Integrated Geophysical Study at the Colonel Henry Anderson Morshead Burial Memorial, Valletta: Preliminary Results

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Abstract. This note covers the geophysical investigations carried out at the Colonel Henry Anderson Morshead burial memorial located within the Saluting Battery complex in Valletta. The main goal of the investigation is to digitally reconstruct the internal part of the memorial as well as the external monument. Furthermore, the derived 3D digital model was used to identify and locate cracks that need to be looked out. The area was also surveyed by means of a Ground Penetrating Radar (GPR) to map the subsoil of the ceremonial square at the city bastion. Here, the main documenting results are briefly presented and described, including the preliminary analysis of the photogrammetric and georadar digital datasets collected at the monument.

Keywords: Non-invasive diagnostics · Ground Penetrating Radar · 3D photogrammetry · Monumental site documentation

1 Introduction

Valletta's Saluting Battery sits in a commanding panoramic position overlooking the Grand Harbour (Fig. 1) and is an integral part of the defensive system built after the Great Siege of 1565. During that siege, the Ottomans had occupied the Mount Sciberras peninsula and installed powerful batteries there, which relentlessly bombarded Fort St. Angelo and the fortified cities of Vittoriosa and Senglea. Following the victory of the Order of St. John, construction of the new city of Valletta began in 1566, designed by military engineer Francesco Laparelli. On the site of an Ottoman battery, a powerful artillery platform was built to control the entire port.

The bastion of St. Peter and Paul, entrusted to the Order's Italian "language", became known as the Italian Post. The structure, quadrangular in shape and inclined outward for greater stability, included a large upper platform capable of housing numerous heavy cannon with an arc of fire not firing range of approximately 270°. In the 17th century, a covered loggia for the knights was added, later rotted away in 1775. In the first quarter of the 19th century, the upper section was transformed into a public garden (Upper

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Barracca Gardens) to which a series of housed commemorative monuments and plaques were added.

The lower section houses the Saluting Battery itself: a rectangular platform with a continuous low parapet, lateral and central powder magazines. From the beginning, it had a ceremonial function: the firing of gun salutes in honor of visiting dignitaries, ships, religious and civil commemorations, as well as salvos to announce key naval and military victories or for state funerals. From 1875, a noonday gun started being fired from here to announce the precise moment of the passage of midday at which maritime chronometers on board ships were to be regulated. Correct time on board ship was crucial for finding the Longitude at sea. This service continued until 1923, when it was replaced by radio time signals.

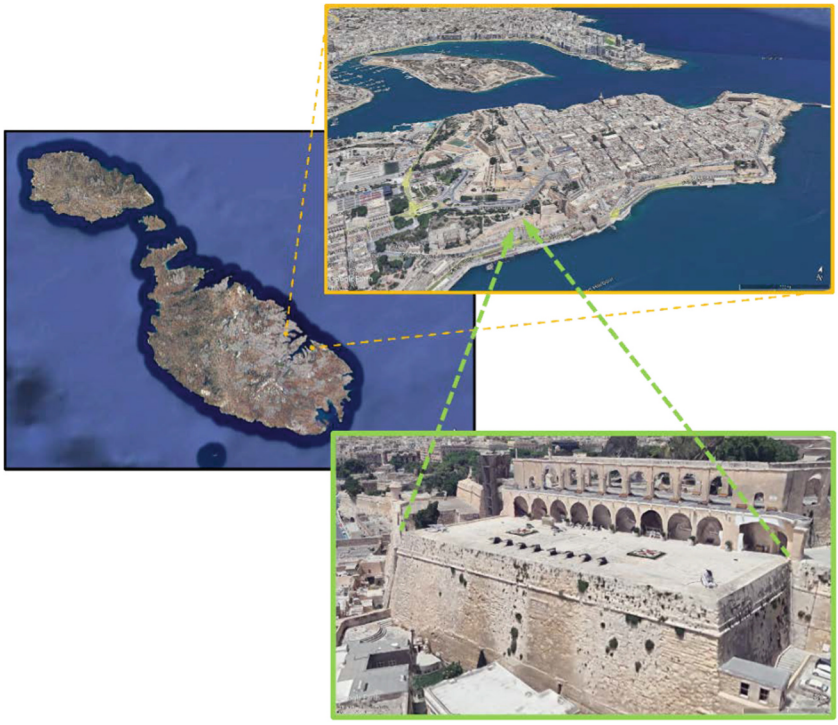

Fig. 1. Satellite view of the Maltese Archipelago, with a virtual perspective over the capital city of Valletta and, in green rectangle, of the bastion including the Upper Barracca Gardens and therein the Colonel Henry Anderson Morshead burial memorial (Google Earth source).

