Topic: **Maritime Security and Force Protection**

CAIMAN Experiment

Abstract

Non-acoustic detection systems can be used in combination with Sonar systems to determine the presence of an underwater threat, such as terrorist divers. The goal of the CAIMAN (Coastal Anti Intruders MAgnetometers Network) joint experiment (Italian Navy, NATO Undersea Research Centre and INGV Marine Geophysics) is the application of High Definition Geophysics Magnetic techniques in a port protection scenario, where conventional measurements of very low magnetic sources, like intruder swimmers, are strongly disturbed by ambient, natural and artificial, background noise and other time-variant magnetic anomalies. Two tri-axial fluxgate magnetometers were deployed on the sea bottom and connected to a shore side measurement station. A team of navy divers, wearing both COTS and EOD equipment, performed some coastal approach runs on each magnetometer alternatively. Magnetic signature data were logged and post processed using MATLAB®. Results demonstrated the effectiveness of high definition time reduction techniques using a self-referred integrated array design.

Keywords: Port protection, Underwater Magnetometers Array, Anti-intruders Underwater Barrier, High Definition Geomagnetism, Magnetic Noise Reduction.

Author: Cdr. Amleto Gabellone
Affiliation: Italian Navy – Institute of Electronics and Communications “G. Vallauri”
Address: MARITELERADAR - Viale Italia, 71 – 57126 Livorno - Italy
Tel./Fax: +39 0586 238 313 - +39 0586 238 205 - Mobile: +39 347 3250977
mariteleradar.vdir@marina.difesa.it

Coauthor: Dr. (Phd) Osvaldo Faggioni
Affiliation: National Institute of Geophysics and Volcanology
Address: INGV – Villa Pezzino, Via Pezzino Basso, 2 – 19025 Fezzano (SP) - Italy
Tel./Fax: +39 0187 794402 - +39 0187 798121
faggioni@ingv.it

Coauthor: Dr. Maurizio Soldani
Affiliation: National Institute of Geophysics and Volcanology
Address: INGV – Villa Pezzino, Via Pezzino Basso, 2 – 19025 Fezzano (SP) - Italy
Tel./Fax: +39 0187 794410 -+39 0187 798121
soldani@ingv.it

Coauthor: Dr. Piero Guerrini
Affiliation: NATO Undersea Research Centre
Address: Viale San Bartolomeo, 400 – 19138 La Spezia - Italy
Tel./Fax: +39 0187 527393 - +39 0187 527331
guerrini@nurc.nato.int

Introduction

Port security has been a buzz phrase ever since the events of September 11, 2001. As an immediate response to the biggest terrorist attack in modern history, the port security work has been concentrated on the shore side of business – inspections of containers with multiple sensors, gate crossing identifications, increased camera surveillance and security patrols, etc. However it seems that the threat which is not being addressed is security in the area from which a terrorist would be likely to launch an attack – from underwater.

Non-acoustic detection systems can be used to determine the presence of an underwater threat like terrorist divers. Magnetic array barriers are already used for underwater surveillance, although magnetic techniques’ detection capability, particularly in port protection scenarios, depends on physic structure of geomagnetic field.

The geomagnetic field is the result of convolution of several magnetic fields produced by numerous sources, natural and artificial, internal and external to Earth, all characterized by different physic quality, form and space position. The effectiveness of port protection magnetic techniques identifies the magnetic security system capability to extract the target magnetic signal from all the convolved signals which form the Earth magnetic field. The system capability is not a technical problem (i.e. sensibility of magnetic sensors) as it fundamentally depends on the very low S/N ratio. This typical metrological problem may be critical to the effectiveness of the magnetic technique in the case of very low signal (i.e. swimmers or divers).

The classic geophysical approach is studying and classifying the natural components of the geomagnetic field and therefore removing them trying to extract the target signal (in the magnetic environmental noise frequency band) using various numerical techniques. This paper reports a new metrological approach based on High Definition Underwater Geomagnetism (HDUG), through measuring the geomagnetic field far from the security barrier and using the obtained magnetic graph for filtering the magnetic graphs coming from the magnetometers' array (guard sensors). If a target signal is present in one (or more) guard device's graph, the filtering process will extract the target signal otherwise the filtering process will get no information.

Critical parameter of this technique is the position of the reference magnetometer: it has to be deployed close to the magnetometers network in order to get a coherent measurement of the geomagnetic environmental field through all the array's sensors (space coherence of the observatory) but in the same time far from guard magnetic sensors in order to not being interfered by the magnetic target signal. This critical distance depends on the difference in the "space stability" of the geomagnetic environmental field components and magnetic signal of target. In general, shorter the magnetic target signal and the geomagnetic time variations signal (and noise) are, higher the frequency of the magnetic signal is.

