How High-Frequency GPR Solved a 2,000-Year-Old Transport Dilemma for the Antikythera Statues

The collection of statues of "Antikythera Shipwreck» is composed from many statues build from white marble coming from the Greek Island of Paros. These statues have been found in the sea bottom of Antikythera Island, south of Peloponnese in 1900, from fishermen.

These marbles, found in pieces have been conserved in the Athens Archaeological Museum in 1970 by installing metallic bars (joints) to fix different parts of them. Unfortunately, the conservation records are missing and there is no information about the emplacement and the size of each bar in these statues.

Ten years ago a part of the Collection of Antikythera Shipwreck had to be transported to Basel Museum (Switzerland) and to be exhibited there for a limited period. This fact implies the necessity to study the static capacity of each statue to be transported, in order to assure his own safe packing methodology and transport. The allocation of these metallic parts into each statue's body becomes now critical to estimate his own static capacity.

To achieve this task, GEOSERVICE Company developed one new, object adapted method, using as basic standard the very well-known method of Ground Penetrating Radar.

The method was applied in five specific statues:

1. The Wrestler
2. The Hermes of Antikythera
3. The Helmeted
4. The Achilles of Antikythera
5. The Ulisse of Antikythera

All these works have been carried out in the National Archaeological Museum of Athens, under the supervision of Mr. Dimitriadis Klisthenis (M.Sc. Geophysicist).

In addition:

- Mr. Yannis Konstantakis (GEOSERVICE), expert in GPR measurements was in charge of all scans.
- Ms. Pepi Avlonitou (GEOSERVICE), expert in graphics design has realized the graphics synthesis of images together with the raster images coming from the GPR processed results. Overlying the GPR results in the according high resolution images has improved the visualization of the specific targets.
- Dr. Mike Langton, Senior Applications Engineer at Guideline Geo MALA and Honorary Visiting Lecturer/Researcher at University of Bradford. Especially Dr. Langton provided to us in GEOSERVICE one continuous support and assistance and we would like to thank him for this contribution among these lines.

In this summary we will describe only the methodology only for the statue Wrestler. However the methodology was the same for all the other statues.

We have used the GPR CX-12 of MALA GEOSCIENCE. The process of scanning was based in performing one two dimensional grid of parallel scans with a grid size (cell) of 5 cm. The X and Y sizes of the grid varied according to the specific area to be investigated. For each target, one separate grid was performed.

The processing was effected using the dedicated software of MALA GEOSCIENCE, named "3D - Vision", licensed to GEOSERVICE. In general, metallic targets appear as strong white areas (reflections) in one black/grey background. In many cases, the parallel use of one metal detector was proved very effective in order to validate with one other physical method the existence of metal. However, the metal detector is unable to give the geometry of the metal and was used only in the binary concept of Y/N for the existence of metal. Although the application of GPR in one two dimensional approach is one relatively easy process and widely applied especially in cement surfaces, in the case of statues or irregular surfaces becomes a very hard application. The reason is the fact that the emitted pulse travels in non-uniform media, composed from air - marble due to the surface irregularity and the resulting reflections do not correspond to the exact depth where they belong. The velocity of the electromagnetic pulse in the air is known (30 cm/ nanosecond) and in the case of marble varies from 10 to 12 cm/nanosecond).

For this reason, one specific velocity calibration was carried out in one flat surface of white marble. The measured/calculated velocity was found to be 10,2 cm/nanosecond.

Figure 1 Calculation of the propagation velocity in the marble using the method of "hyperbola fitting" of the 3D-Vision software

In the following Figure the process of scanning one specific area of the statue "the Wrestler of Antikythera" is presented:

Figure 2 The process of scanning one specific area of the statue "Wrestler of Antikythera"

STATUE "WRESTLER OF ANTIKYTHERA"

The statue "Wrestler of Antikythera" was found partially in sea bottom. Part of the statue (his right side, including the head) was exposed to the sea erosion for more than 2000 years and this fact has as result one significant destruction of this building material. In contrary, the left side of the statue, being buried below the sea bottom into the sand, has been kept intact because the sea microorganisms were unable to affect this side. However, possibly during the excavation or transport, damages have been occurred also in this part and the restoration imposed to install additional iron bars to consolidate the entire structure.

According to the visible cracks, three specific grids have been installed to examine the statue. The result of the raster output from the GPR scan, shows the emplacement of the internal metal bars. In fact the metal

acts as a strong reflector and produces one whitish area in the 3D slices. By replacing the fiberglass grid with one virtual graphics grid and adjusting the images, the location and the extent of each metal bar is mapped on the statue. In this form of visualization, all the following results have been derived from the measurements.

Figure 3 Superposition of the raster image from the GPR scan on the statue (Wrester of Antikythera)

When preparing ancient masterworks for international museum loans, structural integrity is the primary constraint.