Over the centuries, the armament changed several times, reflecting the evolution of artillery: from the muzzle loading ordnance of the Knights' era to the French and British pieces after 1800, to the Smooth-Bore Breech Loading 32-pounders of the 19th century and the Quick Firing guns of the 20th century. During the First World War, salutes were suspended and were resumed with the Armistice of 1918.

In the 1921, following the granting of the self-government by the British agreement was reached between the civil and military authorities over the shared use of the area; the battery was partially opened to the public as part of the upper garden. During the Second World War, the guns were removed and replaced by a Bofors anti-aircraft gun; in 1942, bombings caused much damage, but Colonel Morshead's memorial although badly shaken remained standing. After a brief postwar revival, the battery was closed in 1948 and remained abandoned until 1971.

The Saluting Battery was restored in 2004 on the initiative of Fondazzjoni Wirt Artna – the Malta Heritage Trust. In 2011, eight working replicas of 32-pounder SBBL guns were installed for regular ceremonial firing. Today, the Saluting Battery is one of Valletta's main attractions: the noon-day gun and ceremonial salvos keep a centuries' old tradition alive, combining historical entertainment with the valorization of Maltese heritage.



Fig. 2. Pictures of the experimental data collection: views towards the Upper Barracca Gardens **(a)** and the Colonel Henry Anderson Morshead burial memorial **(b)**; acquisition of close-range photogrammetric data inside the memorial with a customized instrumentation **(c)** and acquisition of GPR data over the monumental square **(d)**.

This paper illustrates the geophysical investigations carried out at the Colonel Henry Anderson Morshead memorial and the main square located within the Saluting Battery complex in Valletta (Fig. 2). The main goal is to digitally reconstruct the external/internal parts of the memorial as well as the potential presence of cultural/historical features below the square pavement. Furthermore, the derived 3D digital model was used to

identify and locate cracks that need to be looked out. The balcony area was also surveyed by the mean of a Ground Penetrating Radar (GPR). The results related to the two analyses are here preliminary presented as the data interpretation is not completed as yet, and planned deeper and more detailed processing is expected to constrain general and local interpretation.

2 Methodology

2.1 Photogrammetric Survey and 3D Digital Model Reconstruction

In recent years, methodologies, technologies, approaches and software for creating digital models have undergone significant advancement and achievements. Acquisition time, post-processing tools and operational cost have also improved considerably, contributing to wider the use of such technologies in several fields. Digitization now allows reliable coverage of artefacts, ranging from small gauge (e.g. an archaeological prehistoric stone tool) to larger scales (e.g. building, urban segments or habitat areas), [1]. Photogrammetry can represent a key factor and in recent years it has been applied to planning, recording, reconstruction, and revitalization of world heritage sites [2–5]. It can also be used for supporting open-pit mine excavation stages and to plan rehabilitation strategies, as well as for forestry and management planning and disaster management [6–11]. One of the 3D digitization and reconstruction techniques is better known as photogrammetry which provides methods to obtain quantitative information. Photogrammetry can be described as the science to obtain reliable information about the spatial properties of land surfaces and objects, without physical contact [12–14]. By using reference terrain coordinates, it is possible to determine distance, area and other geographical information, as well as create detailed cartography. A further advantage of photogrammetric matching techniques is the fact that they are relatively fast and cheap in respect to the traditional laser scanner techniques [15], which are nowadays widely used in terrain models generating large amounts of 3D point data. To build a 3D model using photogrammetry, many types of images can be used such as satellite, airborne, balloon, UAVs (Unmanned Aerial Vehicles), terrestrial and even underwater images. In recent years, UAV photogrammetry imaging applications have increased rapidly due to the lower costs of a UAV for aerial surveying associated with the relative simplicity in operating such systems. With GNSS equipped drones, digital cameras and powerful computers, surveys with an accuracy of 1 to 2 cm are possible [16–20]. The 3D model of the study area has been developed by using the photogrammetry software Agisoft Metashape and the georeferencing process was carried out by using several ground control points collected through a GNSS survey for the topographic survey.