The CAIMAN experiment (Coastal Anti Intruders MAgnetometers Network) shows the application of the above technique for port protection purposes. A SIMAN (Self-referred Integrated Magnetometers Array Network) design was used to build a primitive underwater magnetic barrier. Two tri-axial fluxgate magnetometers were deployed on the sea bottom and connected to a shore side measurement station. A team of military divers, wearing COTS diving equipment (air bottles, compass, etc.), performed a certain number of coastal approach runs on each magnetometer alternatively. Magnetic signature data was logged on the shore side station and a post-processing data analysis was done using MATLAB® to extract the anomaly created by the intruder from the ambient background noise.

Classic underwater geomagnetic techniques for small targets' detection suffer a poor S/N ratio due to the inherent characteristic of the natural and artificial magnetic background HF noise. HF magnetic noise can mask very low artificial magnetic sources – nearly shape-point targets – even static (proud or buried bottom mines) either dynamic (small UUVs and divers).

HDUG increases the magnetic S/N ratio of the target through the zeroing of the time-variations of the Earth Magnetic Field (EMF):

$$H = H(s,t) \Rightarrow H = H(s)$$

Where s = space and t = time

Two different HDUG methods are defined according the operational goals:

- Detection of small (low magnetic source) static targets
- Detection of small moving targets

Addressing the time variations in geomagnetic detection of small targets is a very important issue as these time variations may represent signals with amplitude comparable to the spatial ones (targets). In off-shore surveys and when the effective time variation is unknown, the time-reduction problem is solved by means of cross-over error corrections or using differential measurements systems (Jones, 1999; Marcotte et al., 1992). However, the differential marine magnetometers (gradiometers) are rather large and complex pieces of equipment and underwater towing can be very difficult especially in coastal waters. This fact means that this kind of survey near the coast-line, in navigable channels or inside a harbour is rather problematic. These difficulties appear relevant in case of high definition surveys in shallow waters, for example in case of proud or buried mines or Improvised Explosive Devices (IED) detection.

When the interpolation basic assumption of the cross-over technique fails, typically nearby the shore or in areas characterized by high frequency time variations, the most commonly used alternative method is Time Reduction by means of the comparison between the marine survey and the corresponding magnetic measurements obtained in one or more coastal observatories located near the area of interest (Parkinson and Jones, 1979; Faggioni et al., 1997). This time correction for comparison, called Time Line (TL) procedure, is based on subtraction of geomagnetic field variations measured at the observatory from the quantities obtained from the underwater survey.

A method of detection of terrorist divers in port protection scenarios can be borrowed from techniques already available for protection of marine reserves from underwater intruders. These techniques use standard geomagnetic surveillance arrays where N magnetometers (called Nodal Warning Points) are deployed to measure the geomagnetic field in order to detect possible artificial source signals crossing one or more nodal warning points. The surveillance array, thanks to the high sensitivity of modern magnetometers, could be very effective for small targets, although, in harbour areas where background noise can be very high, the gains in accuracy may again be lost. It happens when a strong magnetic environmental noise (electric power stations, railways, ship traffic, etc.) can mask very low signals generated by underwater intruders who may not be discriminated by the surveillance array.

A further issue is due to the natural time-variations of the geomagnetic field that can have the same amplitude of the artificial time-variations magnetic anomalies generated by the underwater intruders. Therefore, even inside a clean environmental noise, during a middle-high planet geomagnetic activity[1] the surveillance array can be blind.

The method used for the CAIMAN experiment is an evolution of the classic direct observation one (surveillance array) and it is based upon the following concepts:

- System-through observation (zero-level)
- Integrated observation (neural)

The application of HDUG in port protection scenarios consists in using a standard surveillance array system but, instead of measuring the direct geomagnetic anomalies (inside a noisy environment), it measures the difference of the geomagnetic signal between each couple of the array's nodal points (magnetometers).

Assuming that in sufficiently wide areas:

- H_F (natural time-variations of the EMF) = *const.*
- H_N (background artificial noise) = *const.*

A differential measurement between the array's nodes allows eliminating the geomagnetic noise without a-priori filtering process. The CAIMAN system measures therefore the anomaly generated by the target, approaching one nodal point, among the differential geomagnetic signals of the complete array. Two different processing methods can be used for the array's nodes:

- Referred Integrated Magnetometers Array Network (RIMAN)
- Self-referred Integrated Magnetometers Array Network (SIMAN)

In the SIMAN system all the array's magnetometers are used to obtain the zero-level condition. The control unit has to check in sequence the zero-level condition between each pair of magnetometers and signal any non-zero differential function (see figure 1).

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[1] The planet index *K* shows the Earth's natural geomagnetic activity, which is related to the Solar Wind's activity.

