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STEADY-STATE GAMMA-GAMMA DENSITY WELL LOGGING FOR DENSITY MEASUREMENT IN FRIABLE ROCKS

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ABSTRACT. This paper presents a new proposal for the application of the gamma-gamma geophysical well logging to determine densities in friable lithology, denominated **S**teady-**S**tate **G**amma-**G**amma **D**ensity in **F**riable rocks. We detailed calibration and standardization measurement steps for the gamma-gamma well logging tool, as well as the validation steps for density data acquired in the field, specifically, in a mining operation environment. In order to measure density in friable lithology/materials, a gamma-gamma well logging tool is positioned at the bottom of a borehole at approximately 1 meter depth, measuring density in stationary mode, over a data acquisition period of around five minutes. The final density value is defined based on the average of the accumulated measurements per borehole. This methodology was developed to overcome the scarcity of density measurements in friable rocks at Vale's operational mining areas. In addition to operational mine areas, the methodology has been successfully applied to acquire density measurements in waste. Using the proposed methodology, it is possible to acquire approximately 15 density values per day, which would not be possible using conventional methodologies that obtain only 2 or 3 values.

Keywords: radioactive source logging; density in friable rocks; petrophysics

INTRODUCTION

Gamma-gamma or gamma-density well logging is a technique routinely used in the oil industry. For mining applications, the theoretical bases for application in iron ore were developed in previous research hosted by Vale (Pereira et al., 2015; Pereira et al., 2016 and Pereira and Carlos, 2016) and in three patents (Pereira et al., 2017a; Pereira et al., 2017b; Pereira and Carlos, 2019) regarding tool gauging, profiling on geological drilling rods (to correct for the effect of casing) and quality control.

Among the methods commonly used to determine rock density, we can cite the sand bottle method, volume displacement, regular gauge, hydrostatic weighing and the opening of wells or cubes (Braga, 2019). Each of these methods, is performed manually increasing the possibility of introducing uncertainty into the process, and making it also time consuming. The use of conventional techniques in a regular geological research mesh or density characterization of geotechnical structures is impractical.

The development of Steady-State Gamma-Gamma Density in Friable rocks (SS-GGDF) is justified by the high demand for density data to support geological modeling. The methodology consists, basically, of a gamma-gamma well logging tool equipped with a ^{137}Cs radioactive source accumulating measurements in static mode at the bottom of a 1-meter-deep borehole.

The use of this methodology allows the acquisition of measurements over a regular geological mesh in a relatively short time. On average, from the positioning of the density measurement unit to the actual data recording, it takes approximately twenty minutes to acquire a single measurement point. Under regular operating conditions, the daily production is approximately 15 density measurement points.

METHODOLOGY

Steady-**S**tate **G**amma-**G**amma **D**ensity in **F**riable Rocks (**SS-GGDF**)

Gamma-gamma or gamma-density logging is a borehole geophysical methodology used to measure densities along an exploration borehole. Usually, the profiling tool is composed of a radioactive source that can be ^{137}Cs or ^{60}Co. These radioactive sources emit gamma-rays in the range of 0.2 to 2 MeV. The tool is composed of two detectors, one called short detector which is approximately 16 cm (~0.52 ft.) away from the radioactive source and another called long detector which is approximately 29 cm (~0.95 ft.) away from the radioactive source. Figure 1 schematics shows the geometric configuration of the gamma-gamma well logging tool.

