A new diver-held tool that directly measures the total magnetic gradient using a single total-field magnetometer sensor, for locating buried ferrous objects in magnetically challenging environments

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Abstract

A new diver-held magnetometer has been developed that directly senses the total magnetic gradient as a scalar quantity, independent of the orientation of the device. It therefore provides a direct signal if a magnetic (e.g. ferrous) object is in its vicinity, regardless of other ambient geomagnetic effects. The small (7cm diameter x75cm length), battery-powered device is neutrally buoyant, and provides a simple and intuitive audio interface to the diver. The device was field tested in July 2019 during the Lost Ships of Cortés Project offshore Villa Rica, Mexico, an area with strong underlying volcanic geology and large quantities of magnetic sediment that mask buried archaeological materials. Magnetic anomalies were recorded during boat-towed total-field magnetometer surveys, but divers could not identify their source using traditional underwater metal detectors. The new magnetometer decisively and precisely guided divers to an early 16th-century anchor at a range of several meters that was completely buried in magnetite-rich sand with its shallowest point at 50cm below the sea floor.

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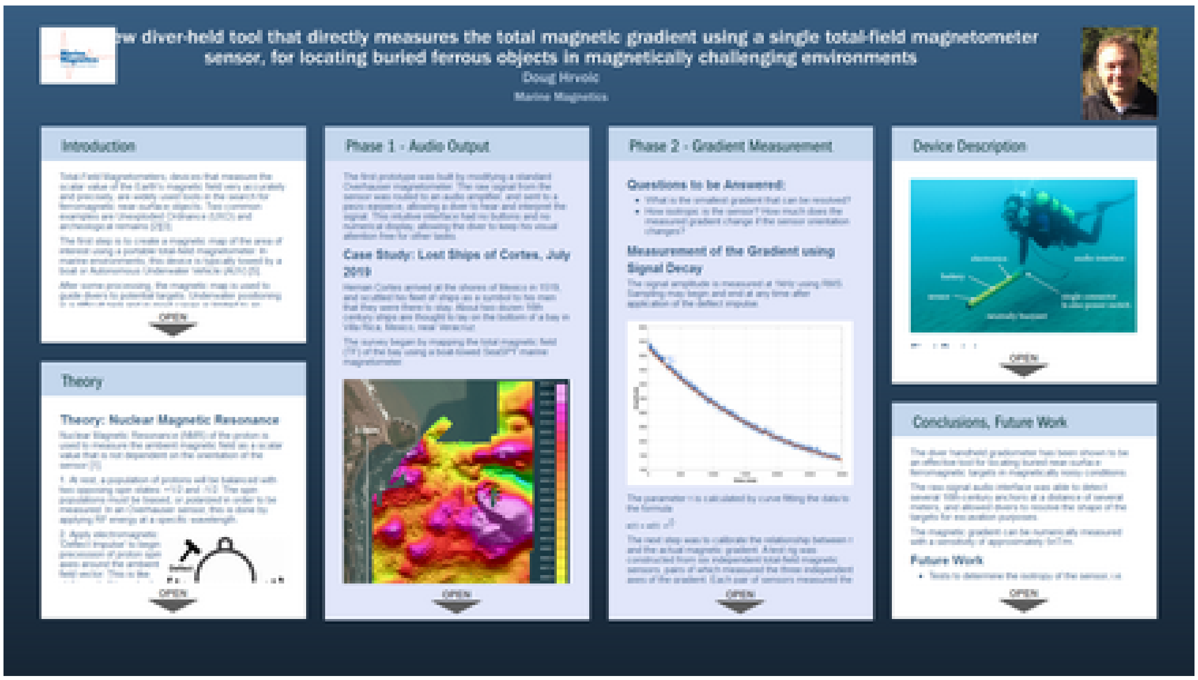

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Marine Magnetics

PRESENTED AT:

INTRODUCTION

Total-Field Magnetometers, devices that measure the scalar value of the Earth's magnetic field very accurately and precisely, are widely used tools in the search for ferromagnetic near-surface objects. Two common examples are Unexploded Ordnance (UXO) and archeological remains [2][3].

The first step is to create a magnetic map of the area of interest using a portable total-field magnetometer. In marine environments, this device is typically towed by a boat or Autonomous Underwater Vehicle (AUV) [5].

After some processing, the magnetic map is used to guide divers to potential targets. Underwater positioning is a difficult task and in most cases is limited to an accuracy of several meters [3][5].

If targets are exposed on the sea floor, divers can use visual guidance to compensate for positioning inaccuracies. But if the targets are buried in sediment, it can be impossible for divers to locate the target.

Clearly, a solution is for divers to carry a tool that can detect targets in-situ. Some of these tools are:

1. Pulse-induction metal detectors can sense conductive materials, but have very short range, especially in salt water [4].
2. Handheld magnetometers sense the total-field, which is an arbitrary value when not in map form. It is also influenced by unwanted magnetic sources such as underlying geology, or magnetic sediment.
3. A traditional magnetic gradiometer would detect the presence of a near-surface target at longer range than a metal detector, but would require multiple total-field sensors, making it bulky and expensive.

This poster describes a magnetic gradiometer that uses a single total-field magnetometer sensor. It is therefore small, easy to handle, and relatively inexpensive.

This gradiometer measures the magnetic gradient as a scalar value, independent of the orientation of the sensor or direction of the gradient. This provides the diver with an immediate indication if a target is nearby, and is capable of guiding the diver precisely to the target's closest point.

