Using a Silicon Drift Detector to Improve an Agricultural Compton Scattering Tomograph for Soil Compaction Analysis

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***Abstract*— The use of sensors in farming have become essential for soil, plants and environment monitoring in order to greater yields, while allowing rational use of inputs and decreasing risks. Although many of them are known, still there are challenges related to sensor's development, characterization and customization for agricultural use, bringing opportunities for research and innovation. This article presents a study for the use of a high-performance silicon drift detector in a customized Compton scattering tomograph to analyze soil compaction in agricultural field. In agriculture the soil compaction causes substantial reduction in productivity and has always been of great concern for farmers. The use of such a methodology enables non-invasive and non-destructive measurements of soil compaction directly in the crop area, i.e., allowing its mapping. Energy resolution and signal-to-noise ratio were evaluated and compared with those from a classic scintillation detector. Based on the results, it was concluded that such a sensor can improve the effectiveness of a Compton scattering tomograph dedicated for soil compaction measurements.**

Keywords-Solid-state sensor; Compton Computed tomography; compaction measurements; agricultural sensor; intelligent instrumentation; soil analysis.

I. INTRODUCTION

Nowadays, sensor-based technologies have emerged for use and investigation on several domains of application.

In the field of tomographic imaging the progress in sensors has been leading many scientists, engineers, and technicians to present additional interest and to devote greater time to their activities.

This has been enlarging the world evolution for decision support systems, which are sensors-technology based. Such aspects, have also expanded economy, i.e., with additional opportunities for many fields of interest, like medical [1], industrial [2], and agricultural [3], among others.

X and γ-ray Computed Tomography (CT) was born with contributions from both the physicist Allan MacLeod Cormack and engineer Godfrey Newbold Hounsfield [4][5]. Later, Cormack came to know the work of the Austrian mathematician Johann Radon [6], who was the first to present a general mathematical solution for the reconstruction of a body from its projections in a space of order (n) that is, enabling the determination of a density function of a studied region through its projections. In fact, Cormack has developed equations to reconstruct an area considering a finite number of projections. Also, he defined a density function, based on the mass attenuation coefficients (cm^2/g), and used back-projection to obtain photon attenuation measurements based on the Beer-Lambert equation [7].

In 1979, Cormack and Hounsfield shared the Nobel Prize in Medicine, due their innovative work based on X-ray tomograph. In this context, it is also important to mention, as important contribution for such a result the pioneering works carried out by Michael Faraday (1831) and Wilhelm Conrad Röntgen (1895). Michael Faraday was one of the first to study the relationship between electricity and magnetism. He discovered, in 1831, that electromagnetic induction and his studies are considered key concepts in current physics, finding applications in several areas including tomography. In 1895, Wilhelm Conrad Röntgen produced and detected electromagnetic radiation in different wavelengths, which he came to call X-rays.

There are different instrumental arrangements based on the interaction of the ionizing energies with matter, which defines the operational modalities for the X and γ-ray tomographs. Here, we are considering two of these approaches, i.e., one based on the transmission and other related to the scattered photons. Transmission tomography uses a collimated beam of radiation, which defines planes as thin as the beam itself and, through several parallel collimated beams, sets of projections can be defined that are taken to image reconstruction algorithms.

In fact, the study of CT applied to agriculture, has begun in the early 1980s, primarily based on transmission tomography and focused on the investigation of water content (cm^3/cm^3), soil density and compaction (g/cm^3), as well as soil porosity (%).

The first customized X and γ-ray minitomograph scanner for soil science applications was built in 1987 [8]. Subsequently, other agricultural tomographs were developed to operate at millimeter scale, i.e., considering either photons transmission or scattering techniques [9-13].

Based on scattering photons technique, the Compton effect was first presented by Compton and Hagenow [14][15].

In fact, conventional transmission tomography techniques and conventional tomography models are based on the use of source and detector on opposite sides. When used appropriately, the benefits of a CT scan far exceed the risks. CT scans can provide detailed information to soil diagnose. Additionally, the detailed images provided by CT scans may decrease the need for agricultural machinery uses

 ISBN: 978-1-68558-083-4

for soil management. However, these models cannot always be used in agricultural applications, such as, for example, in extracting soil measurements directly from either an agricultural field or crop area.