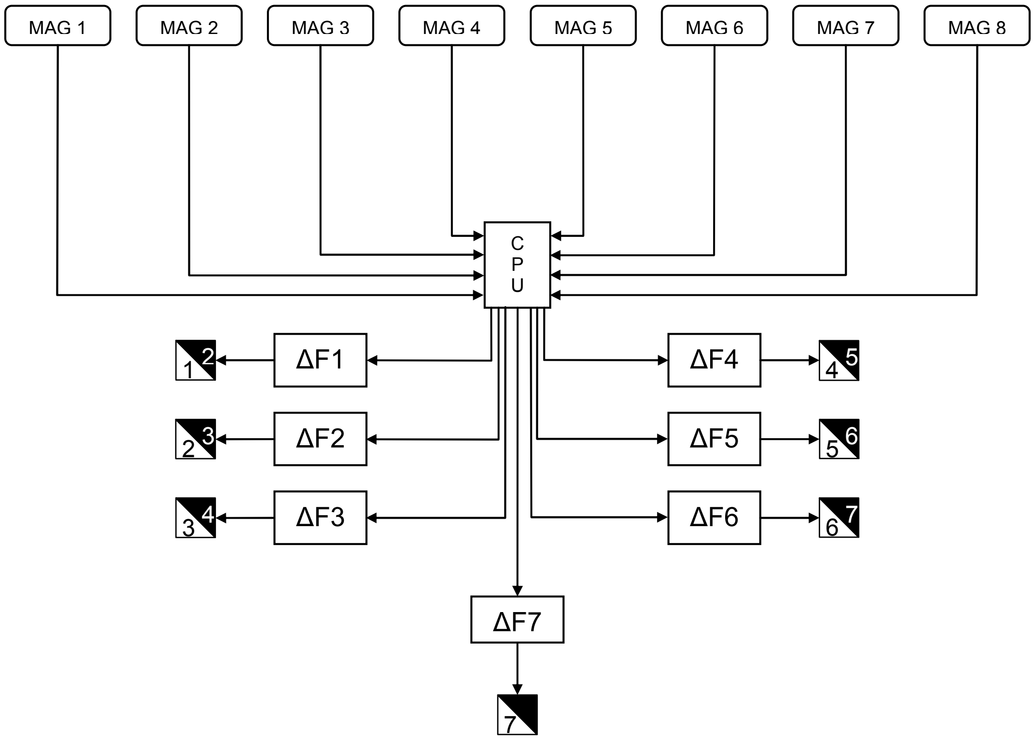

Figure 1 - Scheme of a Self-referred Integrated Magnetometers Array Network.

Signal processing in the SIMAN system gives very good accuracy, although the only issue is related on the ambiguity in case the target crosses a pair of magnetometers at the same distance from both. Such ambiguity can be solved through the evaluation of the differential functions between the adjacent nodes. The drawback is that a SIMAN system requires a continuous second-order check at all the nodes.

The advantage of using a SIMAN system is the possibility to cover an unlimited area. The stability condition is requested only for each pair of the array's magnetometers.

The numerical interpretation of the SIMAN system is equivalent to imposing an environmental filtering to the target's value. Considering only a couple of sensors (see Figure 2), the magnetic field measured by the sensor affected by the magnetic target's source is the superposition of three time-variable components:

- The Earth magnetic field
- The background magnetic artificial noise
- The target's magnetic field

On the other side, the magnetic field measured by the second sensor (too far from the first one to be influenced by the target but enough close to the first sensor to be in condition of geomagnetic coherence) is the convolution of the above first and second components only. The frequency inverse convolution of the total magnetic field gives the measurement of the target's signal only. This method allows a real-time adapting of the filtering process according the total noise conditions and overcomes the problem to a priori set specific cutting frequencies.

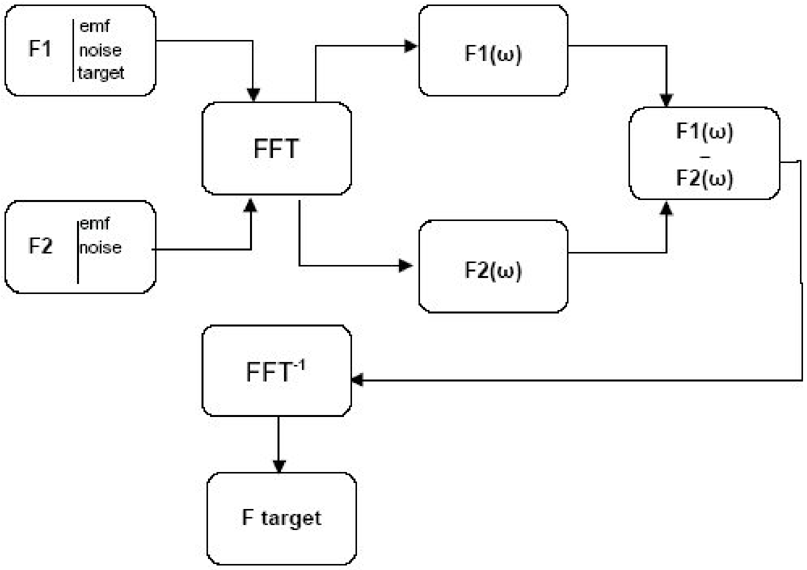

Figure 2 – Signal processing's block diagram of a Self-referred Integrated Magnetometers Array Network.