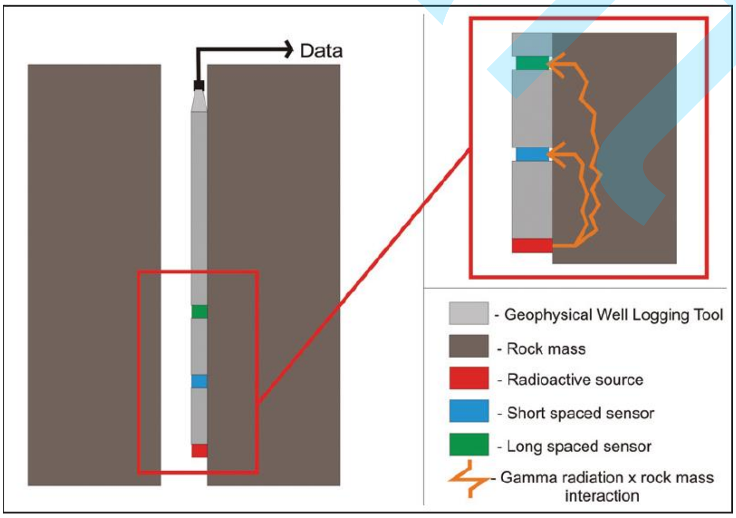

Figure 1: Geometric configuration of the gamma-gamma well logging tool. In the upper right panel detail the gamma radiation source produces gamma-rays that interact with the rock and are registered in the short and long sensors. From Pereira et al. (2015).

Gamma-rays penetrate the rocks matrix and undergo Compton scattering by interacting with electrons in the rock's constituent atoms. Compton scattering reduces the energy of gamma-rays and scatters them in all directions. When the energy of gamma-rays is less than 500 keV, they can undergo photoelectric absorption by interacting with atomic electrons (Ellis and Singer, 2007). The flux of gamma-rays that reach the detector is attenuated by rocks, with attenuation dependent on electron density. Generally, higher density rock corresponds to higher electron density and, consequently, greater attenuation. This configuration, with high electron density, significantly attenuates the gamma-rays resulting in a low count rate by the sensors. In turn, a low-density rock has low electron density that attenuates fewer gamma-rays leading to a higher gamma-ray count rate.

This proposal aims to provide the density of friable lithology and to complement density measurements obtained by conventional methodologies (volume displacement, gauge, etc.) and gamma-gamma logging performed along the geological survey borehole.

The system is mounted on the body of a light vehicle designed for drilling boreholes and acquiring data. It consists of an a system composed of an electric drill with the capacity to drill holes with a diameter of approximately 110 mm and a gamma-gamma well logging tool with a ^{137}Cs radioactive source (Figure 2). As a light vehicle, it can access mine sites that a conventional logging unit could not access and expediting surface density determination process, when compared to conventional methodologies.

Figure 2: A. Drilling and recording unit for steady-state gamma-gamma for density determination in friable rocks. An electric drill (yellow device), intended to a meter-deep borehole excavation, is fixed on the back of the truck. B. Gamma-gamma well logging tool in operation.

RESULTS AND DISCUSSION

Optimal Time Determination

The acquisition time, or accumulation/stacking time, of the steady-state measurement is a critical variable for density measurements using the gamma-gamma well logging tool. The acquisition times recorded and analyzed at this step of the research were three, five and ten minutes, respectively. If the two minutes of acquisition time-frame were chosen, it would still be considered adequate. To ensure that the final distribution of measurements represents a normal distribution of density values, the optimal acquisition time. The final density value for each 1-meter-deep borehole is defined by calculating the arithmetic mean of each of the density values accumulated over that time.

Quality Control

Tool Calibration

Calibration, as considered in the context of this research, is the process of assigning values to measurements recorded by instruments (Hodges, 1988). The gamma-gamma well logging tool is calibrated using substances with standard density, as density of water (1 g/cm^3) and the density of aluminum (2.78 g/cm^3). During the calibration process the tool is left stationary, acquiring data for a period longer than 15 minutes in a drum filled with water and in an aluminum block. Figure 3 shows three different acquisitions (A, B and C measures) performed in the calibration drum with water to calibrate the gamma-gamma logging tool.