The Compton scattering tomograph has source and detector located on the same side in relation to the sample of interest to be sampled. In this way, there is no need to open trenches for soil analysis, as necessary when using the transmission tomographic technique.

In such field of knowledge, Hanson and Gigante have developed a mathematical method to visualize the scattering geometry of the energy distribution and the angular variation of the Compton scattering [16][17]. However, these authors considered the absorption effects to be very small and obtained toroidal surfaces of constant angle and correspondent energies for scattering. Additionally, they emphasized the importance of observing energy contours within a scattered volume, as these determined the magnitude of geometric effects. They also have shown that this type of analysis would be useful as an analytical approach to measurements with X-rays using scattered photons. Besides, it was important to understand the Compton´s photopeak in order to obtain accurate measurements.

In 1992, Cesareo and coauthors published an article on the theoretical basis and applications in techniques that used the interaction of photons with matter considered a broad keV energy range [18]. Analytical applications included Compton densitometry, Compton profile measurements, and Rayleigh scattering to Compton scattering (R/C) ratio measurements. Regarding Compton densitometry, the authors emphasized that this method of analysis can be used to determine the electronic density of the sample, but not its mass density, which can be deduced by knowing the value of the relation regarding the atomic number to the effective atomic mass of the sample, i.e., the (Z/A) ratio.

About the Compton profile measurements, they reported that the technique was considered an important source of information about the modifications of the electron moment distributions in the sample. However, the technique had difficulties in measurements due multispectral incident beam energy and the multiple scattering occurrences. Regarding the (R/C) ratio measurement, the authors reported works that make such measures feasible.

Balogun and Spyrou investigated the influence that materials with high and low atomic number Z exerted on CCT images [19]. These authors used a 662 keV (^{137}Cs) γ-ray source with a rectangular collimator, a Phantom consisting of a cylindrical aluminum (Al) block with 52 mm in diameter and 5 holes arranged in a circle. Two of these holes were 1.2 cm in diameter, while the others were in the range of 5 and 6 cm in diameter.

The holes were made to insert rods whose chemical composition would be of interest to the research. They justified this type of arrangement based on the analysis of the contrast and the signal-to-noise ratio (SNR) evaluation. Such analysis has considered an expectation about 60% in contrast for reconstructed images from a Phantom having diverse materials. The best results for contrast, SNR and accuracy were obtained with the inclusion of Lead (Pb, high Z) and Cooper (Cu, low Z) in the Phantom, and the author's hypothesis have been proved successfully. Likewise, the minimum detectable change in bulk density was equal to 4.2 g/cm^3.

In 1994, Norton developed a technique for tomographic images reconstructing through the number of scattered photons as a function of energy and detector positioning [20]. The result obtained was an electron density image that could be reconstructed by measuring its line integrals over various paths. This result presented an analytical solution for the idealized Compton image reconstruction problem. Norton emphasized that the back-projection method had the advantage of being computationally efficient compared to methods based on numerical systems of equations. Additionally, the author stated that such a solution was based on the use of Monte Carlo method, i.e., has been found iteratively.

This paper presents the use of an embedded X and γ-ray high-performance detector in a Compton scattering tomograph, customized for agricultural soil compaction evaluations on the crop's region. After this introduction, there are Section II, which presents advances in the use of such a technique in agriculture, and Section III with material and methods, considering the main aspects. In addition, there is Section IV with results and discussions, and finally, the conclusions are presented in Section V.

II. EARLY USE OF COMPTON SCATTERING TOMOGRAPH IN AGRICULTURE

The scattering tomography, known as Compton Computed Tomography (CCT), has being used for imaging reconstruction from projections of agricultural soils.

In fact, Cruvinel and Balogun have developed a dual-energy Compton scattering tomograph for agricultural applications [21][22]. The experimental setup consisted of two radioactive sources, one of 662 keV (^{137}Cs) for soil density measurements and another of 59.6 keV (^{231}Am) for soil water content measurements with 2 mm spatial resolution. In such publications, these authors have also presented a deep discussion regarding the comparison with other methodologies, as well as advantages for soil density and water content measurements based on CCT. In such a context, they have shown a linear relationship between the size of soil aggregates and the Compton measurements with a regression coefficient (r^2) better than 0.95 for bulk density and 0.70 for water content.