THEORY

Theory: Nuclear Magnetic Resonance

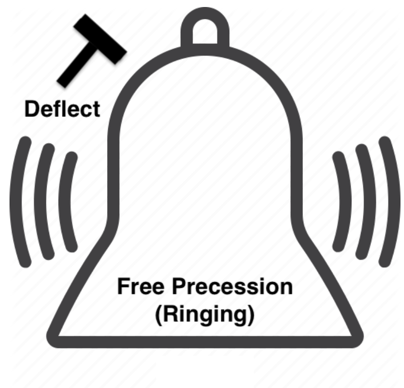
Nuclear Magnetic Resonance (NMR) of the proton is used to measure the ambient magnetic field as a scalar value that is not dependent on the orientation of the sensor [1].

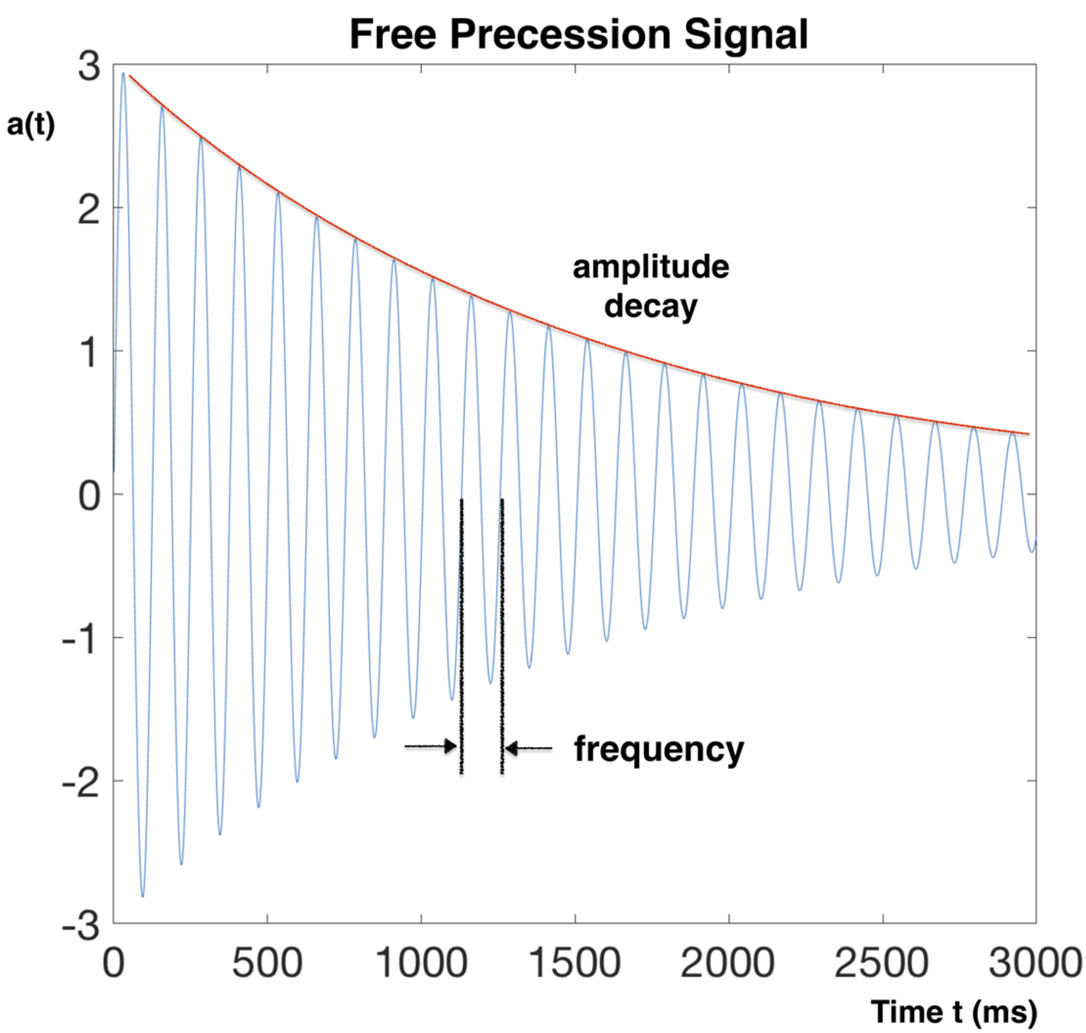
1. At rest, a population of protons will be balanced with two opposing spin states: +1/2 and -1/2. The spin populations must be biased, or *polarized* in order to be measured. In an Overhauser sensor, this is done by applying RF energy at a specific wavelength.

2. Apply electromagnetic 'Deflect Impulse' to begin precession of proton spin axes around the ambient field vector. This is like striking a bell to make it start ringing.

3. Atomic nuclei *resonate* at a frequency that is proportional to the ambient field.

4. The resonance decays as spin axes return to the ambient field direction. This happens at a predictable rate.





The amplitude decays according to [1]:

$$a(t) = a(0) \cdot e^{\frac{-t}{\tau}}$$

Where a(t) is the signal amplitude at time t. This exponential function is dependent on the parameter τ, which is a characteristic of the sensor liquid, and is maximum when the magnetic field across the sensor volume is homogeneous.

As the magnetic gradient across the sensor volume increases, τ decreases proportionately.

