BUILDING THE SYNTHETIC "MAC SYSTEM": AN ANALYTICAL INTEGRATION OF MAGNETIC AND ACOUSTIC SUBSYSTEMS FOR PORT PROTECTION SCENARIOS.

Faggioni O.[1,2], Soldani M.[1,2], Zunino R.[3,2], Leoncini D.[3,2], Di Gennaro E.[4], Gabellone A.[5], Maggiani P.V.[6], Falcucci V.[7] and Michelizza E.[7]

1 – Istituto Nazionale di Geofisica e Vulcanologia, Via Pezzino Basso 2, 19025 Fezzano (SP), Italy
2 – Defence Geophysics Group, University of Genoa, DIBE, SEA Lab, Via All'Opera Pia 11a, 16145 Genova, Italy
3 – University of Genoa, DIBE, Via All'Opera Pia 11a, 16145 Genova, Italy
4 – Italian Navy, Naval Logistic Inspectorate, Piazza della Marina 4, 00196 Roma, Italy
5 – Italian Navy, CSSN ITE "G. Vallauri", Viale Italia 72, 57127 Livorno, Italy
6 – Italian Navy, COMFORDRAG, Viale Giovanni Amendola 1, 19122 La Spezia, Italy
7 – WASS, Via di Levante 48, 57124 Livorno, Italy

e-mail: osvaldo.faggioni@ingv.it

Abstract

In order to obtain a preliminary overview on the effectiveness of the underwater anti-divers magnetic-acoustic "MAC System", we have developed a synthesis between the results coming out from the two different subsystems (magnetic and acoustic), based on two different models, during two different test sections. The section covered by the magnetic component, measured near the NURC dock (La Spezia, Italy) in very noisy port condition, has been remodeled on the sea bottom profile of the access channel to the Italian Navy Base in La Spezia, which presents environmental electromagnetic noise compatible with the NURC's one. In this entrance way has been executed an acoustic port protection experiment, too. The two different covered sections (magnetic and acoustic) have been merged to obtain an integrated synthetic model of the accuracy of the MAC System. The results have pointed out a remarkable increase of the anti-divers covering effectiveness, in particular in the boundary zone of the access way to be protected: the confidence of the MAC System can be considered quite 1 and higher in respect to the sum of the confidence of the two subsystems.

Rationale

During the last five years, 2004-2008, underwater intruders' detection systems for port protection have been developed according to two independent approaches, based respectively on acoustic principles and magnetic effects. The analysis and comparison of the performances of the two approaches highlight their peculiarities: acoustic barriers guarantee optimum volumetric control but exhibit some limitations in peripheral surveillance; on the other hand, magnetic arrays achieve high peripheral security but partially fail at volumetric control. These operational features suggest the integration of both detection approaches into a dual system.

This paper reports the results of the analytic integration of the performances experimentally obtained through the environmental control of the two methods. The synthesis procedure merges the areas controlled by the two systems into one vertical section, representing the real port site chosen as test bed. This integration is obtained through reporting on an unique reference section the measures of both the underwater area monitored by the acoustic and magnetic systems according to the outline of the port scenario. Therefore the control competence areas of the acoustic and the magnetic networks will overlap, thus preventing shadow areas, and consequently preventing possible intrusions. The integration charts of the study show indeed that a port area can be effectively and fully protected by the dual system. In the band of maximum uncertainty of detection, the lack in performance featuring each method, when taken individually, is counterbalanced by the co-occurring presence of the cooperating detecting approaches, both having a good degree of confidence. The analysis of the system performance should be done by dividing the reference section into three sub-regions, covering the depth range from the surface to the sea bottom. The accuracy in control by the acoustic method is maximized in the medium-low depth area close to the surface, while magnetic systems completely lack in precision. In the intermediate region, both methods would perform similarly, with the acoustic system still proving more accurate than the other. Finally, in the proximity of the sea floor, the magnetic approach ensures maximum effectiveness, whereas acoustic systems do not yield significant information. In such a scenario, the dual system will optimize its performance by picking the highest-confidence information in compliance with each specific operating region.