The minimum density detected was 0.13 g/cm^3, i.e., with an accuracy of 2%. Besides, the minimum value of the water content detected was about 0.10 cm^3/cm^3, i.e., with an accuracy of 5%. In 2003, these same authors have presented the use of a NaI(Tl) scintillation detector and the qualification of the use of a photopeak in the region of 250 keV to carry out Compton measurements (Fig. 1). In such a research work, the Compton images obtained showed good resolution contrast, shape and edge definition.

Additionally, they reported that in Compton scattering photon tomography the choice of scattering energy was dictated by the scattering angle, materials to be examined and the size or depth of the sample. For soil analysis, the use of low energy photons (⩽ 60 keV) was indicated for studies of surface phenomena, such as soil sealing. In situations that require depth information, such as soil compaction, higher energy photons would favor the analysis.

In 2004, Roy and Pratt compared Klein-Nishina cross-section measurements for the whole atom (energy range from 11 keV to 40 keV) with the theory and used a synchrotron-type X-ray source [23]. Compton scattering measurements were performed with a scattering angle equal to 90°. The results showed experimental comparison of the cross sections measured with conventional and synchrotron sources with the predicted values of the Compton scattering factor, that means, an Incoherent Scattering Factor (ISF). The measurements made with conventional sources were presented in a dispersed way, having a difference in the magnitude of the ISF in the range of 5% to 50%, while the measurements with the synchrotron fell in a narrow range of low percentage of difference. The authors highlighted the need for studies on Compton scattering measurements in the region below 10 keV in order to confirm the adequacy of the theoretical treatment.

In 2009, Yao and Leszczynski presented an analytical approach to approximately separate the unknown information from the Klein-Nishina cross-section formula and express it through the primary intensity of X-rays in the detector [24]. These authors reported that the spatial distribution of the first order Compton scattered could be described by the Klein-Nishina cross section formula assuming that the source energy spectrum, the geometry of the imaging system and the volumetric information of the scattering medium were known, including geometry and radiation distribution properties. Such information was mixed up and generally could not be completely separated. The authors also considered an approximate formula in which characteristics were separated from the information from the X-ray source and the imaging system. The approximation obtained was compared with the exact solution of the Klein-Nishina cross section and with the simulations carried out using the Monte Carlo method. The result obtained showed that the approximate relationship between the first order scattering and the fluence of the primary intensity in the detector was useful in estimating the scattered radiation in physical projections of a specimen.

In 2010, Pratt and co-authors reviewed the standard theory on Compton scattering of valence electrons and described findings that required modification of the usual understanding by looking at the consequences for the experiment [25]. In such a work, the authors demonstrated that the estimate made by Eisenberg and Platzman for the validity of the impulse approximation theory and its application to Compton scattering was incorrect, although the qualitative conclusion remained intact. They pointed out that the impulse approximation provided a good description of Compton scattering in the peak region, but failed when considering low-energy resulting photons.

In 2011, Şahin and collaborators measured water retention in soils using Compton scattering. The experimental arrangement used a γ-ray source 133Ba (500 mCi, 356 keV) and a NaI(Tl) scintillator detector [26]. The soil used was a Holocene or Fluvial Neosol (Entisol) according to the North American classification (USA).

Additionally, the chosen spreading angle was 90° and the soil thickness varied from 5 to 55 mm with a 5 mm pitch. The mass attenuation coefficient value obtained was 0.102 cm^2/g and the relationship between the amount of water added and the intensity of scattered radiation showed a correlation coefficient (r^2) equal to 0.99. The authors concluded that the performance of the method with Compton scattering based on the standard curve showed that the results obtained from the evaluation of the analytical uncertainties were satisfactory.