A RIMAN system consists of a magnetometers array system and an identical stand-alone magnetometer (referring node) deployed within the protected area. The zero-level condition is obtained through the comparison of the signal measured by each of the array's magnetometers with the signal measured by the referring magnetometer. If the protected area is confined we can assume the total background noise (H_F + H_N) constant and therefore the difference between each array's sensor and the referring one is around zero. The zero-level condition can be altered only in presence of a target approaching one or two (in case of middle-crossing) sensors of the array. Signal processing of the RIMAN system is accurate and the risk of numeric alteration of the registered rough signal is very low. A standard data-logger system has to measure the signals coming from each of the array's magnetometers and respectively compare to the reference signal. The comparison functions $\Delta F(1,0)$, $\Delta F(2,0)$, …., $\Delta F(N,0)$ are subsequently compared to the reference level 0 and then only the non-zero differential signal is taken. It means that the target is crossing a specific nodal magnetometer. For example, if the target is forcing the barrier between nodes 6 and 7, the only differential non-zero functions are $\Delta F(6,0)$ and $\Delta F(7,0)$ which will indicate the target's position. A quantitative analysis of the differential signals can also show the target's relative position to the two nodes. If the protected area is too wide to allow a stability condition of the total background noise, the RIMAN system can be divided in more subsystems, each of one using an intermediate reference node, which have to respect the stability condition among them. The intermediate reference nodes have finally to be related to a common single reference node. However in such situations the SIMAN system is preferred (see next paragraph).

The effectiveness of an Underwater Magnetic Network Barrier (UMNB) using High Definition Geomagnetism depends, like any geophysics measurements system, on the target related data content. The most important characteristics are stability and sensitivity. These factors principally depend on the system's geometry (sensors' position). The stability of a UMNB is the detecting capability independently from the environmental noise. In other words, the stability is the system's capability to estimate the threshold of the ambient noise that interferes with the target's measurement. As already explained, the geomagnetic field is a time-space variable function. Rendering stable a UMNB means to separate any target measurement from the time-space variations of the ambient noise (independently from both time-space noise's amplitude, phase and wave length). The space-variations are obtained through zero-level techniques (comparison among the measurement nodes) that can reasonably reduce the time-variations. However the zero-level techniques do not allow a sufficient reduction of space-variations as the measurement nodes are positioned within the natural environmental field which depends on the magnetometers' position.

The correct positioning of the measurement nodes is achieved after some measurement steps:

- Measurement of the local static geomagnetic field;
- Evaluation of the IGRF;

- Assessment of the distance between two nodes according the expected signal's wave-length.

The sensitivity of a UMNB is the minimum value of the target's magnetic signal that the system is able to detect. This parameter is not the instrumental sensitivity of well known magnetometers like SQUID (Superconducting QUantum Interference Device), or Alkaline Gases class or Proton Precession, whom sensitivity can be better then 0.1 nT[2]. The basic concept of High Definition Underwater Geomagnetism is based on the capability to associate the minimum magnetic signal to an expected target with almost no false alarms.

The minimum magnetic signal depends on two factors:

- The amplitude of the target source
- The distance between the sensor and the target

If for example we expect a minimum of 2 nT from our target's source, the maximum distance between each couple of sensors needs to be the double of the decreasing distance when the target's signal value is 2 nT. Bigger distances will not measure the minimum requested signal (see figure 3).

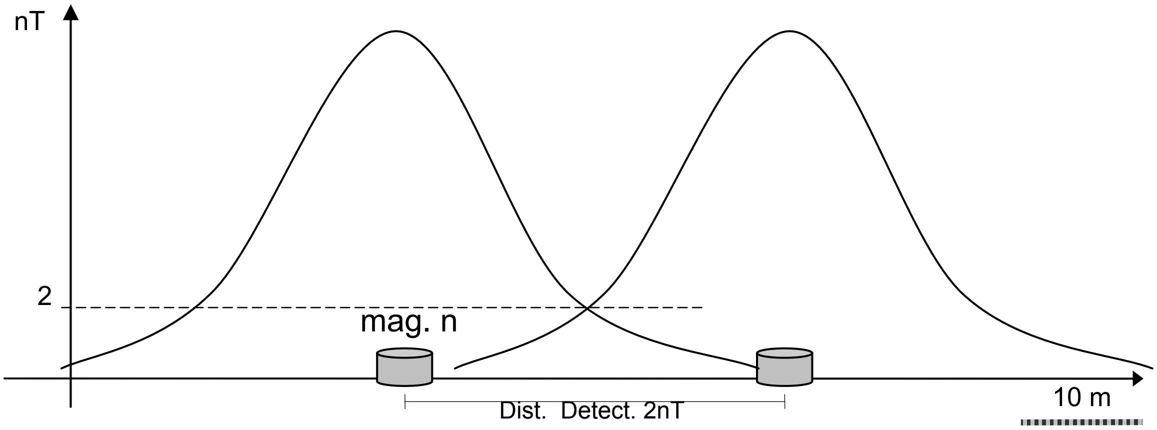

Figure 3 – Concept of minimum detecting distance (sensitivity) between two magnetometers.