Two Independent Measurements

Total Magnetic FIeld:

$$B \propto frequency$$

Total Magnetic Gradient:

$$\nabla B \propto \tau$$

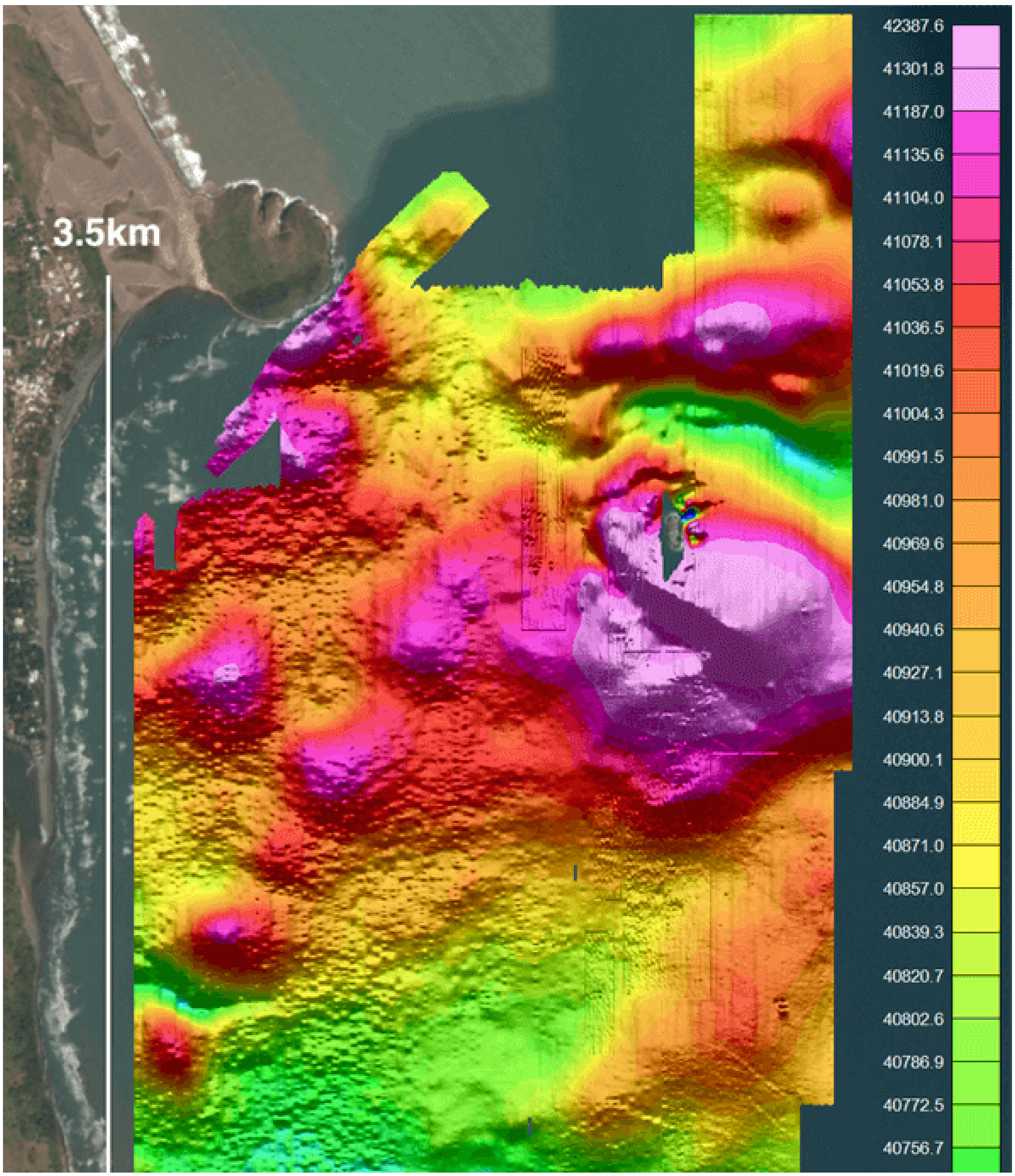
PHASE 1 - AUDIO OUTPUT

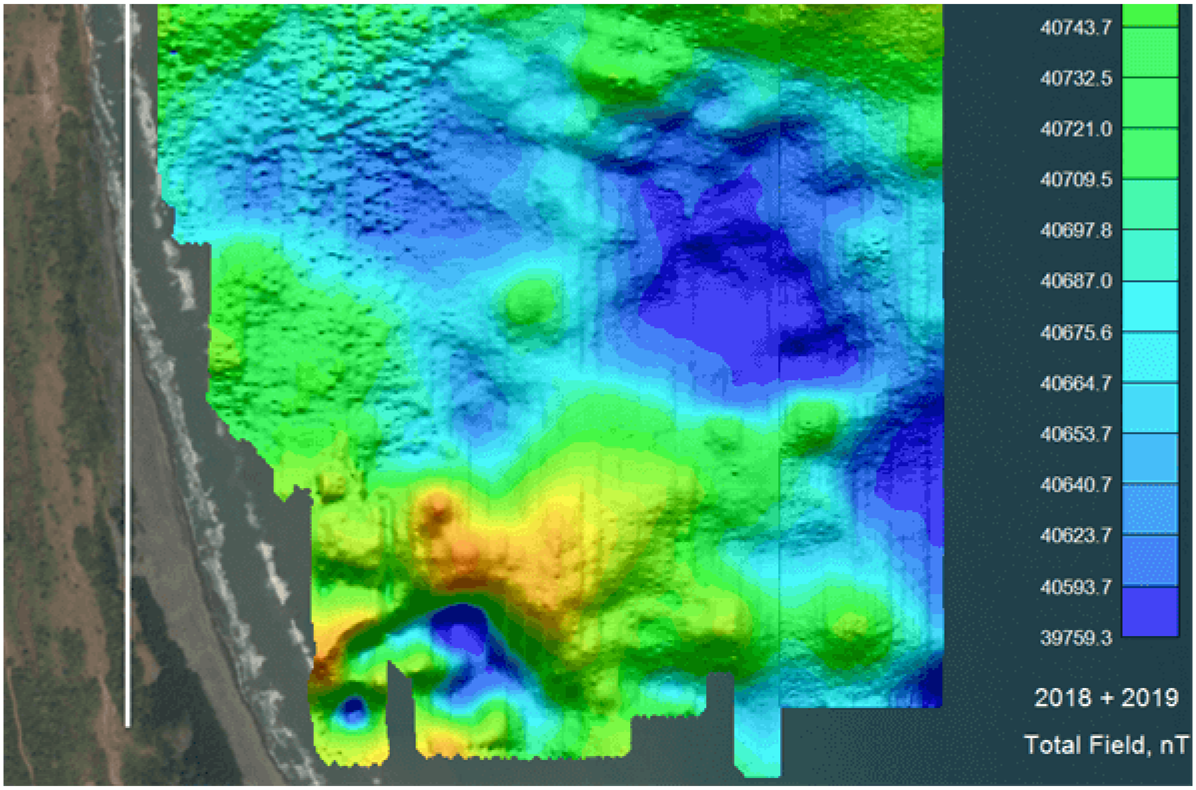
The first prototype was built by modifying a standard Overhauser magnetometer. The raw signal from the sensor was routed to an audio amplifier, and sent to a piezo earpiece, allowing a diver to hear and interpret the signal. This intuitive interface had no buttons and no numerical display, allowing the diver to keep his visual attention free for other tasks.

