants for Security Training and Testing (NESTT) materials having known values of **Zeff** and **Density (**presented in **Table 2)**, concept developed at the *Lawrence Livermore National Laboratory*, California and manufactured by *XM Division of VanAken International* – USA**.**

We made the dual-energy **DR** accuracy test with 11 different-shape samples of simulants from **Table 1**, that covers all the range of explosives from black powder, slurries and emulsion to datasheet and semtex, and the result is presented in **Figure 3**.

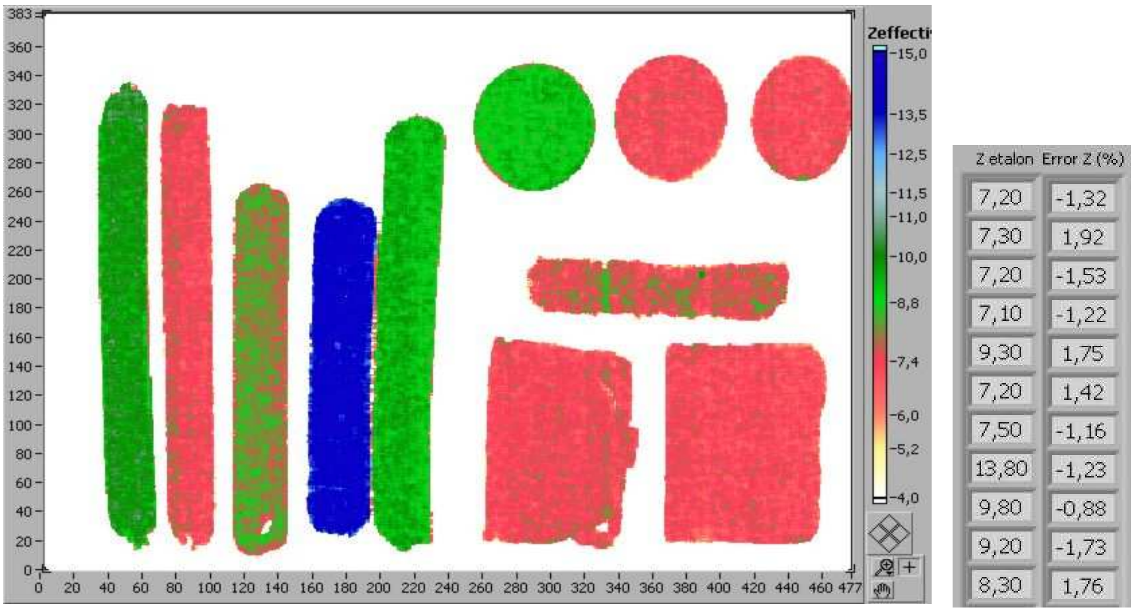

Figure 3. The dual-energy DR of 11 samples of explosive simulants and the measurements errors

A maximum error of ± **2%** between simulants reference values and **DR** measured values has been achieved for the entire range of **Zeff** between 5 and 15 atomic units.

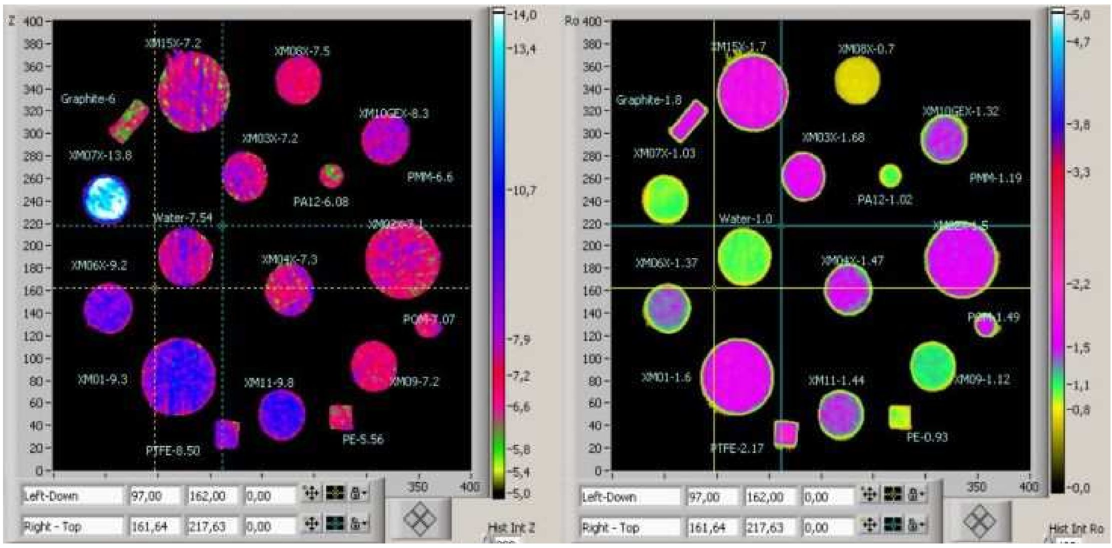

Figure 4. The dual-energy CT of the 11 samples of explosive simulants and other domestic materials at 400 projections