Test Area

The synthesis of the performances of the two subsystems (magnetic and acoustic) is carried out by projecting the magnetic model into the test area of the acoustic model. The acoustic system has been tested near the “Duca degli Abruzzi” basin, into the Italian Navy Base in La Spezia (Fig. 1). The critical area to be protected is represented by the section delimitated by the green line and the cost line. The only way to enter into this zone is an access channel (into the protection’s barrier) with a length of nearly130 [m] and a maximum water depth of about 11.50 [m]. Fig. 2 shows the critical zone to be protected (A) and the extern zone (B), separated by a black dashed line, and the displacement of the control system (MAC System), represented by a red dashed line; Fig. 2 highlights the morphological features of the entrance way seafloor, too: the central sector is characterized by an approximately constant depth, the NE sector (green light) is characterized by an intense vertical positive gradient of depth, while the SW sector (red light) is characterized by a lower vertical positive gradient of depth. The vertical section’s

thickness of the passage, protected by the MAC System, is an instrumental feature: in fact, it depends on the depth at which the sensors have been displaced.

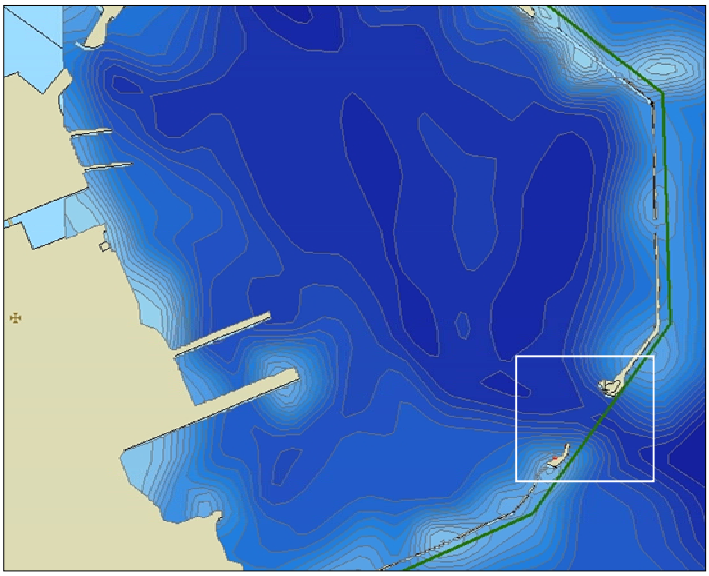

Fig. 1 - Test Area: Duca degli Abruzzi basin (La Spezia, Italy).

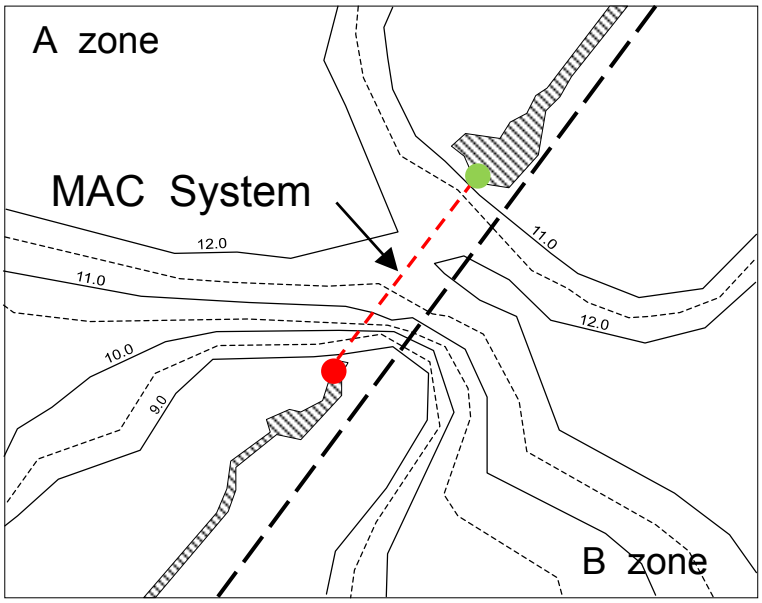

Fig. 2 - Bathymetric map of the observed area; the dashed red line represents the MAC System position.