Case Study: Lost Ships of Cortes, July 2019

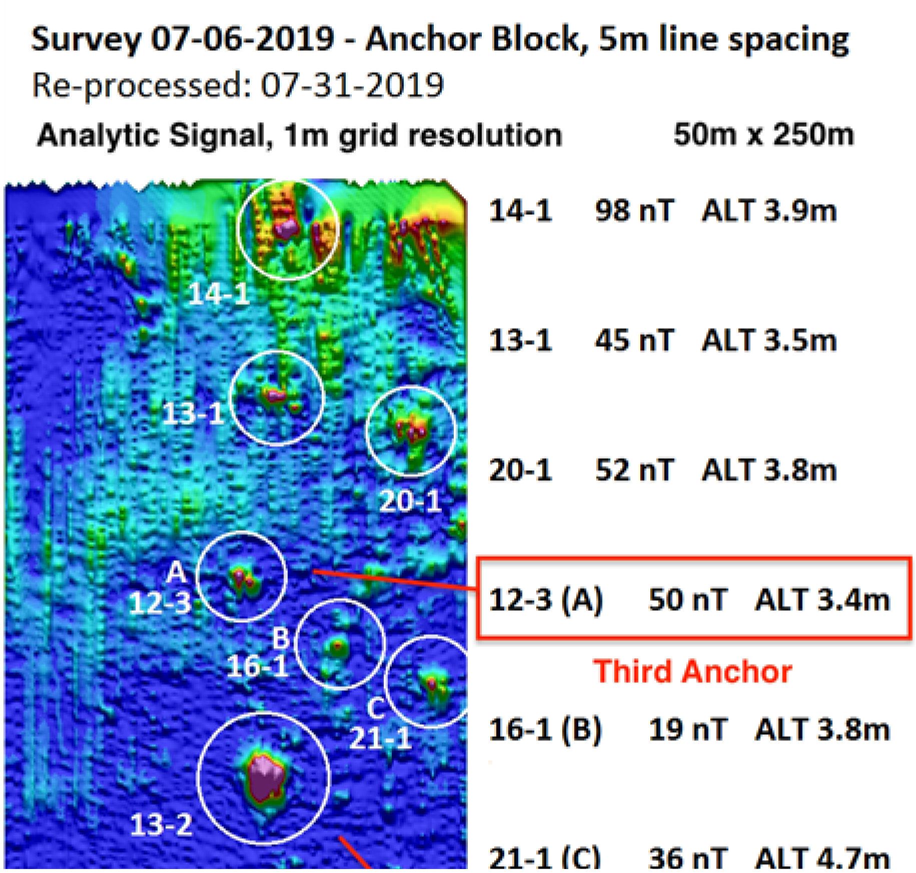
Hernan Cortes arrived at the shores of Mexico in 1519, and scuttled his fleet of ships as a symbol to his men that they were there to stay. About two dozen 16th century ships are thought to lay on the bottom of a bay in Villa Rica, Mexico, near Veracruz.