Experiment Description and Results

The experiment's objective was the validation of a SIMAN-UMNB in its minimum configuration (two magnetometers, named MAG 1 and MAG2). The selected experiment area was located in the North-East side of the Palmaria Isle (La Spezia, Italy). This sea area is characterized by a medium-high geomagnetic ambient noise. Its ambient noise is principally due to strong artificial transient magnetic signals caused by railways, electric power-stations, port activities and electric lines.

The experiment consisted of recording of static and ELFE geomagnetic field variations during multiple runs performed by a military diver's team. The two tri-axial fluxgate magnetometers were positioned at a water depth of 12 meters at a respective distance of 50 meters. The diver's runs were performed at zero CPA (Closest Point of Approach) at about 1 meter from the bottom along 50 meters tracks centered on each magnetometer. The runs' bearing was approximately E-W and W-E. The two magnetometers were cable-connected with their respective electronic control devices (deployed at 1 meter form the sensor) to a data-logger station placed on the beach coast at about 150 meters. The target source for the experiment was a military diver. The Italian Navy COMSUBIN (Special Forces Command) provided a team of divers equipped with standard air bottles system. The sea floor instruments consisted of two ULTRA-Electronics LBM6 gimbals-mounted fluxgate magnetometers and an azimuth compass. The instruments were housed on a concrete stand that served as stabilization platform and as ballast. The LBM6 is a high sensitivity three axis magnetometer providing a RS232 digital output. The LBM6 includes a very high performance 3-axis fluxgate magnetometer together with analogue to digital conversion and a microprocessor controller. The

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[2] These instruments are able to detect very low magnetic signals but their data content is not meaningful as it can be associated to various sources or to different environmental noise sources.

fluxgate sensors and electronics are provided in separate packages with a 10 metres interconnection cable. The LBM6 magnetometer provides a very good resolution with a noise level of better than 10 pT RMS (from 0.01 to 1 Hz). The LBM6 is configured to allow a very wide static field range up to ±80,000 nT while the high resolution small signal channel has a dynamic range of ±400 nT.

The analysis of CAIMAN experiment follows some preliminary steps to assess the stability and sensitivity (see above) of the arranged basic magnetometers array. Then the HDUG time reduction methods are applied to separate the target's anomaly form the background ambient noise. The preliminary processing steps are:

- Stability Assessment
- Evaluation of the background ambient noise correlation between the two magnetometers
- Evaluation of the target's signal decorrelation between the two magnetometers
- Sensitivity Assessment
- Evaluation of the detection width (ray of the detection sphere in a 3D environment) of the single magnetometer

A set of direct measures from the two magnetometers is shown in Figure 4 (x-axis components), Figure 5 (y-axis components) and Figure 6 (z-axis components).

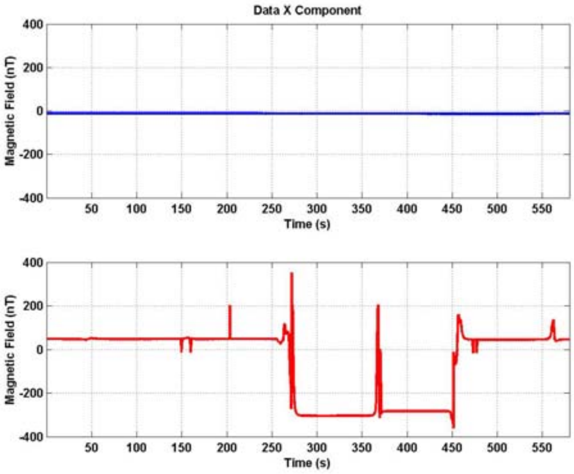

Figure 4 – MAG 1 (blue) and MAG 2 (red) x-axis components.

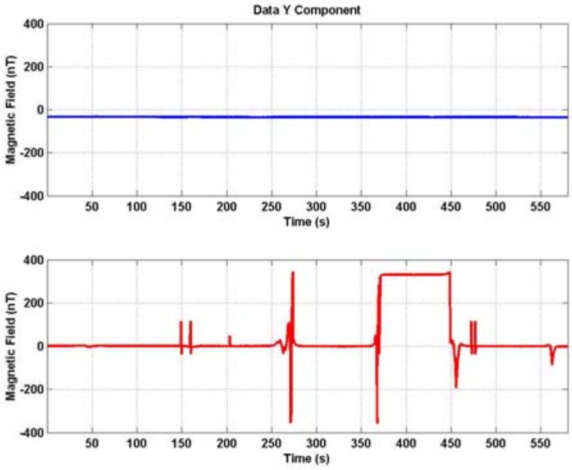

Figure 5 - MAG 1 (blue) and MAG 2 (red) y-axis components.