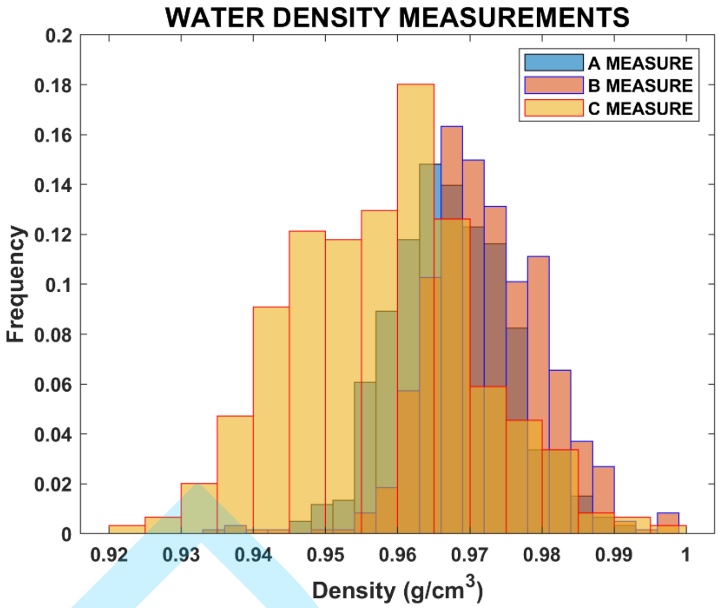

Figure 3: Density measurements in three different acquisitions (A, B and C measures) performed in the calibration case filled with water.

In Figure 3, each color represents a different acquisition (A, B and C measures). The distribution of density measurements for each acquisition is similar, indicating a homogeneity of water density measurements.

Figure 4 shows three different acquisitions performed in the aluminum calibration block for gamma-gamma borehole logging tool.

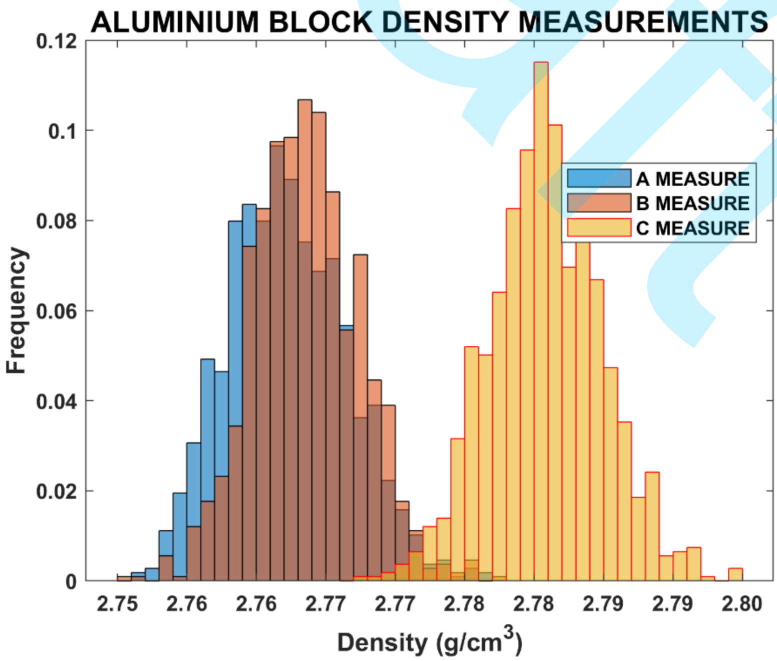

Figure 4: Density measurements in three different acquisitions (A, B and C measures) performed on the aluminum block. Note that two of the three different dataset populations are very close indicating the homogeneity of the aluminum density measurements.

The peaks of the histograms for the two closely aligned datasets (A and B measures) are approximately 2.76 g/cm^3. The third dataset (C measure) has its peak approximately 2.78 g/cm^3, indicating a slightly different density. Despite this slight variation, the density measurements of the aluminum block show consistency, with differences appearing in the second decimal place.

Tool Standardization

After the tool has been calibrated to standard densities, the standardization process takes place. The standardization of the gamma-gamma well logging tool is performed in the Vale's standardization field, in continuous depth acquisition mode and in a standardization jig with bearing steel balls in steady-state. The gauging field consists of four cylinders with different densities commonly found in iron ore exploration (Pereira et al., 2016). The density measurements of the blocks were certified by the Instituto de Pesquisas Tecnológicas de São Paulo (IPT) and show the density range values of 1.5 g/cm^3, 2.5 g/cm^3, 3.5 g/cm^3 and 4.5 g/cm^3.

Figure 5 shows the records in counts per second (cps) and the densities (g/cm^3) recorded in each gauging blocks at Vale's standardization field. On the right side (in red color), counts per second is plotted against the density values (on the left, in blue color) for each density gauging block with 1.5 g/cm^3, 2.5 g/cm^3, 3.5 g/cm^3 and 4.5 g/cm^3. Note that counts per second have lower values at higher densities and higher counts have relationship with lower densities.