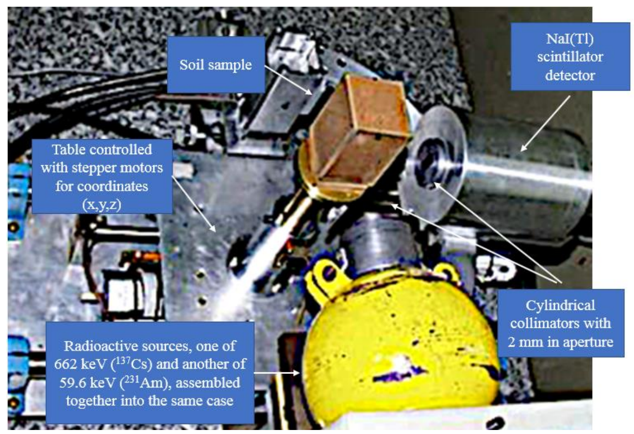

Figure 1. Laboratory version of the Compton CT scanner for agricultural soil and water analyzes [21].

In 2011, Cruvinel and Scannavino Junior have published an instrumental evolution on Compton scattering, i.e., the development of a field densitometer that uses an X-ray source and digital signal processing to measure the soil density of arable soils [27].

In recent times, one may find progress in agriculture technologies, that means, in terms of the use of sensor-based techniques for soil analysis. In fact, either nom-ionizing or ionizing radiations have been used, and challenges are still related to decrease invasiveness of the measure probes for data acquisition, as well as improvements in accuracy and precision of the measurements.

Furthermore, also improvements have been required in computational models to help decision-making directly on farm [28-31]. Likewise, the intelligent agriculture industry is expanding quickly, bringing and presenting new solutions to the farmers practically daily.

III. MATERIALS AND METHODS

Considering the CCT´s instrumentation for soil analysis (Fig. 2), the detector positioning is established from the selection of the scattering angle, which determines the Klein-Nishina cross section and the energy of the scattered photons. Besides, the collimators diameters of the source and detector, together with their lengths, determine the aperture half-angles that influence the intersection volume of the field of view established between source and detector.

From a Compton process the scattered photons number (dS) can be observed by equation (1), which shows the contributions of the linear attenuation coefficients, both for the incidence (μ_1) and scattering energy (μ_2), as well as the Klein-Nishina differential cross section ($d\sigma^{KN}/d\Omega$). Then, in order to account for these, we can write, for the number of singly scattered photons detected at the detector during a counting time of (t) seconds:

$$dS = \varphi_0 \exp\left(\int_{x1} \mu_1 dx\right) \frac{d\sigma^{KN}}{d\Omega} \rho \cdot \frac{N_A Z \xi t}{A} \exp\left(\int_{x2} \mu_2 dx\right) dV d\Omega \quad (1)$$

where exponential factors are introduced to take care of the attenuation of the primary and scattered photons within the sample, (ξ) is the detector's photopeak counting efficiency at the scattered photon energy, (x1) and (x2) represent the photon's path lengths in the sample, from the source to the scattering center and back to the detector, respectively, (ϕ_0) is the incident photon flux of energy (E_0), (ρ) the soil bulk density, (A) the mass number, and (N_A) is the Avogadro's number.

Furthermore, a commercially available Silicon-Drift-Detector (SDD) was used in such instrumental arrangement [32-34]. The performance of the SDD can be observed in Fig. 3, i.e., efficiency versus energy. The SDD sensor used in this study has a discrete external Field Effect Transistor (FET) and it uses a dedicated feedback capacitor and a well-proven method of pulsed charge restoration. This allows stability and provide more accurate X and γ-ray measurement.

In addition, as part of the used methods, the Filtered Back-projection Algorithm (FBP) was also considered [35][36]. In fact, the tomographic image reconstruction is a process to estimate a slice f(x,y) image from a set of projections p(t,θ). In such application, each sampled point of each projection collected at angle (θ) is correspondent to the scanned scattered photons intensity for one of the geographical positions of the sampled region. The basis of the mathematical model for the Compton`s image reconstruction can be such a reconstruction algorithm. The FBP algorithm is often referred as the convolution method using a one-dimensional integral equation for the reconstruction of a two-dimensional image. This method is the most common reconstruction algorithm used today for CT application. It uses projections and their Fourier Transform (FT), i.e., considering Q(w) as the filtered $P_\theta(t)$ projection. To get the reconstructed image, the resulting projections for different angles (θ_i) are added to estimate f(x,y). The reconstruction model can be presented, in its discrete form, as follows.

$$f(x,y) = \frac{\pi}{K} \sum_{i=1}^{k} Q_{\theta i}(x cos\theta_i + y sen\theta_i) \quad (2)$$

where (K) represents the numbers of the interval of angles (θ_i) during the scanning process.