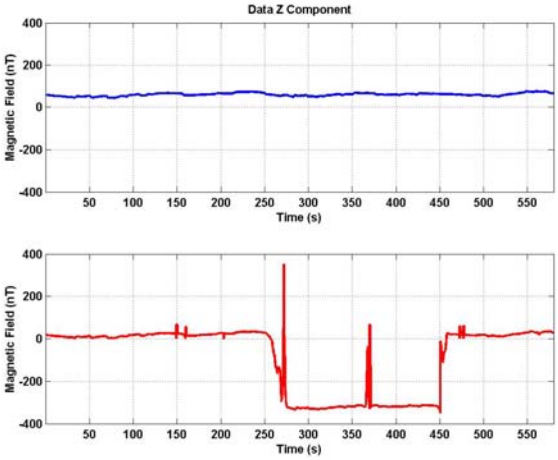

Figure 6 - MAG 1 (blue) and MAG 2 (red) z-axis components.

Qualitative analysis shows that the amplitude of the dipolar pulse generated by the magnetic source is totally within the two magnetometers' measurement dynamic range and sometime the dipolar pulse saturates the instrument's measurement range (see MAG 2 – red curve - in Figures 4, 5, and 6). In this case the diver's run was performed on MAG 2.

Another set of direct measures acquired by the two magnetometers is shown in Figure 7. Magnetic field is measured at 50 Hertz for nearly 9 minutes, during the diver's run (go/back) following a horizontal track on magnetometer nr.1 (MAG 1).

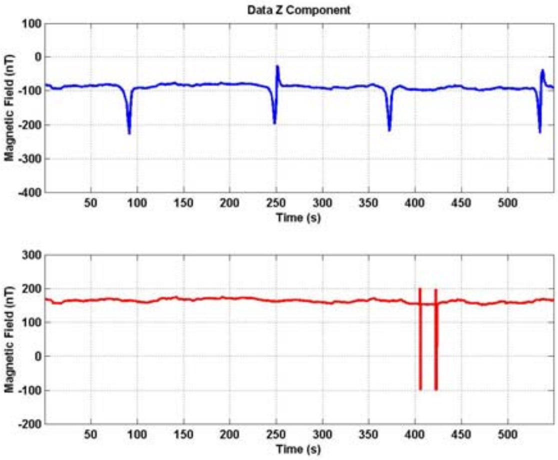

Figure 7 – Magnetic source's z-axis component (blue line: magnetometer nr. 1 – red line: magnetometer nr. 2.

The four dipolar pulses in the sequence acquired by MAG 1 show the time instants around the Closest Point of Approach (CPA) referred to the transducer's position. Some pulses are completely negative, while others are partially positive: this different polarity depends on the diver direction (go or back) above the transducer. However, in the sequence acquired by MAG 2 there are some undesired spikes (instrumental measurement errors): we avoid them by an opportune filtering process, as shown in Figure 8; in this way, filtered sequence acquired by MAG 2 is nearly constant.

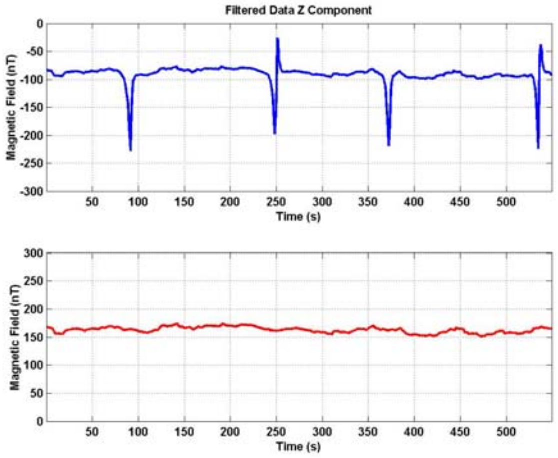

Figure 8 – Filtered z-axis components – see previous figure.

Different duration and amplitude of pulses are caused by different diver speed and depth (different distances between the diver and the magnetometer). In addition these depend on the magnetometers' detection range and on the spatial orientation of the three flux-gate coils (see Figure 9).