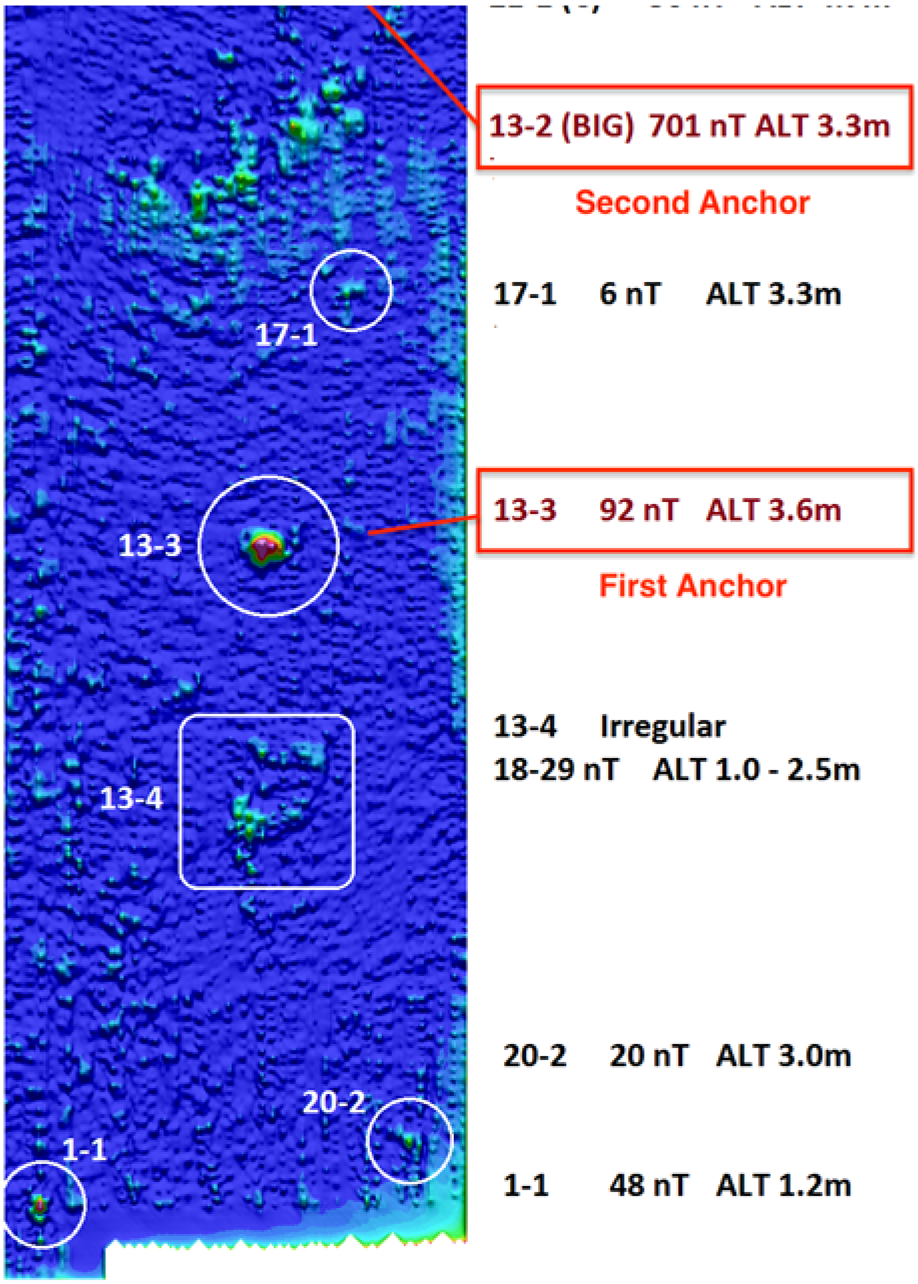
The survey began by mapping the total magnetic field (TF) of the bay using a boat-towed SeaSPY marine magnetometer.





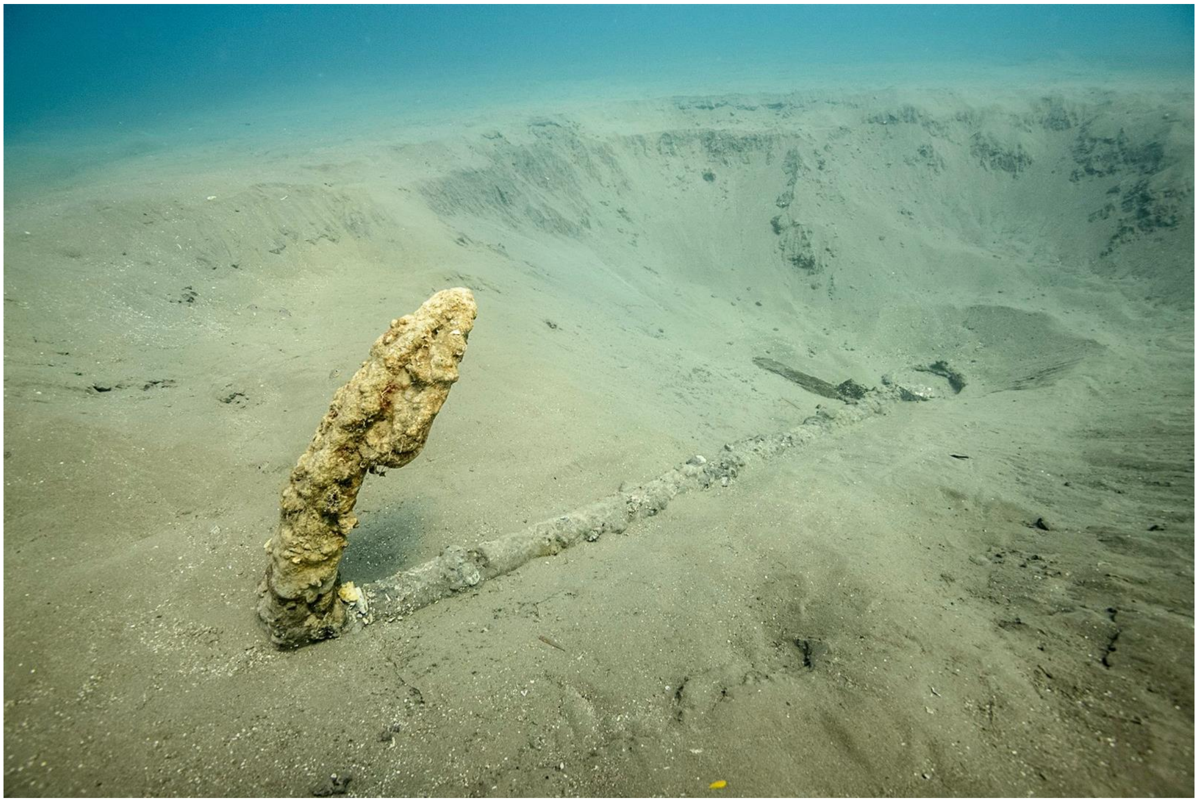
Strong volcanic underlying geology created widely varying TF signals. The Total Gradient, or Analytic Signal (AS) map was computed from the TF grid, suppressing most geological effects, and allowing many near-surface targets to be identified. A zoomed area of the above map is shown below.





Large amounts of highly mobile sediment in the bay visually obscured all targets that were investigated. Furthermore, the sediment (sand and clay mix) was strongly magnetic due to magnetite content, and prevented the operation of pulse-induction metal detectors.

[VIDEO] https://www.youtube.com/embed/cNl-UzgDrB0?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
The diver-held gradiometer was able to detect a target at an initial range of several meters, and precisely guided divers to the target's closest point below the sea floor. The image shows the target after several days of excavation.