These morphological conditions produce three different responses in the magnetic coverage percentage of the vertical surface: we will have a red sector in which the passage of an intruder is totally controlled from the seabed to the sea surface, a central sector in which the gap between

controlled water's zone and the sea surface becomes relevant, and a green sector in which the system provides an intermediate response. So, the access channel has to be divided into three different sectors: the final response of the magnetic protection of the entrance way is obtained by merging the results of the three distinct sectors (green, central and red).

The Magnetic Subsystem

"MACmag" is the magnetic component in the design of a magnetic-acoustic port (and coastal) protection system for defence against divers (Fig. 3; Faggioni et al., 2008). MACmag's role is the defence of peripheral regions of ports and coastal environments in which the discrimination of targets by acoustic sensors (nowadays the main component of defence) is obscured by physical obstacles or by reflection and reverberation.

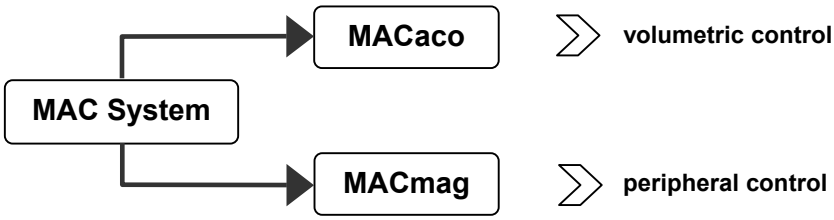

Fig. 3 - Basic structure of the MAC System and the spatial performances of magnetic and acoustic subsystems.

Magnetic sensors available today have extremely high sensitivities and, in principle, are capable to detect signals generated by divers without difficulty. In practice, this prerogative is strongly compromised by the spectral content of the Earth's magnetic field in port areas characterized by an extremely wide band and by amplitude components often exceeding the target's one. If we indicate by E_i the energy associated with the ith elementary spectral component of the magnetic field, the information content Q of the field is given by (Kanasewich, 1981):

$$Q = \sum_{i=0}^{N} E_i ,$$

whereas the information capacity C_i, that is the capacity to associate an individual elementary spectral component with its physical generator, is given by the ratio of the energy E_i to the total energy in which it is dispersed:

$$C_i = E_i / Q.$$

Values of C_i range from 1 (monochromatic signal), to 0 (white noise or insufficient target signal amplitude):

$$\lim_{Q \to E_i} C_i = 1; \lim_{Q \to \infty} C_i = 0; \lim_{E_i \to 0} C_i = 0,$$

Now, we name "N" the noise measured by both the magnetometers we use (one magnetometer as sentinel and one as reference), and "T" the target signal acquired only by the sentinel magnetometer, if the signals F(N+T) and F(N) measured from the two magnetometers are acquired with the same clock, then the filtering operation is a simple subtraction; in the case of uncertainties (even minimal) in the clock timing, the filtering operation is performed in the frequency domain (with an increase in numerical inaccuracy, see Fig. 4).

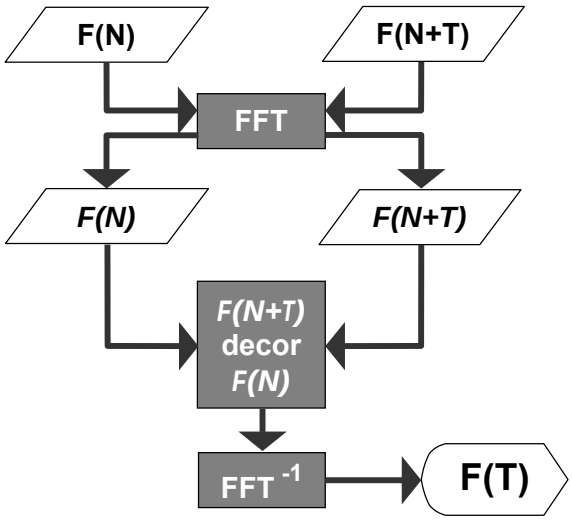

Fig. 4 - Computing procedure to MACmag target F(T) signal identification.