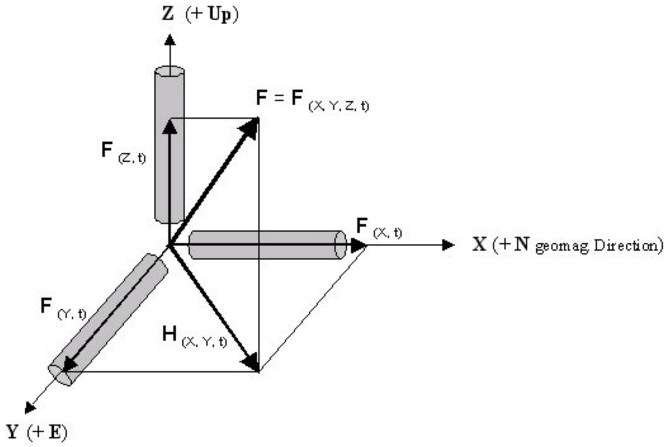

Figure 9 – Spatial orientation of the three fluxgate magnetometer's coils.

After expanding a single run (a single dipole signal only – see figure 10) and the background noise measurements between two runs (see figures 10 and 11), it is possible to assess that:

- The MAG 2 (figure 10 – bottom) is not influenced by diver passages above MAG 1 (figure 10 – top), because of the correct decorrelation distance between the two transducers (50 meters).
- The measured background noise is properly correlated between the two magnetometers (see figure 11). The differential reduction (figure 12) shows this correlation.

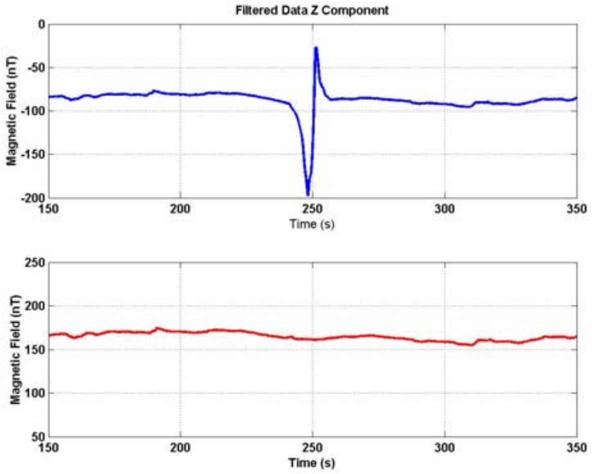

Figure 10 – Zoomed graphic of a single run on MAG1.

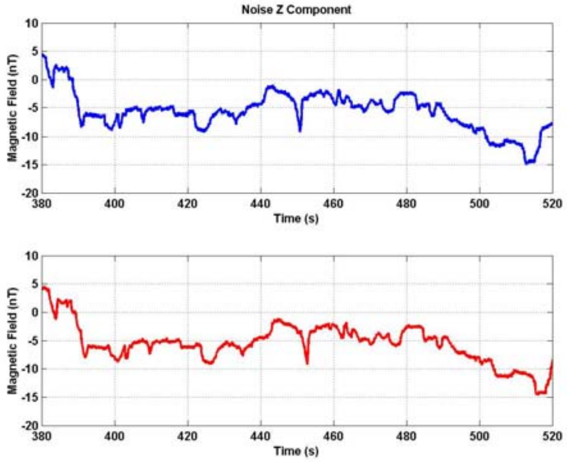

Figure 11 – Zoomed graphic of background noise measurements between two runs on MAG1.

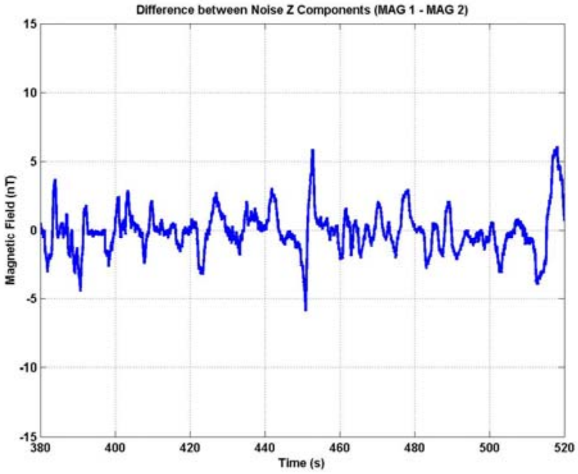

Figure 12 – Differential reduction of the above background noise measurements.

Transducer depth, duration of pulses, and diver speed and depth get the ray length of a detection sphere with 2 nT sensitivity (space region, centred in a magnetometer, inside which the transducer is able to detect the diver) to be nearly 10 meters (Figure 13).

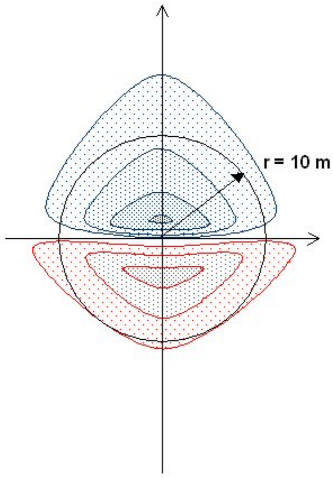

Figure 13 – Estimated detection sphere (ray = 10 meters) of each magnetometer.