The processing of the images taken by the drone survey follow 4 main stages as sketched in Fig. 3 and summarized hereafter.

1. *Image acquisition and selection*: Images were acquired through the use of a digital camera installed on the drone assuring a good amount of image overlapping. Preliminary processing was carried out in order to discard those of poor quality.
2. *Camera alignment*: At this stage common points are selected on all the photo kept for the processing and matches through the use of photogrammetry software Agisoft

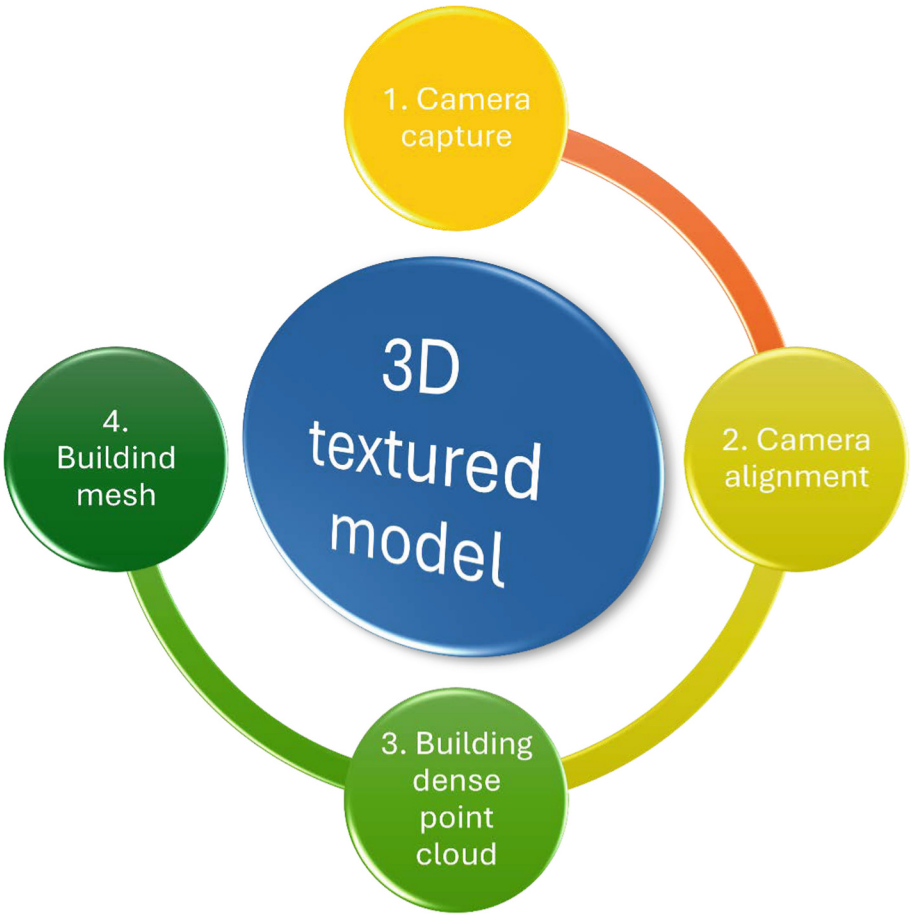

Fig. 3. Workflow processing to obtain the final 3D model.

Metashape. It also identified the position of the camera for each picture and refined camera calibration parameters. As a result, a sparse point cloud and a set of camera positions were obtained.

3. *Building dense point cloud*: The third stage involved the building of a dense point cloud based on the estimated camera positions corrected by the addition of ground control points to georeference the point cloud. If necessary, dense point cloud may be further edited and classified prior to export or proceeding to 3D mesh model generation.
4. *Building the mesh*: At this stage, the software was used to reconstruct a 3D polygonal mesh representing the object surface based on the dense or sparse point cloud according to the user's choice. Some corrections, such as mesh decimation, removal of detached components, closing of holes in the mesh, smoothing, were performed. Building texture: After the mesh geometry was reconstructed, the texture procedure

has been performed and the 3D model was created. It can be exported in several digital formats.

2.2 Ground Penetrating Radar

A wide range of geophysical techniques has been fruitfully applied to historical and cultural heritage sites, including electrical resistivity, frequency- and time-domain induction electromagnetics, magnetics, ground penetrating radar, gravity, seismics, radiometric surveys, thermography, multispectral, ground-based radar interferometry, and aerial and satellite remote sensing [21, 22].