The interface with the user is performed by a computer algorithm developed for communication between the control system and the SDD data acquisition, and it is also able to reconstructed the CCT images.

Besides, the algorithm allows to organize tasks to receive and collected data of soil compaction and in organizing an image bank for future use and analyzes, i.e., interpretation of spatial variability of soil compaction in A-horizon of the soil landscape.

For validation, a databank of soil CCT images were obtained considering an experimental agricultural plot, located at the geographic coordinates 21°57'13.9"S and 47°51'10.9"W, i.e., at the National Laboratory of Precision Agriculture (LANAPRE) in São Carlos, SP, Brazil.

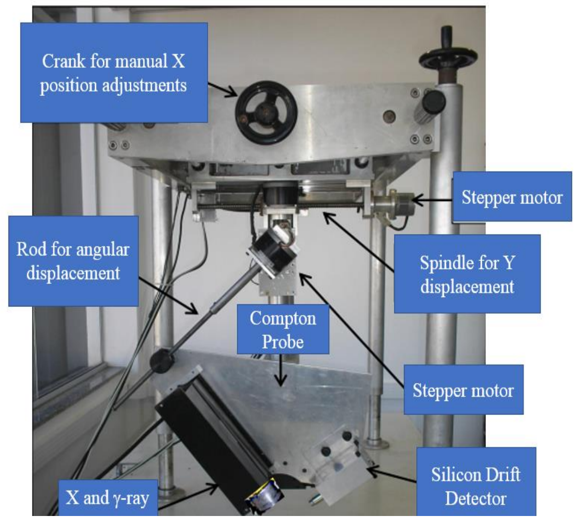

Figure 2. Instrumentation and probe of the customized and portable Compton scattering tomograph for soil compaction analysis.

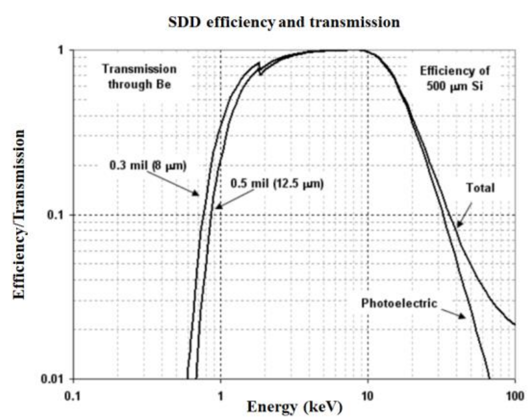

Figure 3. Efficiency versus energy for the SDD.

The mechanical module of the CCT is composed of a XYZ table for the spatial localization of the measurement Compton`s probe for soil compaction. The XYZ table is sustained by fuses and linear shafts of dislocation over the support structure. The imaging area of the CCT allows to image a Region of Interest (ROI) equal to 1.0 m x 0.50 m. It is sustained by three adjustable legs, with two at each frame extremity and one that is centralized on the opposite side to facilitate the entire leveling of the structure.

IV. RESULTS AND DISCUSSION

The used SDD is a state-of-the-art semiconductor detector based on the principle of side-ward depletion. When it was customized to be used in the CCT a comparison has been made with the measuring obtained with a NaI(Tl) scintillation detector. As an observed result, the SDD has presented advantages in comparison to the use of a NaI(Tl) detector. Such a comparison is summarized in Table I.

TABLE I. COMPARATIVE RESULTS FOR THE DETECTORS VARIABLES

Detector Characteristics	NaI(Tl) scintillation	SDD
Effective area (mm^2)	16	100
Thickness (mm)	76.2	0.26
Energy resolution (FWHM) @ 662keV (keV)	46.3	16.5
Signal-to-Noise ratio (SNR)	4	83

It is observed that, the energy resolution for 662 keV gamma rays is a function the workable temperature of the SDD, when considering the shaping time constants equal to 0.5 and 1 μ s. It was also observed that cooling reduces noise contribution. Nevertheless, an acceptable energy resolution is obtained up to SDD temperatures around 50 °C, which is useful for agricultural field use. Figure 4 shows the CCT working region evaluated for the SDD.