This result can be obtained by two different architectures of the magnetic subsystem: one architecture employs the magnetic field acquired from the previous or next sensor in the array as noise reference (so that each instrument in the array operates both as sentinel and as reference); the other architecture employs a sensor array and an other external instrument as noise reference (so that all the instruments in the array operate only as sentinel). The first architecture is known as a SIMAN-type network (Self-referred Integrated MAgnetic Network), the second one is a RIMAN-type network (Referred Integrated MAgnetic Network), (Faggioni et al., 2009; Gabellone et al., 2007). The system employed in the present work consists of two magnetometers in a SIMAN configuration. However, this configuration does not represent a full operational unit of the SIMAN network because a target crossing halfway between the two sensors induces the same signal in both magnetometers and, consequently, the target removal in the filtering process. In practice, a full operational unit needs a third magnetometer which

allows a comparison $\Delta F_{(12)}$ between the first pair of sensors and $\Delta F_{(23)}$ between the second pair, such that the removal of the target can occur for at most one pair only (see Fig. 5) but not for the whole system.

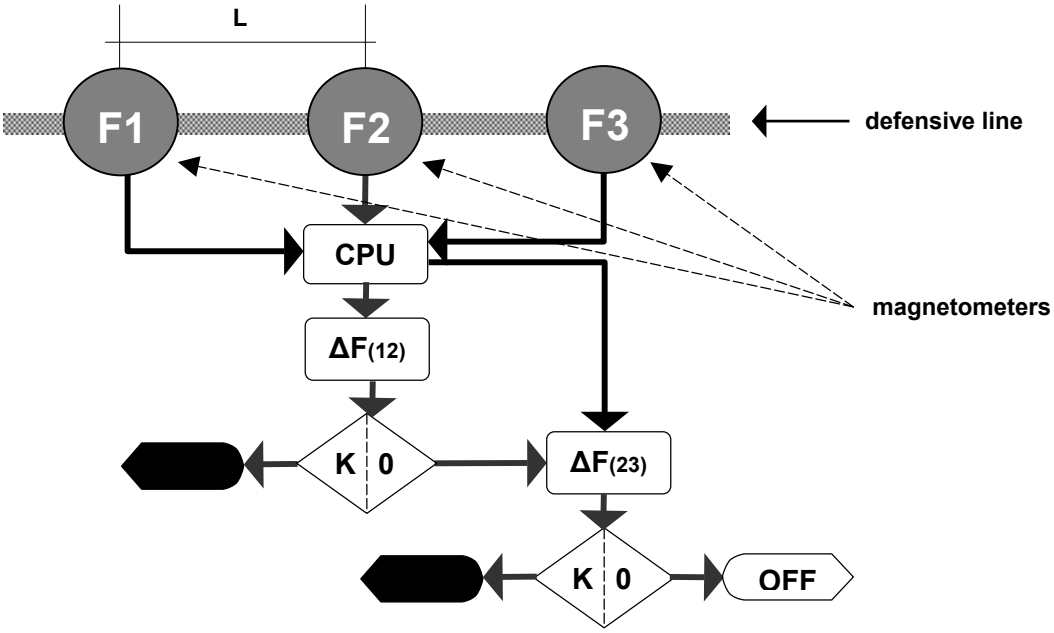

Fig. 5 - Operative structure of the elementary cell of the MACmag subsystem.

The experimental configuration employed, including the two magnetometers, is clearly suitable for experimental validation of the MACmag component, with the exclusion of target crossings halfway between the two sensors. The magnetic system has been tested in environmental conditions of high, medium and low noise and with two different targets, military and civil divers. The results obtained are reported in Fig. 6. The briefer source (military diver signal) has been tested in high electromagnetic noise to submit MACmag to the greatest operative stress. After the processing procedures performed by the MACmag, the passive energy (p.E.: energy not linked with the target) turns out being much lower than the informative one (i.E.: energy of the target's signal), also in worst operative conditions. For what concerns the civil target in a medium noise environment, the passive energy results to be irrelevant compared with the target's signal processed by the MACmag. On the base of the signal temporal duration and the target estimated velocity, we can compute the distance from the sensor at which the target signal can be detected by the sentinel with an intensity of at least 2 [nT] (minimum informative threshold level for divers according to Italian Navy parameters). Such distance indicates the amplitude of the vertical water section that a magnetometers array, displaced on the sea floor, can control with effectiveness (Gabellone et al., 2008). This section changes in reason of the amplitude of the target signal: commercial divers can be detected at a higher distance than

military divers. This considerable effect has been represented in Fig. 6, where the white temporal window in which the magnetic signal is greater than 2 [nT] has a higher duration for the civil diver.