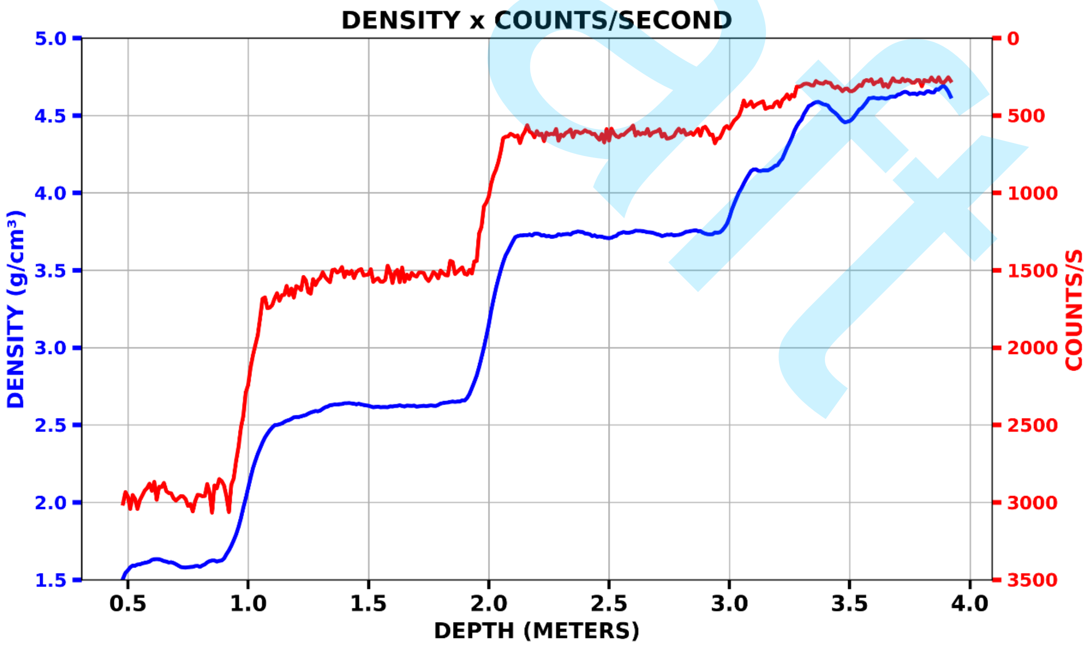

Figure 5: Counts per second versus density for each density gauging block. The blue line represents the measurements obtained from four gauging blocks (1.5 g/cm^3, 2.5 g/cm^3, 3.5 g/cm^3 and 4.5 g/cm^3), which form well-defined plateaus corresponding to the density of each block. The red line represents the corresponding counts per second.

Figure 6 shows three different acquisitions (A, B and C measures) of density measurement performed on the standardization jig. The standardization jig consists of bearing steel spheres with approximately 4.1 g/cm^3, simulating the density of iron ore. The acquisition time of density measurements is greater than 15 minutes.