Among them, ground-penetrating radar (GPR) is one of the most reliable, flexible and diffused methods thanks to its effectiveness (provided suitable environmental conditions) in identifying shallow natural and anthropogenic features with a high spatial resolution [3, 23–32]. GPR techniques have different on-field implementations, which mainly differ in the use of reflected or transmitted electromagnetic (EM) signals to study inaccessible domains of the medium. When only one surface of investigation is available, the most usual applications involve the use of zero- or quasi-zero-offset acquisitions by moving the GPR device in contact with the ground surface and recording the electromagnetic signals backscattered by the underlying scenario [32]. Reflections, refractions, and diffractions are generated in correspondence to the variations in the electromagnetic properties of the materials, producing the differences in velocity between the crossed subdomains [33, 34]. When a target inside the background medium has edges or dimensions comparable with the radar wavelength (that is, related to the velocity of the signal), diffraction is produced and electromagnetic waves are scattered in various directions. Even the minimum size of a recognizable target (spatial resolution) strongly depends on the wavelength of the electromagnetic signal, but it is also a function of the depth, having better resolutions for the shallowest domains [33, 34]. Signal attenuation across a medium is mostly dependent from the frequency of each component of the EM waves and to the properties of the crossed material, especially its electrical conductivity [33, 34].

GPR is de-facto a primary method for inspecting paved surfaces, in particular historical and precious pavements to search for past uses signs, archaeology, voids and possible metallic targets, like the expected scenario of the investigated semi-space at the Saluting Battery bastion. GPR can map buried foundations, ancient walls, and old road levels hidden beneath current paving. It has been used successfully in complex sites to reconstruct hidden architectural features [3, 4, 23–32, 35]. Furthermore, the GPR technology is extremely sensitive to changes in the physical properties of the subsurface, making it easy to identify air- or sediment-filled voids, like in the cases of buried rooms, crypts or burials. GPR systems detect metal objects (such as historical artifacts, pipes, or reinforcement) with high precision due to their high electromagnetic reflectivity and a particularly high Signal-to-Noise response.

The technology behind the probing system employed for the case in study is the Stepped-Frequency Continuous-Wave (SFCW) GPR, a subsurface imaging technology that transmits a sequence of discrete frequencies in linear “steps” rather than a single broadband pulse (Fig. 4). Unlike traditional Pulsed GPR, which operates in the time domain, SFCW GPR operates in the frequency domain:

1. *Sequential Stepping*: The radar sends out a sine wave at one frequency, then moves to the next, covering a wide range (Ultra-Wideband).
2. *Amplitude & Phase*: For every step, the receiver measures the amplitude and phase of the reflected signal.
3. *Synthetic Pulse*: Using an Inverse Discrete Fourier Transform (IDFT), the system converts the collected frequency data back into the time domain to create a high-resolution image of the subsurface.

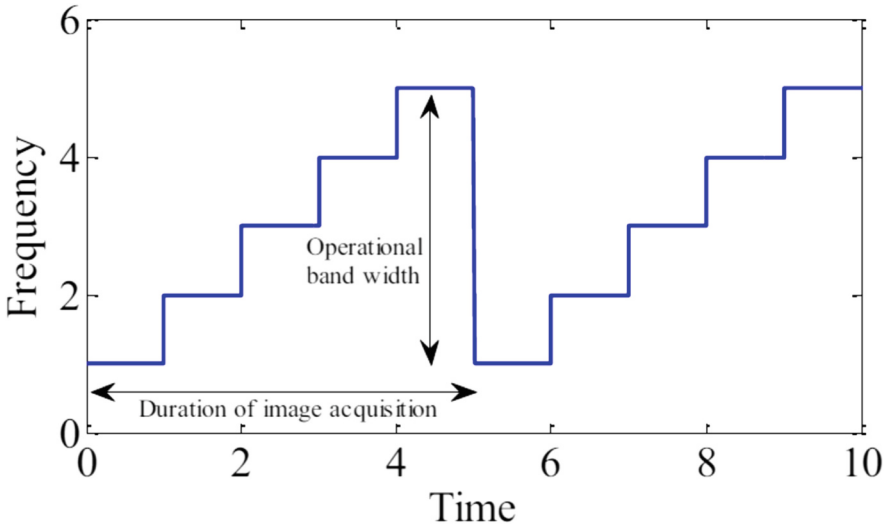

Fig. 4. Illustrative spectrum of a Stepped Frequency Continuous Wave signal (from [36]).