The detection sphere with minimum sensitivity of 2 nT and detection range of 10 meters is obtained through a 2D extrapolation of the experiment's mono-dimensional model. The detection sphere allows the physical positioning of the magnetometers' barrier to cover a specified sea area.

To evaluate the effect of a stronger background noise on the acquired data, we show (Figure 14) two sequences (filtered Z components) acquired in NURC bay using the same sensors a few days after the CAIMAN experiment: this figure shows that in this new condition the diver passages above MAG 1 are masked by a strong environmental noise disturbing both magnetometers. A direct traditional measure of the target's magnetic anomaly is not possible anymore.

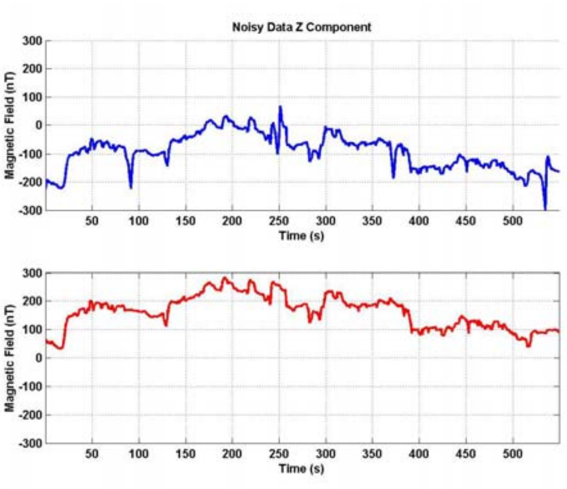

Figure 14 – Filtered z-axis components.

To extract the target's signal, the difference between noise corrupted data of the two magnetometers (MAG 1 – MAG 2) was calculated. As the noise is nearly the same for the two magnetometers (this is true if the two sensors were properly placed), we found a time referred curve (Figure 15) that is quite similar to the one of Figure 8 - MAG 1. Therefore the diver's signal acquired by MAG 1 is extracted from the total field. This technique demonstrates that the environmental noise has no effect on diver's detection, under the hypothesis that noises measured by the two magnetometers are strongly correlated: e.g., a threshold level equal to -320 nT could be used to detect divers' passages.

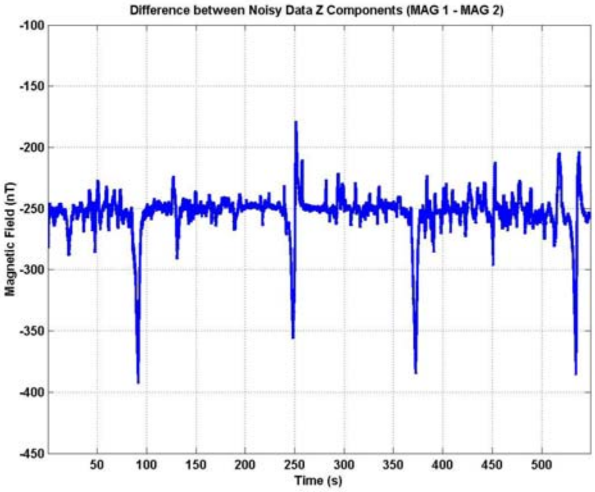

Figure 15 – Differential evaluation and extraction from noise corrupted data of the target signal (z-axis component).

Conclusion

Visual detection and acoustic detection are the primary methods used to counter the intrusion of swimmers or underwater vehicles. Acoustic detection in shallow water is difficult, but is more easily accomplished with a combination of other non acoustic methods. The experiment results prove that these systems could work as a stand-alone barrier against underwater intruders or can complement the acoustic systems' capabilities of detection and tracking through a proper data fusion process.

The CAIMAN experiment demonstrated the effectiveness of High Definition Underwater Geomagnetism techniques for detection of low magnetic sources like military divers within a significant magnetic background noise. The experiment was a first approach to assess the feasibility of use of HDUG in port protection scenarios as the measurement conditions were almost favorable (target's magnetic signature much higher than expected and tracks performed on the CPA route). However more realistic conditions (very low S/N ratio) confirmed that the HD correction strategies can successfully remove or reduce the temporal variations of the geomagnetic field.

A SIMAN design was used to build a primitive underwater magnetic barrier employing the two available tri-axial fluxgate magnetometers as nodal points of the array. The stability and sensitivity analysis of the two nodal points allows the creation of a detection sphere of minimum sensitivity's ray to evaluate the physical positioning of the magnetometers' barrier to cover a specified sea area. The 2D extrapolation of the experiment's mono-dimensional model shows that the minimum expected target's signature can be considered independent from the natural and artificial time-variations of the environmental noise of comparable levels.

A HDUG techniques relieve therefore the array's designer of a prior filter's engineering to trim down the magnetic background noise variations. Due to the unpredictability of these variations, an a priori filtering can remove also the target's information content of the measured data.

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