The target (13-3 in the AS map above) was a ship's anchor. The closest point (tip of the fluke) was buried under 0.5m of sand and clay. Wood found on the anchor's stock was carbon-dated to the late 15th century, indiciating with high likelihood that this anchor belonged to Cortes' fleet.

Two other nearby targets were also detected with the handheld gradiometer, and after excavation were identified also as anchors. Their style of fabrication indicates their origins were also approximately 16th century.

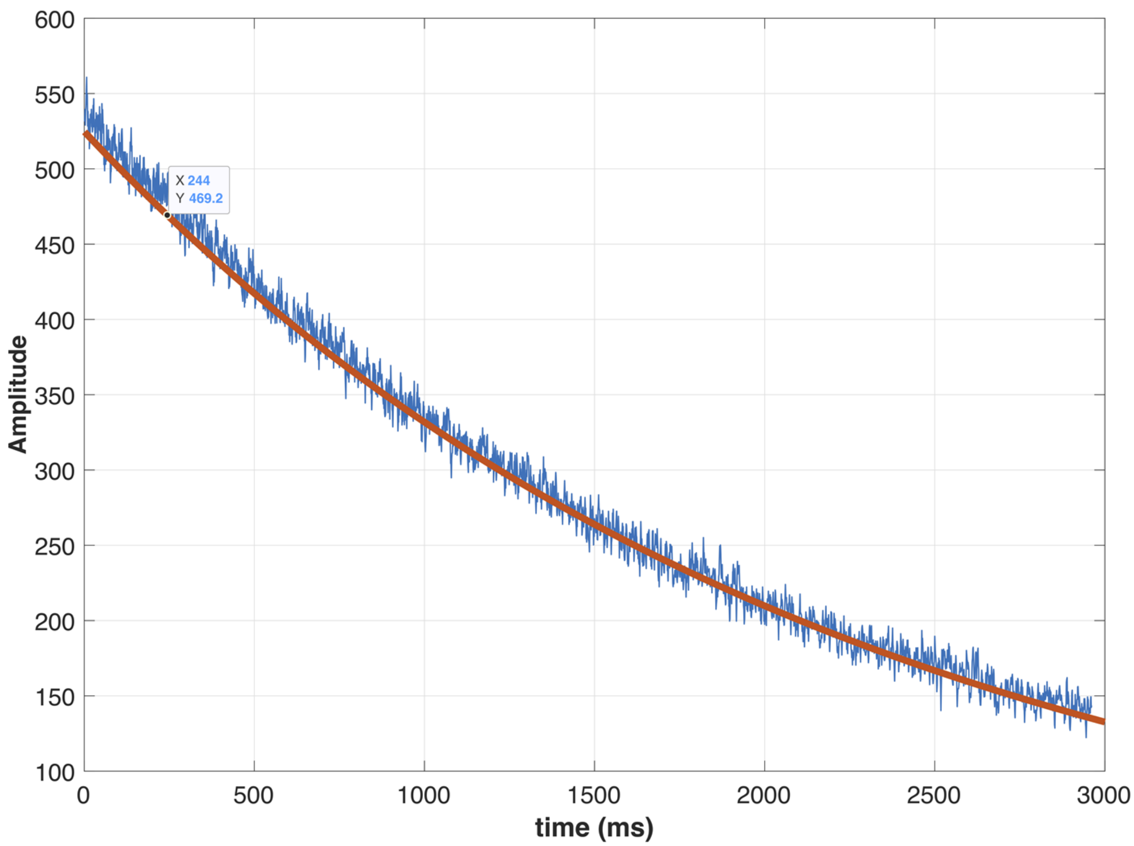
PHASE 2 - GRADIENT MEASUREMENT

Questions to be Answered:

- What is the smallest gradient that can be resolved?
- How isotropic is the sensor? How much does the measured gradient change if the sensor orientation changes?

Measurement of the Gradient using Signal Decay

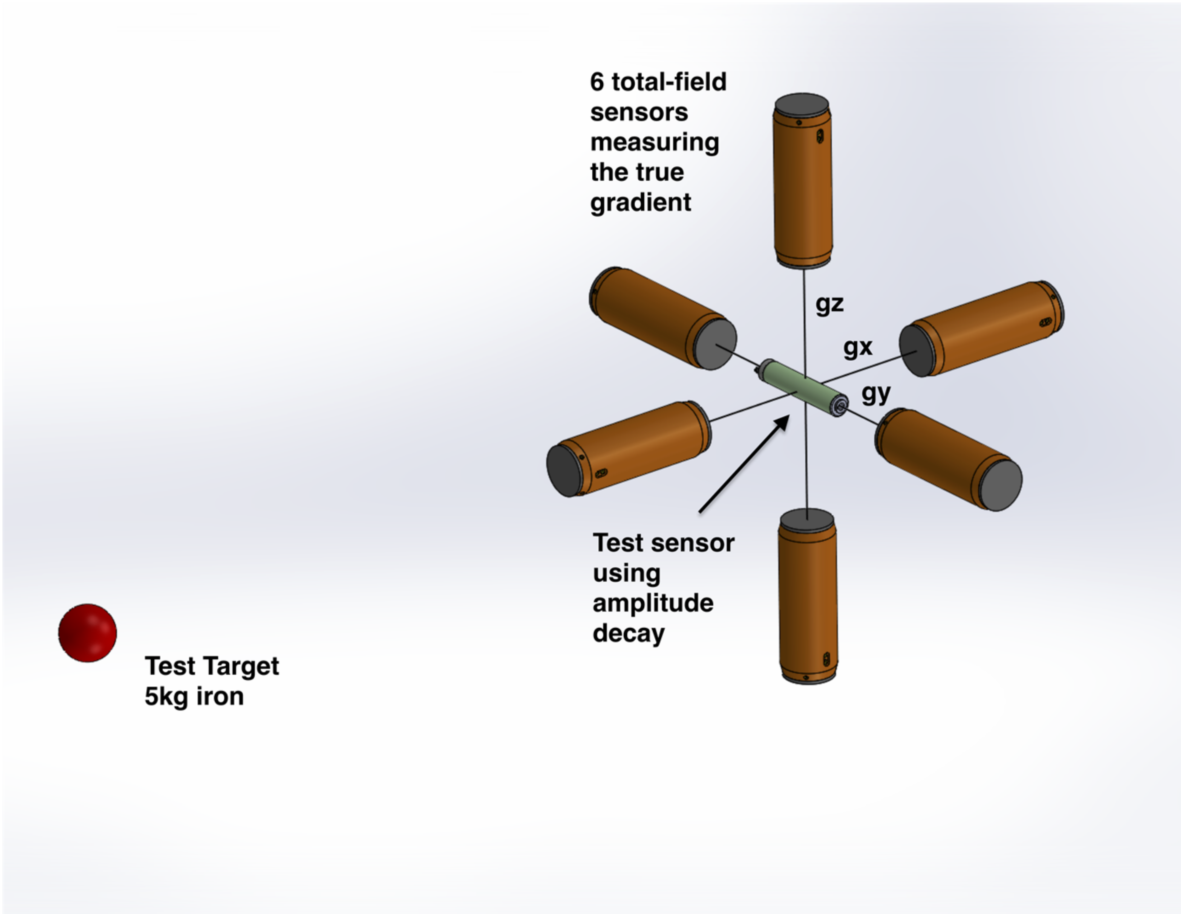
The signal amplitude is measured at 1kHz using RMS. Sampling may begin and end at any time after application of the deflect impulse.