The same test but with various materials, including the above 11 samples of explosives simulants, have been scanned by **CT** at 400 projections and the **Zeff** and **Density** tomograms are presented in **Figure 4**.

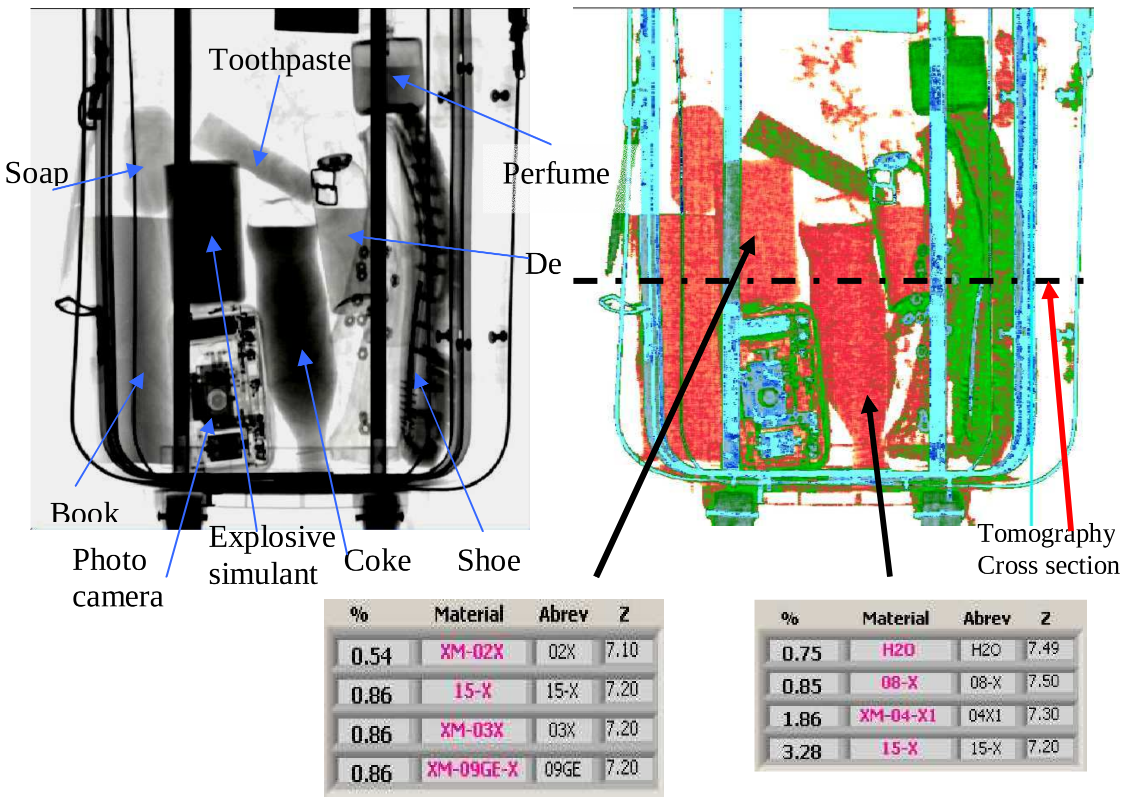

Figure 5 – The scanned baggage classical DR and Z_{eff} scale images and the material identifications technique

A maximum error of ± **3%** between simulants reference values and **CT Zeff** measured values and a maximum error of ± **2%** between **Density** simulants reference values and **DR** measured **Density** values has been obtained. The measurement covers the entire range of **Zeff** between 5 and 15 atomic units and of **Density** between 0.6 gr./cm^3 and 3 gr./cm^3.

Another test has been further made with a real hand-baggage filled in with various items: shoe, book, coke, cream, soap, cologne, photocamera and a cylinder of explosive simulant. The attenuation coefficients and **Zeff** images of the hand-baggage **DR** scan are presented in **Figure 5,** together with the result of automate identification of two materials, water with a 0.75% difference, and a 0.54% difference for explosive simulant measurement.