In the lead-up to an exhibition at the Basel Museum in Switzerland, the National Archaeological Museum in Athens faced a complex conservation challenge: safely transporting priceless 2nd-century BC Pariah marble statues recovered from the famous Antikythera Shipwreck. To stabilize these heavily fractured sculptures during 1970s restoration efforts, conservators inserted internal metallic dowels and joint pins. However, all conservation records detailing the exact location, length, and trajectory of these internal reinforcements were missing.

Before designing custom packing, isolation crates, and transport frames, structural engineers needed answers:

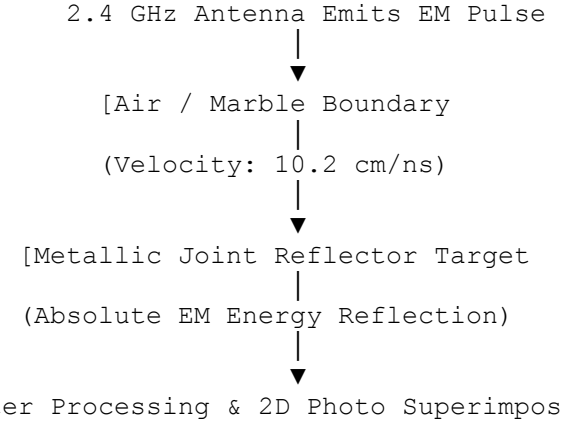
- *Where were the load-bearing pins located?*
- *How far into the marble did they extend?*
- *Which structural fractures contained internal metal, and which were unreinforced?*

To resolve this without invasive sampling, GEOSERVICE was commissioned to execute a non-destructive testing (NDT) campaign across the collection.

Ground Penetrating Radar (GPR) is widely utilized in civil engineering to map rebar in flat concrete, but adapting electromagnetic wave propagation to irregular, three-dimensional heritage sculptures presents distinct technical hurdles. Surface curvature, varying air-stone gaps, and complex wave attenuation in weathered marble require refined calibration.

To address these parameters, GEOSERVICE executed a dedicated survey workflow:

- **Instrumentation & Resolution:** We deployed a MALA Geoscience CX-12 GPR system utilizing a high-frequency **2.4 GHz antenna**. This configuration achieved a high spatial resolution of **0.5 cm** with a maximum target depth penetration of **50 cm**—ideal for detecting narrow metal pins inside solid marble.
- **Precision Velocity Calibration:** Electromagnetic pulse velocity varies significantly between air and marble. Using hyperbola fitting algorithms on a flat control surface of pure white marble, our team calculated a precise wave propagation velocity. This allowed us to convert two-way travel times into accurate millimeter-depth measurements of internal targets.
- **Grid Mapping & Secondary Validation:** Scans were executed in orthogonal 2D grids with a dense 5X5 cm cell spacing directly over suspected fracture zones. To eliminate false positives, a high-sensitivity electromagnetic metal detector was run in parallel to confirm metallic presence.



3D Raster Processing & 2D Photo Superimposition

By combining processing software with specialized graphics integration, the GPR amplitude slices were superimposed directly onto high-resolution raster images of the statues. This provided conservators and logistics teams with intuitive 3D structural overlays.

Key Observations across the Collection:

- **The "Wrestler of Antikythera":** GPR scans across high-stress zones confirmed metal dowel placement at every visible external crack. Interestingly, scan data across the right arm revealed reflection signatures characteristic of iron corrosion product expansion—indicating a reinforcement likely inserted during the ancient sculptor's production phase rather than modern restoration.
- **The "Hermes of Antikythera":** Scanning confirmed structural integrity throughout the head assembly while mapping the exact embedment depth of support pins in the lower and upper right foot sections.
- **The "Helmeted Statue":** Extensive internal metal networks were mapped across heavily corroded sections, providing the exact load-bearing data necessary to model the statue's static capacity during transport.

This project demonstrates that high-frequency GPR offers a repeatable, fast, and entirely safe methodology for heritage structural diagnostics.

For conservators, structural engineers, and art handling specialists, integrating high-frequency NDT into pre-transport protocol delivers three key benefits:

- **Accurate Static Capacity Modeling:** Logistics teams can design bespoke packing and support structures based on actual internal load paths rather than assumptions.
- **Historical Diagnostic Insights:** High-resolution dielectric contrast makes it possible to distinguish between 20th-century stainless/iron restoration joints and ancient structural modifications.
- **Zero Risk to Artifacts:** High-frequency electromagnetic scanning delivers zero physical stress, zero thermal load, and zero radiation to delicate calcite stone.

Whether evaluating stone sculptures, historic masonry, or ancient architectural elements, non-destructive geophysical techniques provide the critical clarity needed to preserve cultural treasures for future generations.

Is your institution planning an upcoming international loan or structural conservation assessment?

Contact us to discuss how custom high-frequency NDT solutions can protect your collection.

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