The experimental GPR data collection has been carried out with a zero-offset antenna setup constituted by a Screening Eagle SFCW GPR, model Proceq GS8000 Pro, with a modulated frequency over range of 40–3440 MHz, odometer and a multiband GNSS positioning system (including GPS + Glonass + Galileo + Beidou constellations). GPR system was controlled during the acquisition by the operator through a tablet connected to the internet for immediate data upload to a processing cloud environment provided by the GPR manufacturer with the availability of the most common processing steps, including band-pass filtering, background removal, gain correction, data interpolation and 3D C-scans production.

3 Data Acquisition, Processing and Results

3.1 Photogrammetry and 3D Digital Model

In this study, a small endoscopic camera and a LED light system were used in order to maximize the safety (towards the monument) during data acquisition as well as make use of the small opening realized specifically for the survey. The images were acquired

keeping the camera at the minimum focal length, while the image resolution was set at the highest level in order to acquire good quality textures. The images were taken from different-looking directions and about 80% forward overlap and 75% side overlap.

Throughout the area of interest, several markers were placed on the ground and the walls of the monument. The use of the marker was necessary to ensure correct and precise spatial-referencing of the area in order to properly export the final 3D to scale from which all the mapping and measurements have been taken. We performed four separate photogrammetry surveys and the 3D model of the study area has been developed by using the photogrammetry software Agisoft Metashape and the spatial-referencing and scaling process was carried out by using ground control points collected. More details about the processing can be found in [18]. A 3D laser distometer was used to collect the exact position of the markers and to enhance the topographical survey, which helped to produce the requested CAD (computer-aided design) drawing which will accurately detail the surveyed points. The site survey and the final CAD allows to produce a wide range of information which can be used to produce drawings. The survey results can be used for:

- Drawings – Plans, elevations, sections and lighting plans;
- 3D Point Clouds – The information can be used to produce 3D models of a site;
- Photographs – Useful for people who are looking for information about a site;
- Schedules – Including mapping of hidden structures/features

The monument was also surveyed by the use of a small Lidar instrument which is a method for determining variable distance by targeting an object or a surface with a laser and measuring the time for the reflected light to return to the receiver. It can also be used to make digital 3D representations of areas.

Figure 5 shows the 3D-derived model of the entire structure from different angles. It is possible to notice that the coupling of all the data permitted to create a unique 3D digital model which includes also the crypt underneath the “saluting battery square”. By using the 3D model we were able to map, with high precision, the location, as well as the thickness, of several features. In this case, we measured, as an example, the size of the coffin as well as of the internal part of the crypt.

3.2 Ground Penetrating Radar

The experimental GPR data collection has been carried out with a zero-offset SFCW GPR system, namely the Proceq GS8000 Pro model (40–3440 MHz). Data were acquired in a free-path fashion, following the automatic real-time generation of brief amplitude maps while continuing walking, allowing the operator to correct their path and fill the eventual empty areas between the lines distant more than the interpolation radius. After the campaign collection activity is closed and data is sent to the processing cloud environment provided by the GPR manufacturer, they are processed following the most diffuse standards, including band-pass filtering, background removal, zero-timing and gain correction, velocity analysis and time-to-depth correction, migration, Hilbert-transform, data interpolation and 3D C-scans production. In the following Fig. 6, a global view of the processed 3D dataset is provided, with color scale indicating the instantaneous amplitudes of the GPR signals, and, laterally, a histogram of the statistical distribution