A calibration curve for the pixel value in ($kg.m^{-3}$) was carried out by using a set of well-known soil samples and a conventional penetrometer.

Figure 5 shows, as one example, a 100 mm x 50 mm Compton image from the organized databank. It was collected for analysis from the agricultural experimental field. In such a result the pixel is equal to 2.5 mm^2, and the total amount of pixels per image is equal to 800 (20x40). The source energy used was equal to 662 keV (^{137}Cs). The total amount of time to collect all projections and to have a final Compton image reconstructed was equal to 30 minutes.

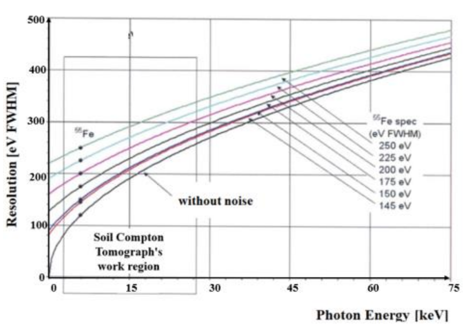

Figure 4. The CCT working region evaluated for the SDD based on 145 eV resolution.

For a given collimator size, length, and, its distance from the scattering center, scattering volume increases with increasing angle in the back-scattering geometry. The best volume resolution was found within the 90°±5° scattering angle range. Though volume resolution also decreases towards the forward scattering angles, resolution rate loss is much more pronounced in the backscatter angles.

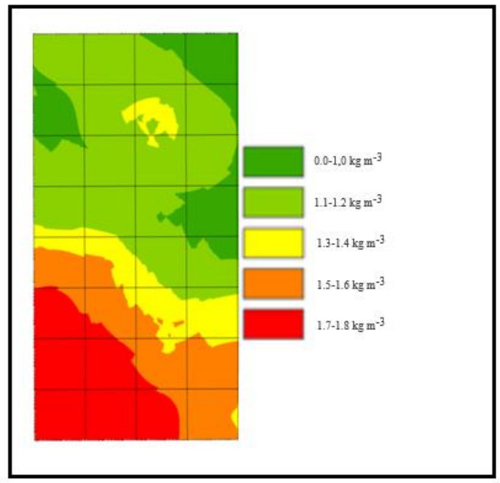

Figure 5. An example of Compton image from the agricultural pilot. The pseudo-color scale is calibrated in ($kg.m^{-3}$) and represents the soil compaction presented in the scanned area. From the grid used over the image one may have 25 pixels per block.

The use of CCT has enabled non-invasive analysis of the interior of the agricultural soil. Therefore, it has allowed the evaluation in situ of the A-horizon into an experimental area, as well as the information about its spatial soil compaction variability.

Soil compaction can have both desirable and undesirable effects on plant growth. A slightly compacted soil can speed up the rate of seed germination because it promotes good seed-to-soil contact. In fact, as soil compaction increases beyond optimum, yields begin to decline. In dry years, soil compaction can lead to stunted, drought-stressed plants due to decreased root growth. Without timely rains and well-placed fertilizers, yields will reduce.

In wet weather, yields decrease with any increase in compaction. Soil compaction in wet years decreases soil aeration, increasing denitrification. All these factors add stress to the crop and lead to yield loss, i.e., favoring food insecurity.

V. CONCLUSION

We have carried out studies related to the application of the SDD, and started its use in a customized Compton scattering tomograph for agricultural applications. The physics aspects of such a detector, that includes a solid-state based-sensor, was also evaluated for its well operation and functioning. Besides, result have shown advantages when using the SSD in comparison with a NaI(Tl) detector, since it presented good energy resolution, high SNR, as well as suppression of the Compton background. Further, an agricultural validation was considered using a set of Compton images for evaluating the spatial variability of soil compaction in kg.m^{-3}. In fact, such a result has proved to be possible non-invasive analysis of the compaction level of agricultural soil layers, directly on the field. For the future, it is planning to include a soil moisture sensor with the Compton probe, as well as to use algorithm to support decision making to orient agricultural machinery in precision soil compactness corrections.

ACKNOWLEDGMENT

This research was partially supported by the Brazilian Corporation for Agricultural Research (Embrapa).

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