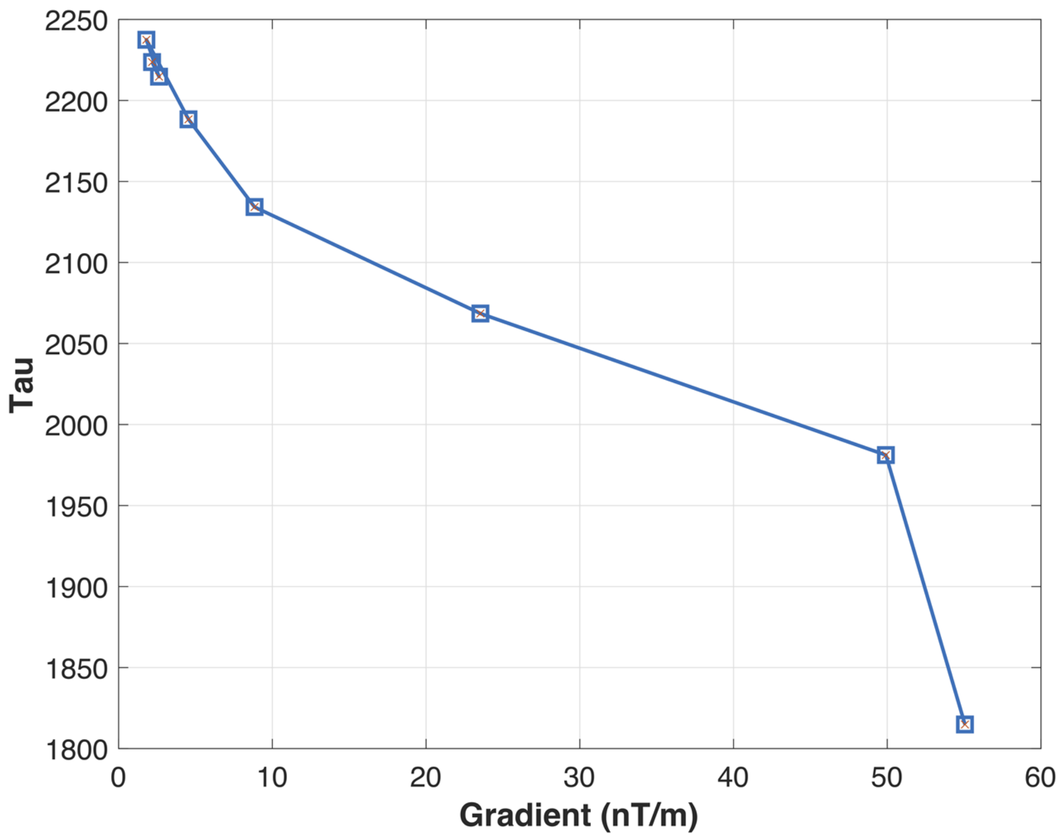
The parameter τ is calculated by curve fitting the data to the formula

$$a(t) = a(0) \cdot e^{\frac{-t}{\tau}}$$

The next step was to calibrate the relationship between τ and the actual magnetic gradient. A test rig was constructed from six independent total-field magnetic sensors, pairs of which measured the three independent axes of the gradient. Each pair of sensors measured the gradient over a 1m baseline.



The total-field Overhauser sensor being tested was placed in the centre of the rig. Then, a magnetic object was placed several meters away, initially out of detection range. The rig was kept stationary while the magnetic object was brought closer. At each position, the value of the measured six-sensor gradient vector was recorded, along with the value of τ, measured by the seventh sensor.