We continue the accuracy investigation by doing a cross section tomogram of the hand-baggage in the region of dashed line from **Figure 5** and we obtained **Zeff** and **Density** tomograms that are presented in **Figure 6,** together with the result of automate simulant measurement that indicates a 0.4 % difference in **Zeff** and a 0.6 % difference in **Density.**

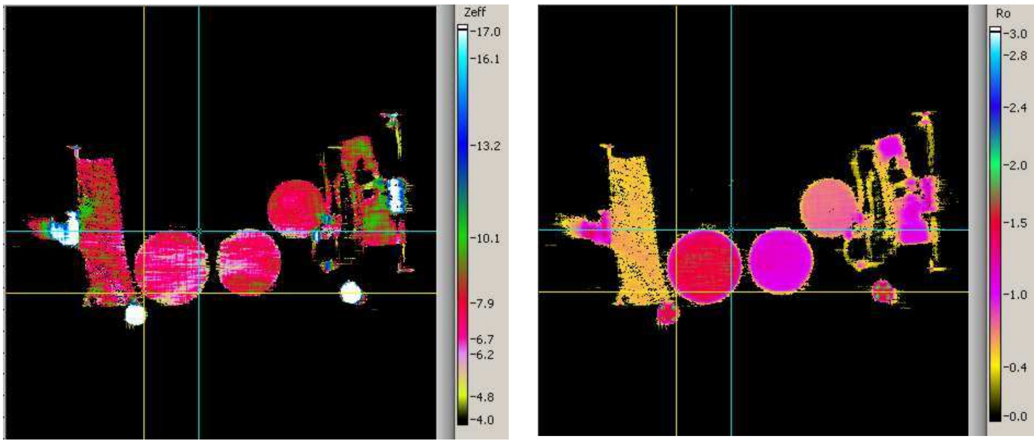

Fig. 6. The baggage cross-section tomogram and the simulant detection

full error	Err Z	Err Ro	formula	abrev
1.1	0.4	-0.6	XM-02X	02X

3. Non-rotational algorithm for tomography

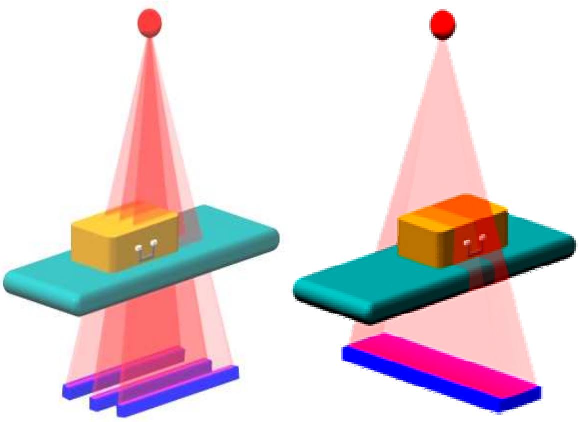

Figure 7. Non-rotational scan tomography

The idea of using a non-rotational or translational algorithm in tomography scanning method (presented in **Figure 7**) instead of classical rotational one is to strongly reduce the cost and the size of the actual luggage tomograph that could become in this way a first level machine that integrates a fully explosives detection technique. We begun our work by implementing an algebraic iterative reconstruction algorithm, a program for generating different objects for being scanned and a program for generating the object related translational scan data. With all programs chained we made the fully encouraging simulated test that has been presented in (7). Now, we present the first attempt to acquire experimental data by adding a simple translation stage, not very precisely mounted, on the laboratory machine presented in **Figure 1**. Because we knew from the beginning that the mechanical design of the new set-up is not the adequate one for our goal, due to huge misalignments, we made that for getting the first experimental result of the new algorithm test. First translational scan test has been made with four metallic pins positioned as presented in **Figure 8** and the data has been acquired for 220 translation steps (or 220 projections) for checking the algorithm convergence.