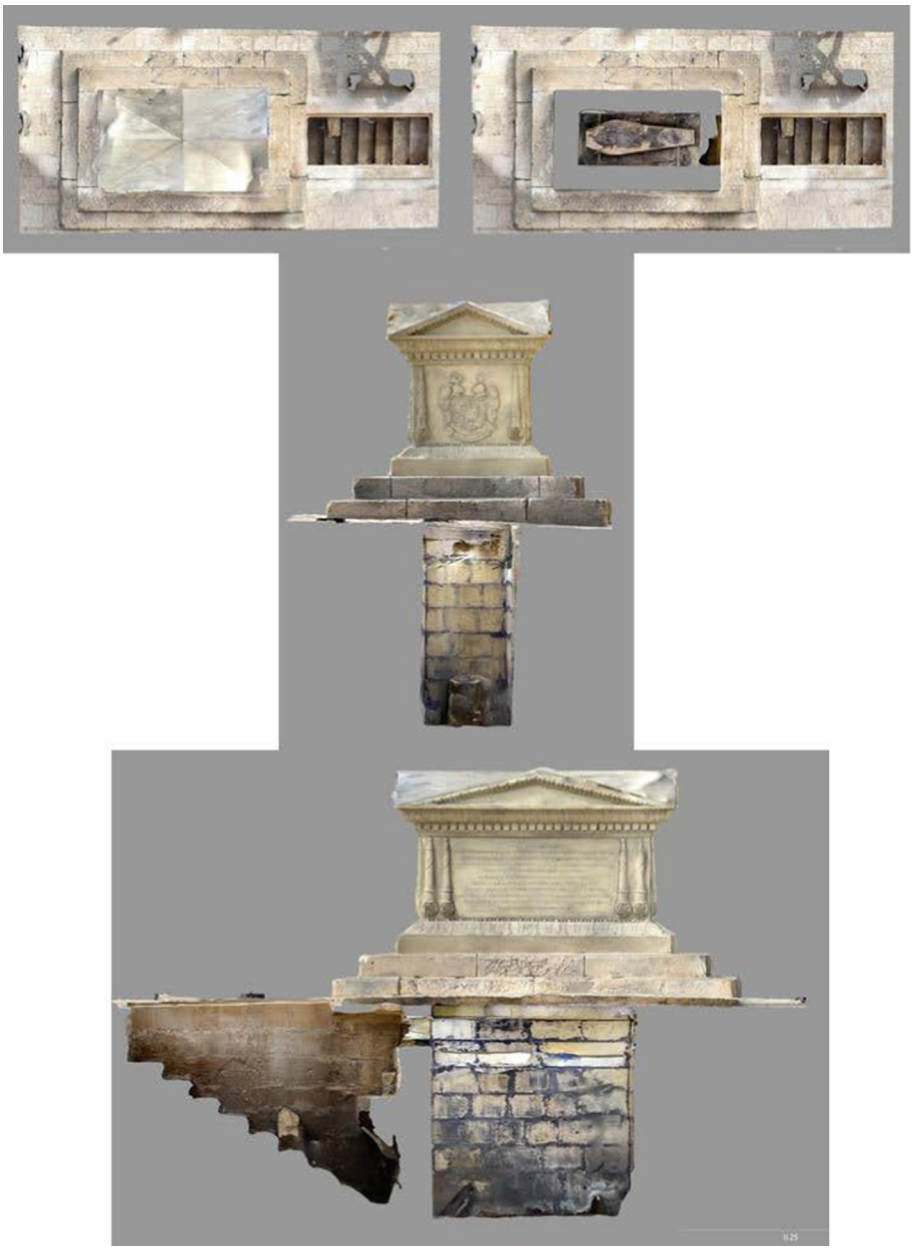

Fig. 5. Images of the 3D digital model of the memorial monument and its underneath structure.

of each amplitude value. It is possible to evaluate how much stretched the color scale is, and the quite regular distributions of the red tones indicating the few most energetic radar events.

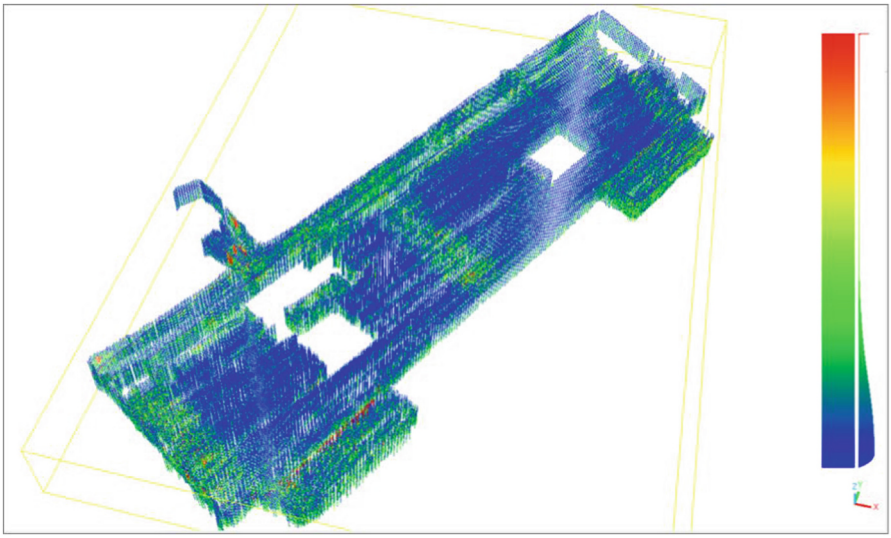

Fig. 6. Volumetric distribution of the GPR signals below the monumental square; color-bar represents the amplitudes range of the recorded wavelets after the data processing and the histogram shows the data statistical distribution along the same amplitudes range.