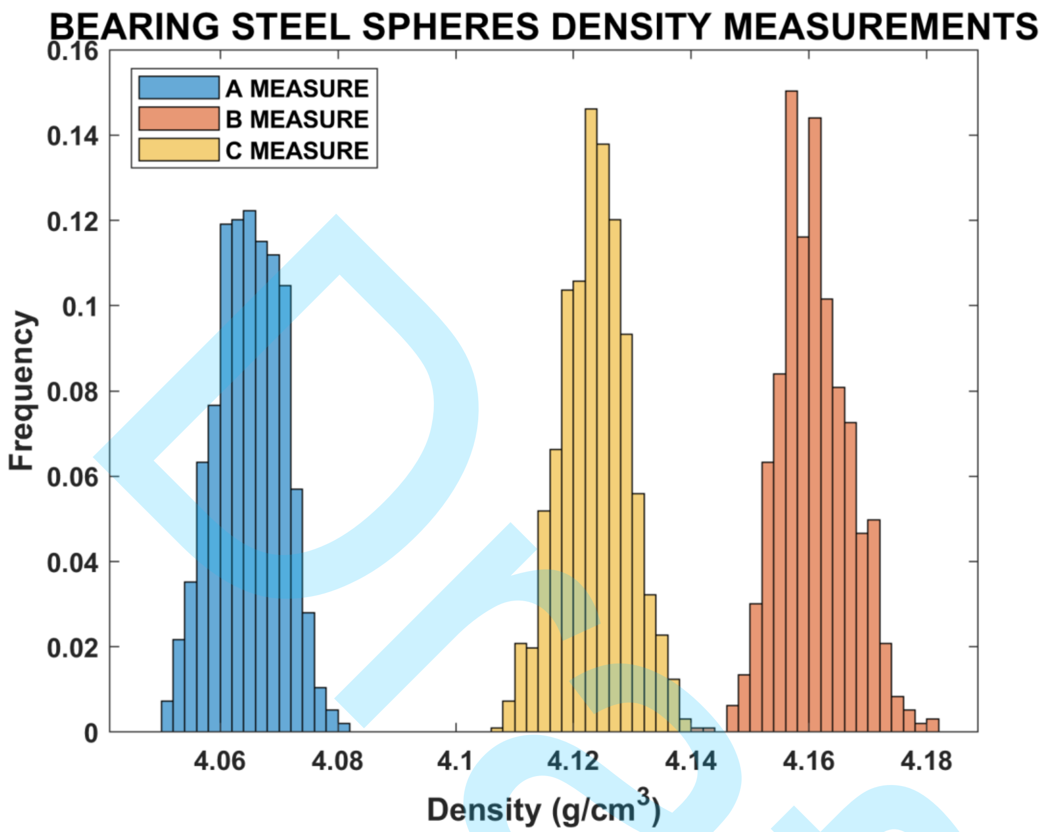

Figure 6: Density plots of measurements in three different acquisitions (A, B and C) performed on the standardization jig.

The three different populations of data could be due to the heterogeneity of the distribution due to positioning of steel bearing balls in the jig or to the different positioning of the tool in the jig. Another explanation for this difference is due to the voids between the spheres inside the jig.

Instrumental Drift Analysis

This procedure is performed before and after the field campaigns, in the water drum and in the aluminum block that are used for calibration tool. It aims to analyze the repeatability of density measurements over time.

Field Activities

Repeatability Tests

The number of the field repeatability measurements is made proportionally to the number of density measurement records performed in the field. A recommended value for the number of repeatability measurements would be every ten density measurements, when the first borehole of the day is measured again and so on. In exceptional cases, such as the extraction of a bench, carried out on the same day as the density measurement, it is suggested to return to the point closest to the measurement at the beginning of the working day. The aim of this step is to analyze the repeatability of density values acquired in the field. Figure 7 shows the repeatability analysis of a density measurement performed in a mineral deposit owned by Vale.