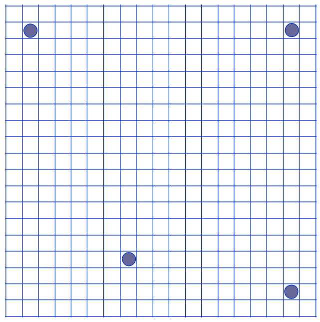

Figure 8. The four-pins object

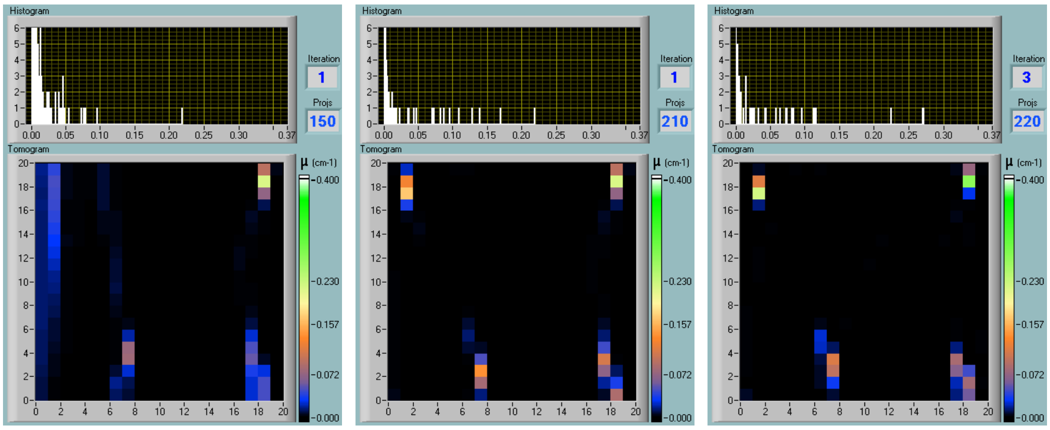

Figure 9. The four-pins object reconstruction

As expected, in **Figure 9** the reconstruction algorithm shows that the iterative reconstruction algorithm has a poor convergence. The three images have been taken at the 1st iteration and at the 150th and respectively the 220th projections and the last at the end of 3rd iteration. The further iterations convergence continued to be very poor due to mentioned misalignment. We compute for each reconstructed tomogram presented also its histogram for getting additional information about the convergence, knowing that when the materials are grouping in peaks the algorithm's convergence is quite good. Obviously, that has not been happened in our case and we decide to change some of the geometry parameters - like distance between X-ray source and the line detectors, for instance – for seeing if some improvements in algorithm convergence could be achieved.

After many attempts of changing the geometry distances, with values ranging between 0.15 mm and 0.45 mm, we reached a better convergence that is presented in **Figure 10**. Still the image is blurred but we stop here the process because the number of correction combinations was quite large.

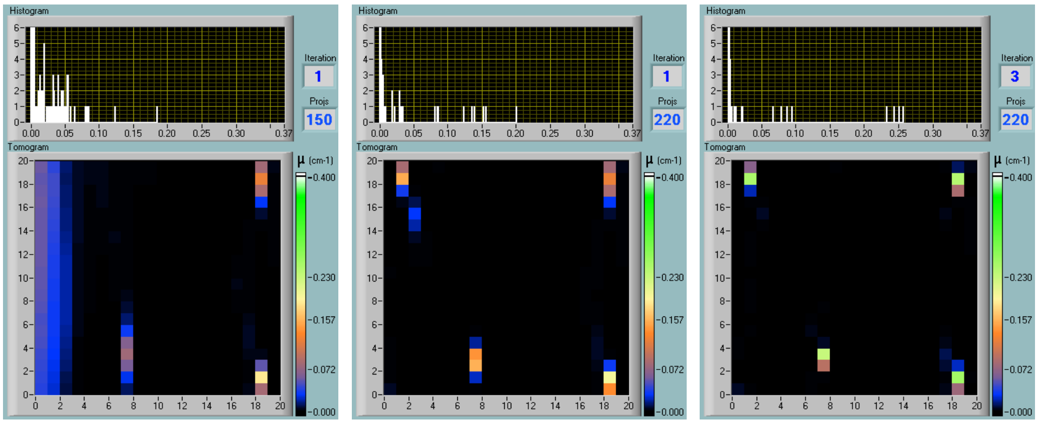

Figure 10. The four-pins object reconstruction after correction

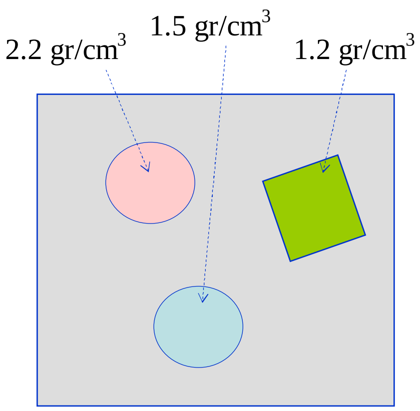

Figure 11. Three different samples

We decide then to do the further test taking into account the corrected values for three different organic materials as shown in **Figure 11.**

Reconstructed images at 1st, 5th and 16th iterations are presented in **Figure 12** where the poor convergence is still present but, at least, the three scanned objects are reasonable separated in the tomogram and similar tendency could be seen in histogram.

