Combining Measurements with Three-Dimensional Laser Scanning System and Coded Aperture Gamma-Ray Imaging System for International Safeguards Applications
2010 IAEA Symposium on International Safeguards, 1–5 November 2010, Vienna, Austria

A. C. Raffo-Caiado\textsuperscript{a}, K-P. Ziock\textsuperscript{a}, J. P. Hayward\textsuperscript{a}, S. E. Smith\textsuperscript{a}, J. S. Bogard\textsuperscript{a}, C. B. Bochnen\textsuperscript{a}, J. Gonçalves\textsuperscript{b}, V. Sequeira\textsuperscript{b}, David Puig\textsuperscript{b}, O. Peixoto\textsuperscript{c}, S. Almeida\textsuperscript{c}, O. Calzetta\textsuperscript{c}

\textsuperscript{a}Oak Ridge National Laboratory
P.O. Box 2008, MS-6165
Oak Ridge, TN 37831-6165, USA

\textsuperscript{b}European Commission – Joint Research Center, Ispra
Institute for the Protection and Security of the Citizen (IPSC)
TP 210, 21020 Ispra (VA), Italy

\textsuperscript{c}Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials
Av. Rio Branco, 123 – group 505
Rio de Janeiro, RJ, Brazil 20040-005

Abstract. Being able to verify the operator’s declaration in regard to the technical design of nuclear facilities is an important aspect of every safeguards approach. In addition to visual observation, it is necessary to know if nuclear material is present or has been present in undeclared piping and ducts. The possibility of combining the results from different measurement techniques into one easily interpreted product should optimize the inspection effort and increase safeguards effectiveness. A collaborative effort to investigate the possibility of combining measurements from a three-dimensional (3D) laser imaging system and gamma-ray imaging systems is under way. The feasibility of the concept has been previously proven with different laboratory prototypes of gamma-ray imaging systems. Recently, simultaneous measurements were conducted with a new highly portable, mechanically cooled, High Purity Germanium (HPGe), coded-aperture gamma-ray imager and a 3D laser scanner in an operational facility with complex configuration and different enrichment levels and quantities of uranium. With specially designed software, data from both instruments were combined and a 3D model of the facility was generated that also identified locations of radioactive sources. This paper provides an overview of the technology, describes the measurements, discusses the various safeguards scenarios addressed, and presents results of experiments.

1. Introduction

A technical collaborative effort was established in 2008 to investigate the use of a three-dimensional (3D) laser imaging system combined with gamma-ray imaging for international safeguards applications [1]. The objective of the combined system is to provide the international safeguards community with a tool to verify that the process system design is consistent with the operator’s declaration as described in the Design Information Questionnaire (DIQ) and that the nuclear materials are located in the process systems and components in accordance with the operator’s declaration. The combined system also has the potential for detecting nuclear materials in areas that are undeclared if the operator has not taken measures to effectively shield the piping/containers where the material is being withdrawn. The possibility of combining different measurement techniques into one tool will optimize the inspection effort and increase safeguards effectiveness.

The work is being conducted in the framework of technical cooperation agreements between the U.S. Department of Energy (DOE) and the European Atomic Energy Commission (EURATOM) and
between DOE and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC). The complete collaboration includes the following DOE national laboratories: Oak Ridge National Laboratory (ORNL), Lawrence Berkeley National Laboratory (LBNL), and Lawrence Livermore National Laboratory (LLNL). The effort also counts on the technical support and expertise from two regional safeguards organizations: EURATOM’s Joint Research Centre at Ispra, Italy (JRC-Ispra), and ABACC.

The submission and verification of nuclear facility design information usually occur during the earliest stages of construction, and the information is periodically re-verified over the operating life of the facility. The design information is verified during construction to define and include the nuclear material processing areas. Regional and international safeguards inspectors continue to re-verify the design information during what are called design information verification (DIV) activities conducted over the life of the plant, from construction through commissioning, operation, and shutdown to decommissioning. The 3D laser component of the system under investigation would be the key instrument to establish the baseline of the design of facilities as well as to detect changes to the 3D volume if shielding is added after baseline measurements have been performed.