The graphical interpretation of preliminary GPR results is given in the following Fig. 7, where, with a different palette from the previous Fig. 6, amplitude scale is produced in a monotone ramp from white/light-gray (low amplitudes voxels) to dark reds (high amplitudes). The palette extension and coloring is a little less effective in highlighting short-range patterns but allows to clearly identify large areas/volumes with peculiar values ranges which can possibly be attributable to the signatures of different historic pavement finishes which are currently invisible at the surface due to the modern restorations (green highlighted volumes). Two large volumes correpsonding to the areas bordering the current cannoon battery also present a distinctive medium-to-high amplitude response, and can be attributable to the remaining signature of the ancient pavement or to different structural composition of the bastion at its limits. The most reflective targets noticed in the previous Fig. 6 are globally still recognizeable and locally even clearer and more contrasted with regards to the background. The orange dashed area/volume close to the colonnade seems to be the most interesting and candidate to further detailed analysis and investigations.

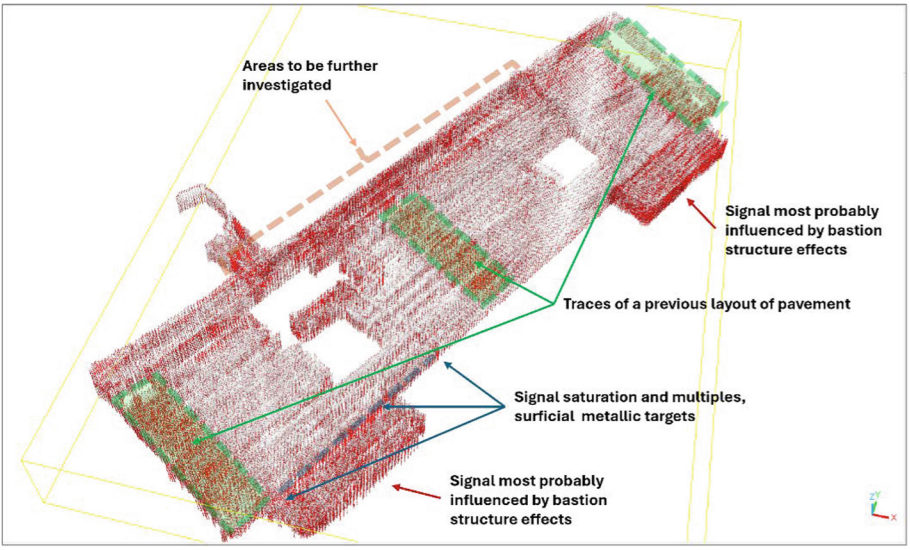

Fig. 7. Preliminary interpretation of the volumetric distribution of the GPR signals below the monumental square (color-scale from bright, low amplitudes, to dark red, high amplitudes).

4 Concluding Remarks

The application of geomatics and geophysical techniques, that is becoming a diffuse integration in high-level diagnostic investigations of Cultural Heritage sites, demonstrated here at the Colonel Henry Anderson Morshead burial memorial and the Saluting Battery square (bastion of St. Peter and Paul in Valletta, Malta) the capacity to reliably and deeply document the precious assets in detailed 3D models of visible and invisible parts through a low-invasive approach. Thanks to a customized acquisition setup, the photogrammetric survey allowed, among other results, to detect internal structural defects of the underground burial room, that we plan to map and fully interpret in a next detailed analysis. The ground penetration radar allowed to reconstruct the reflective behavior of the first volumes below a large and precious paved monumental area in a totally non invasive fashion: the preliminary interpretation of GPR datasets possibly points to the signs of the past and/or recent uses of the area (from a historic pavement remains, to cannonballs and bullets, from superficial metallic features to structural components of the bastion). The current analysis -which needs to further detailing- currently excludes the presence of large burials, but a large part (around 10% of the surveyed area) needs for additional investigation due to a diffuse -apparently incoherent- high-amplitude GPR signal response.

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Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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