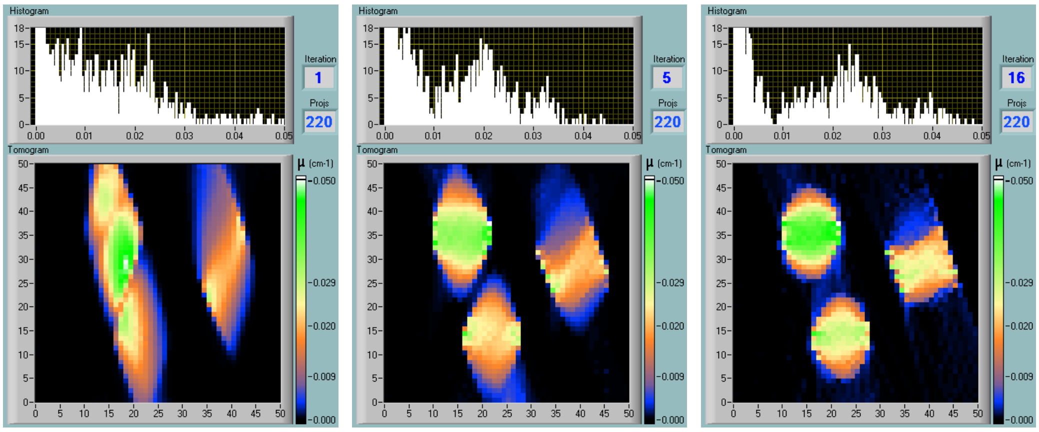

Figure 12. The three organic materials reconstruction

4. Concluding Remarks

The ability of the dual-energy X-Ray **DR** and **CT** in detecting explosive materials in luggage control has been proved to be quite good, a maximum 2% error is obtained for $\mathbf{Z_{eff}}$ measurement. in **DR** Also, a maximum of 3% eror for $\mathbf{Z_{eff}}$ and 2% for **Density** measurements has been obtained in **CT** tests. Both results are very encouraging and the method will be further tested by implement it in a dedicated luggage screening devices.

The first experimental attempt of the non-rotation algorithm presented above was not a fully satisfying one according with our expectation. We will further pay more attention to the misalignment effects by studying them first by simulation and a geometry that is less sensitive to misalignment will be found. Also, we will try to build a new precisely positioned set-up for getting better experimental results, where all the unwanted effects would be strongly suppressed.

Acknowledgements

This work was partially supported by the Romanian Ministry of Education and Research, grant Security 1R/2005.

References

1. Dual Energy Computed Tomography and Digital Radiography investigation of Organic and Inorganic Materials" – P44; Proceedings of the 9th European Conference on NDT - ECNDT Berlin September **2006** – CD-ROM; M.Iovea, O. Duliu, et all
2. *Dual-Energy Tomography and some of its application*; *CT DAY Conferance* at University of applied Sciences Wels – Austria, 19 september **2006** – CD-ROM; M. Iovea ;
3. Dual-energy Digital Radiography and Computer Tomography Applications in Geosciences, The 4th International Colloquium on Mathematics in Engineering and Numerical Physics –invited papers, 6-8 October **2006**, Bucharest, Romania; M. IOVEA, O.G. DULIU, G. OAIE, M. NEAGU, C. RICMAN, G. MATEIASI
4. Dual-energy Computer Tomography and Digital Radiography Applications in Non-destructive Control of Materials, Proceedings of the 6th Conference of the Balkan Union of Physics, Istanbul, Turkey, August **2006**; O.G. DULIU, M. IOVEA, M. NEAGU, G. MATEIASI
5. Recent results in X-Ray Radioscopy and Tomography for improving the explosives detection technique in luggage control" - Safety and Security Systems in EUROPE Conference; Nov30-Dec01 **2006** Potsdam Germany- CD-ROM; Mihai IOVEA, Gabriela MATEIASI, Marian NEAGU.
6. Dual energy X-ray computer axial tomography and digital radiography investigation of cores and other objects of geological interest; (**2005**) - Engineering Geology; M. IOVEA, G. OAIE, C. RICMAN, G. MATEIASI, M. NEAGU, S. SZOBOTKA, O.G. DULIU
7. Pure Translational Tomography - a Non-Rotational approach for Tomographic Reconstruction – Tu.1.4.1; Proceedings of the 9th European Conference on NDT - ECNDT Berlin September **2006** – CD-ROM; M.Iovea, G. Mateiasi, M. Neagu