Currently, the standard for performing nondestructive assay measurements is to use scintillator or semiconductor gamma-ray detectors to look for the gamma signatures given off by uranium isotopes. Several limitations are encountered with this practice: (1) uranium deposits are sometimes located behind heavy processing equipment, hindering physical access to the source of radiation; (2) an adequate survey of a radiation area requires considerable manpower and time; (3) radiation detectors are omnidirectional in that they do not provide information related to the direction of incident radiation; and (4) when collimation is used to restrict the detector’s field of view, systematic errors from uncertainties of alignment and deposit geometries can lead to significant uncertainties in the amount of fissile material that is present.

In previous studies, the performance of pinhole, coded-aperture, and Compton gamma-ray imaging systems were investigated [2]. The results of several measurements conducted at ORNL did not favor a pinhole imaging system, but they showed that coded-aperture imaging was very promising for locating sources of enriched uranium. Other work showed that Compton imagers were promising for locating sources with higher energy emissions, and work by L. Mihailescu et al. [3] has demonstrated the feasibility of combining both types of imaging at intermediate energies.

The collaboration mentioned above is directed toward investigating both Compton and coded-aperture gamma-ray imaging systems. DOE funded upgrades to the hardware and software of the prototype systems that resulted in their miniaturization for improved deployability. In this paper, the results of recent measurements conducted at ORNL with the new coded-aperture imager and the 3D laser instrument are shown. The results were successfully combined in real time. Nevertheless, such experiments were conducted in a controlled environment. In order to guarantee that the system can provide accurate images in an industrial/operational setting, field tests are required. A field test in an operating radiological facility safeguarded by ABACC is planned.

### 2. Instruments Used During Joint Measurement Campaign

For the sets of measurements conducted at ORNL, the team used a 3D laser scanning system developed by JRC-Ispra for DIV. The system is able to create 3D maps of rooms and objects and identify changes in positions and modifications with a precision on the order of millimeters. An earlier model of the 3D laser scanner was made available to ORNL by JRC-Ispra under a collaborative project concerning investigation of applications for the 3D-DIV system at DOE facilities in the United
States. ORNL tested and evaluated the system and documented the procedures for use, hazard analyses, and identification of additional safeguards applications in a joint technical report [4]. The new model of the 3D laser scanner was purchased for this investigation (Fig. 1).

![Image 1](image1.png)

**Fig. 1.** A Zoller+Fröhlich Model 5006i 3D laser that is being used to complete the project. The battery is part of the single unit, which also stores the image. The unit can be transported in two containers: one for the laser head and another for the tripod.

During the past year, a new HPGe coded-aperture gamma-ray imaging system has been developed to make an instrument that is both more transportable and robust. The original instrument (Figs. 2–3) was designed as a laboratory prototype that was suitable for limited demonstrations in field environments. The imager, including detectors (with cryostats), electronics, and desktop computer, is mounted on a cart to provide mobility and pointing capabilities, has a footprint of ~2/3 m × 2 m, weighs ~ 100 kg, and requires cryogen refills every few days (Figs. 2–3) [5].

![Image 2](image2.png) ![Image 3](image3.png)

**Fig. 2.** Prototype of coded-aperture imager. Both the planar and coax detectors are cooled by liquid nitrogen. The coax detector was not used for image acquisition. **Fig. 3.** Prototype of coded-aperture gamma-ray imaging system.
The new instrument is described in detail in Ziock et al. [6] and is shown in (Figs. 4–5). Briefly, it is tripod mounted, weighs about 25 kg, operates with a laptop computer, and is mechanically cooled. It is based on a commercially available 16 × 16 doublesided strip HPGe detector (PHDs Co.) 11-mm thick with a 5-mm strip pitch (with 500 μm gaps). The detector is read out using the 32-channel system provided by the manufacturer. The vendor’s software provides interpolated positions with sub-strip resolution achieved by comparing transient signals observed on strips on either side of the one above an event that collects the charge carriers [7]. The system also provides the depth of interaction for the events by comparing the difference in arrival times between the holes and electrons collected on the opposite faces of the device [8]. The detector achieves a position resolution of order 1 mm in all three dimensions and an electronics-limited energy resolution of order 1.4 keV full width half maximum (FWHM). A 1.5 mm thick tungsten modified uniformly redundant array (MURA) coded-aperture mask [9] is used to encode the images onto the position-sensitive detector. The mask is designed so that each source in the field of view projects a unique shadow pattern onto the detector. The patterns from different source locations are mutually “orthogonal” so that an artifact-free image can be recreated from the measured shadow pattern even if multiple or extended radiation sources are in the field of view. Masks with both base 19 and base 31 patterns are available for different measurement situations. The data is collected in equal-time mask/anti-mask configurations for improved performance in environments with nonuniform backgrounds. Since the MURA is antisymmetric on a 90 degree rotation, the change from mask to anti-mask can be performed remotely using the controlling computer [10]. The imager is combined with a visible-light stereo imaging system. The image fields of the stereo and gamma-ray imagers are carefully aligned so that the dense-stereo data from the stereo camera can be used to orient the gamma-ray images with the 3D laser scanner output [11].