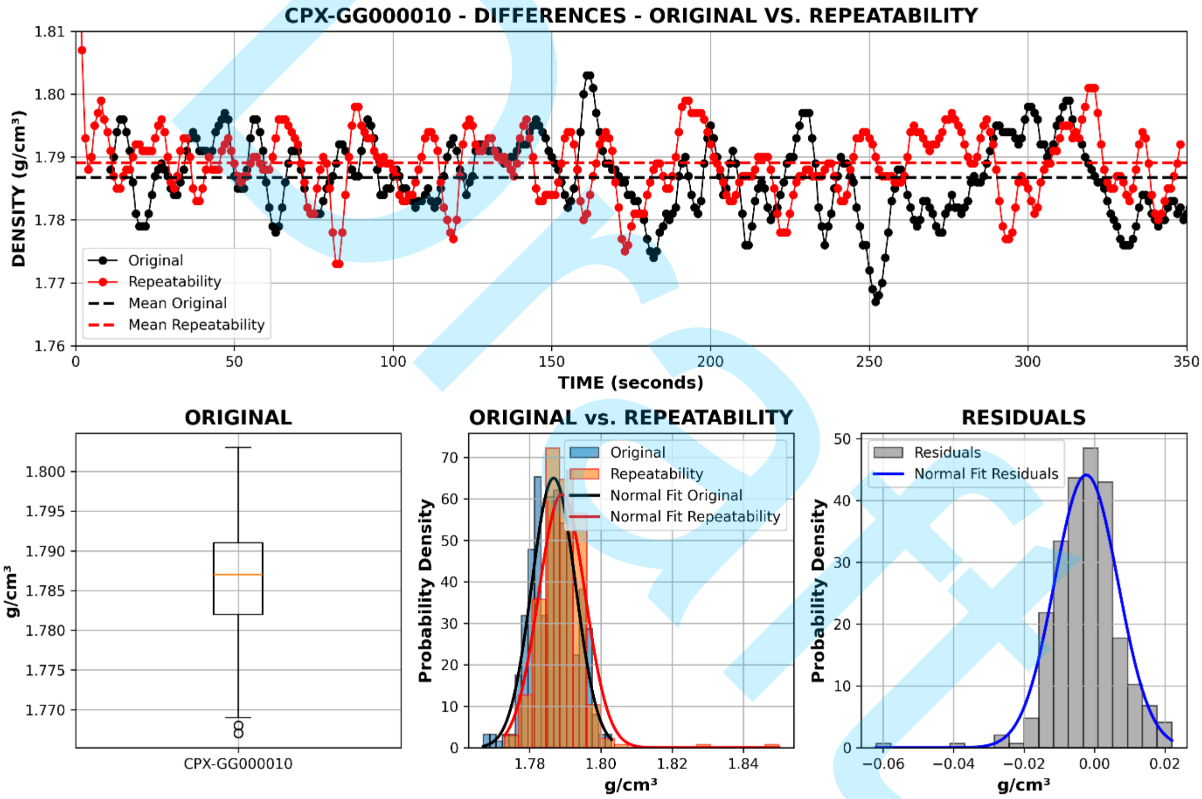

Figure 7: Upper Panel: The time-accumulated density values for the original dataset (black line with dots) and the repeatability dataset (red line with dots). The means are represented by black and red dashed lines, respectively. Lower Left Panel: A boxplot displaying the original density values. Lower Middle Panel: The probability density distributions of the original and repeatability datasets, with their respective normal fit curves. Lower Right Panel: The distribution of residuals between the original and repeatability datasets, with a normal fit curve overlay.

The upper panel indicates that the original density values and repeated measurements fluctuate over time but no more than 0.05 g/cm^3 in average. The boxplot in the lower left panel shows the central tendency with median around 1.787 g/cm^3. The lower middle panel shows that the distribution of the repeated measurements matches with the original measurements. Finally, the lower right panel shows that the residuals are centered around zero, suggesting that there is no systematic bias between the original and repeated measurements, demonstrating good repeatability.

CONCLUSIONS

A new methodology was developed to determine the density values in friable rocks mounted on a light vehicle (drilling and acquisition unit), called Steady-State Gamma-Gamma Density in Friable rocks.

The methodology has been used to obtain density measurements in friable lithology in Vale's mines including applications such as the density characterization of waste pile. As an example of its application, in a mine operation there were approximately 10 measurements taken using conventional techniques and after applying our methodology reaches approximately 400 measurements distributed in different lithologies in a well geological mesh.

The controls applied for calibration and standardization of the gamma-gamma well logging tool were developed for this work, for example, the determination of the optimal measurement time, the use of calibrations/standardization in the reference materials (water and aluminum), and the implementation of standardization in the measurement jig with bearing steel balls.

The proposed methodology offers an enhancement in density value acquisition. This innovative approach stands out for its significant improvement in the ability to acquire density values when compared to the standard practices that are widely currently employed in conventional methods, leading to more effective processes.

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DATA AND MATERIALS AVAILABILITY

The data and materials used in this research are not publicly available due to confidentiality agreements.

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Carlos, D. U.: Conceived and designed the study, interpreted the results, and wrote the initial manuscript and approved the final version. **Pereira, W. R.:** Drafted manuscript sections and approved the final version of manuscript. **Gárzon, N. P.:** Actively participate in the discussion of results and drafted manuscript sections. **Prieto, R.F.:** Drafted sections of the manuscript and critically reviewed the manuscript and approved the final version of the manuscript.