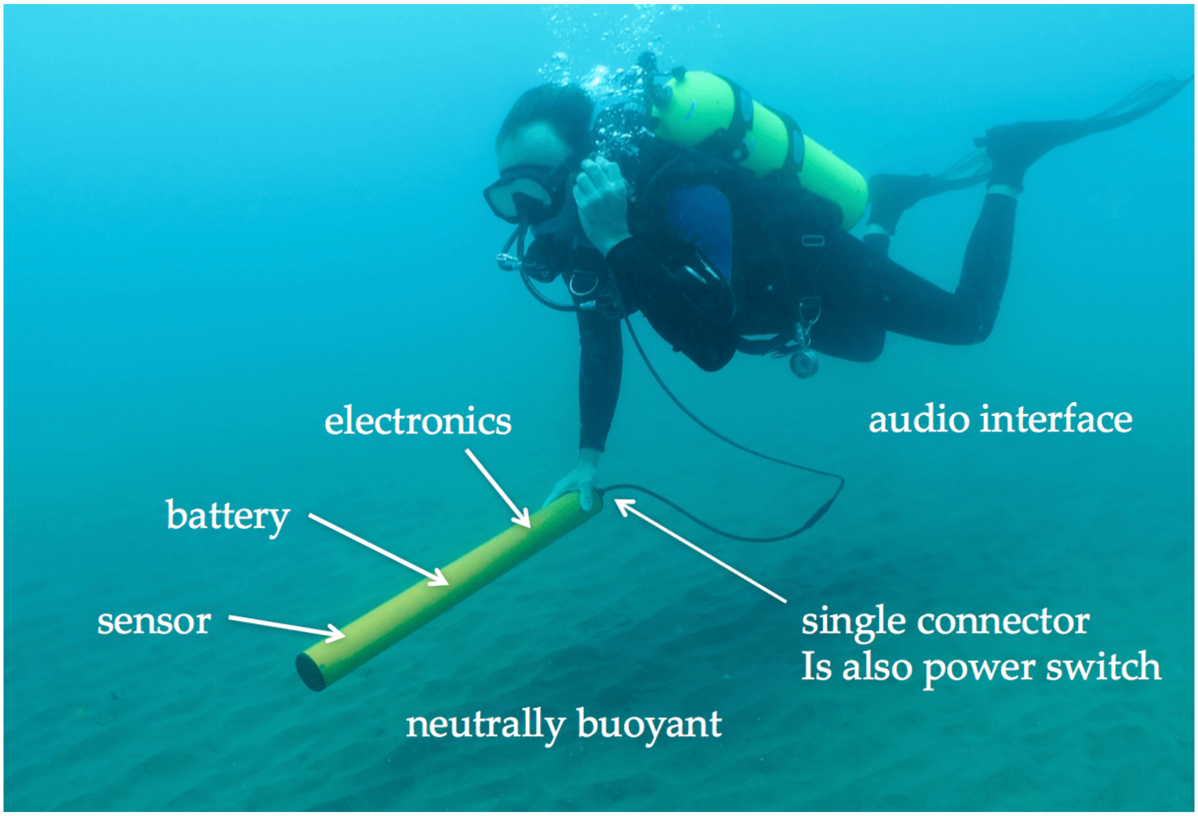


The calibration data show:

- Zero-gradient τ is approximately 2230ms
- A magnetic gradient of 5nT/m is reliably detectable using amplitude-decay.
- The relationship between τ and magnetic gradient is nonlinear (as expected)

Sensor isotropy results have not as-yet been collected.

DEVICE DESCRIPTION



First Prototype

The device is a neutrally buoyant pressure vessel with a single LED to indicate power-on. There are no buttons. The device is turned on by plugging in the audio interface cable, and it automatically begins operating. The diver interacts with the device by listening to the audio output. This allows the diver to give his full visual attention to his surroundings and fellow divers. Eventually, the audio signal becomes intuitive, and the diver begins to sense the presence of nearby ferrous objects.

This is the device that was field tested at the Lost Ships of Cortes Project in July 2019.

Second Prototype

The second prototype has the ability to measure the magnetic gradient numerically using the precession signal decay time. Numerical measurement of the gradient is more sensitive than what is detectable to the diver through the audio interface. Small gradients, as low as 5nT/m are displayed on an intuitive LED bar. Strong gradients continue to be communicated to the diver through the audio interface. This extends the maximum detection range of the device, and preserves its ability to precisely position targets when the diver is closer to the target.

CONCLUSIONS, FUTURE WORK

The diver handheld gradiometer has been shown to be an effective tool for locating buried near-surface ferromagnetic targets in magnetically noisy conditions.

The raw-signal audio interface was able to detect several 16th-century anchors at a distance of several meters, and allowed divers to resolve the shape of the targets for excavation purposes.

The magnetic gradient can be numerically measured with a sensitivity of approximately 5nT/m.

Future Work

- Tests to determine the isotropy of the sensor, i.e. how much does the measured gradient vary if the sensor orientation changes.
- Modifications to the sensor geometry to make it as isotropic as possible, if necessary.
- Modifications to signal processing techniques to improve the minimum detectable gradient.

Acknowledgements

Thanks to the Lost Ships of Cortes Project (LSOC) for allowing distribution of images and data related to the project.

All magnetic maps were created with Oasis Montaj by Seequent-Geosoft.

ABSTRACT

A new diver-held magnetometer has been developed that directly senses the total magnetic gradient as a scalar quantity, independent of the orientation of the device. It therefore provides a direct signal if a magnetic (e.g. ferrous) object is in its vicinity, regardless of other ambient geomagnetic effects. The small (7cm diameter x75cm length), battery-powered device is neutrally buoyant, and provides a simple and intuitive audio interface to the diver. The device was field tested in July 2019 during the Lost Ships of Cortés Project offshore Villa Rica, Mexico, an area with strong underlying volcanic geology and large quantities of magnetic sediment that mask buried archaeological materials. Magnetic anomalies were recorded during boat-towed total-field magnetometer surveys, but divers could not identify their source using traditional underwater metal detectors. The new magnetometer decisively and precisely guided divers to an early 16th-century anchor at a range of several meters that was completely buried in magnetite-rich sand with its shallowest point at 50cm below the sea floor.

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