3. Results of Tests Conducted with the Coded-Aperture Imaging System and the 3D Laser Scanner

A one-week measurement campaign was conducted in a chemical makeup area located immediately above hot cells in which neutron-activated targets from ORNL’s High Flux Isotope Reactor are dissolved for extraction of the activation products. A complex of piping and valves (Fig. 6) allows operators to produce aqueous solutions used for target dissolution and product extraction in the hot cells. Visible images of the complex plumbing in this building were generated using the
Zoller+Fröhlich Model 5006i 3D laser imager acquired by ORNL (Figs. 7–8). Sealed sources of uranium enriched in the $^{235}$U isotope were placed within the framework of the plumbing to simulate pipes or valves containing nuclear materials for imaging (Fig. 9).

Fig. 6. Digital photograph of area where measurements were conducted.

Fig. 7. The 3D laser scanner and the HPGe coded-aperture gamma imager placed next to each other to show proportions.

Fig. 8. The 3D laser scanner positioned and set to scan the area.
Fig. 9. 3D map of the scanned area showing the detection of three differences from the baseline scan: (1) line source (long red); (2) plastic bag below the line source (blue-greenish); and (3) the removal of the previous aluminum can source (red cylindrical shape below the line source).

The following radioactive sources were used in the measurements:

- **CRM Enrichment Standards - U₃O₈ in sealed aluminum cans**  
  (Distance to the source 1.8 m, time 200s [mask] + 200s [anti-mask])
  - NBL-0002  - 52.49% enriched - 101.72 g U²³⁵ - Total 193.79 g U
  - NBL-0001  - 20.11% enriched - 39.10 g U²³⁵ - Total 194.43 g U
  - NBS 446-078  - 4.46% enriched - 7.54 g U²³⁵ - Total 169 g U

- **Line source – U₃O₈ in epoxy in plastic tube**  
  (Distance to the source 1.8 m, time 400s [mask] + 400s [anti-mask])
  - 0.13 g/cm 93.16% enriched - 12 g U²³⁵ - Total 13 g

The sequence of images in Fig. 10 shows how the gamma image is combined onto the laser scan. In this sequence, the source was located at 1.8 m distance from the detector. It was 7.54 g U²³⁵ enriched at 4.46%. The gamma-image sensor and stereo-image device are physically connected and calibrated to one another so that the two images can be overlaid. The stereo vision rig serves as a bridge between the gamma camera and the laser scanner. It is physically aligned and calibrated to the gamma imaging device. Common alignment allows the gamma data to be projected onto the 3D laser scan. Software developed by JRC-Ispra allows the combination of the 3D laser map and gamma image to be performed in real time.
4. Conclusions and Recommendations

Tests in an operational facility at ORNL were conducted using both the 3D laser scanner and the new portable coded-aperture gamma-ray imager. The principle of combining outputs from two different commercially available technologies has been proven and demonstrated. The combination of these images is now performed automatically and in real time. The coded-aperture HPGe detector was capable of detecting a line source of 7.54 g of U$^{235}$, 4.46% enriched, at a distance of 1.8 m during 200 seconds of counting time.

The final task of the project aims at conducting measurements in real facilities. In preparation for these field trials, the new detector is currently being characterized to measure lower energy sources at distances higher than 2.5 m. The field trial is tentatively scheduled for April–May of 2011.

As future goals, which are beyond the scope of the current project, experiments should be directed toward determining enrichment capability, coupling with neutron imaging, and exploring the use of a NaI detector to perform measurements in a facility with process material (i.e., in a UF$_6$ flow loop).
References