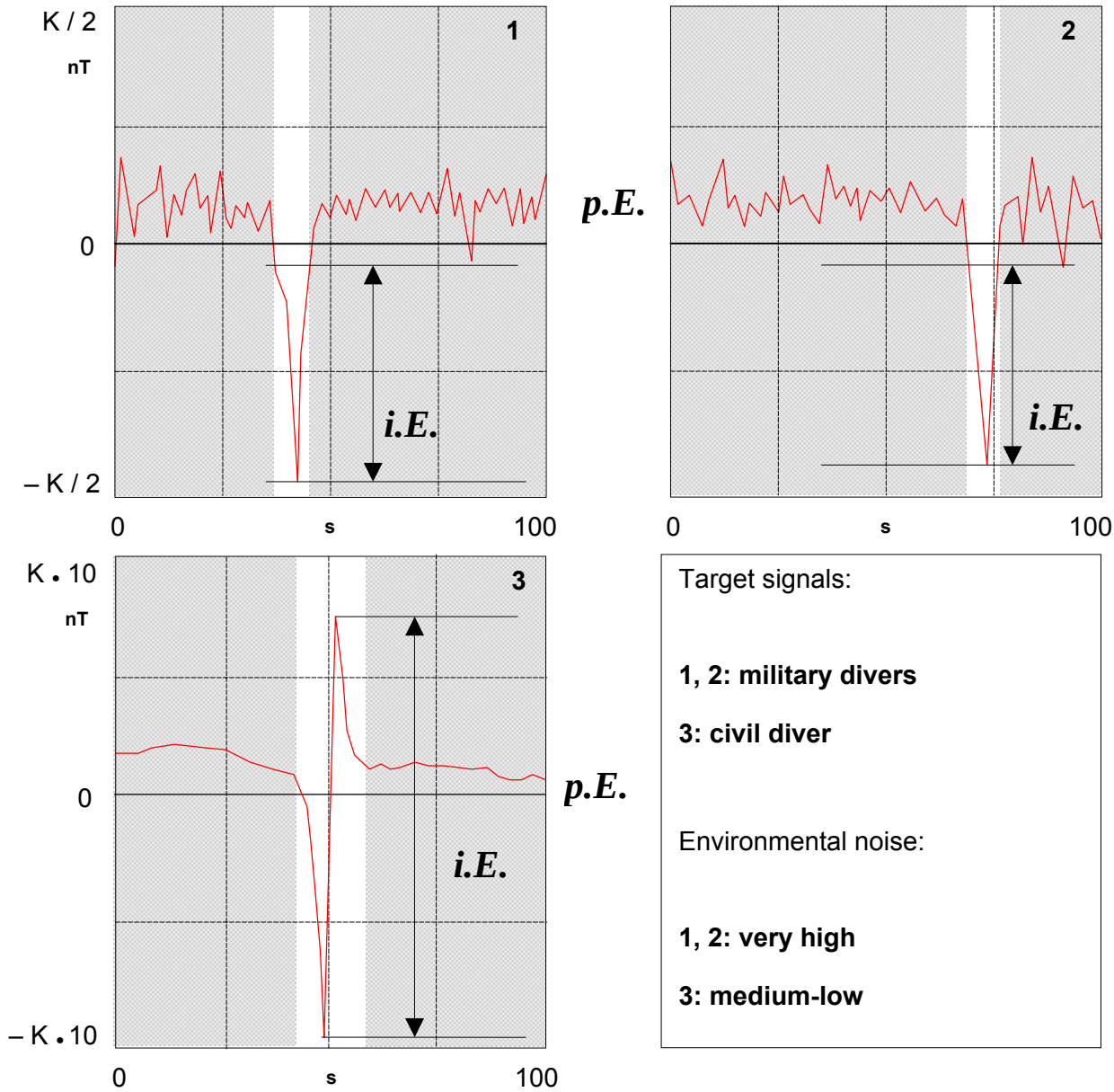

Fig. 6 - Examples of magnetic detection of civil and military divers in various magnetic environmental conditions by the MACmag subsystem.

This greater signal's temporal duration of the civil diver is not connected to a different swimming velocity, but is related to the higher amplitude and spatial persistence of the civil magnetic signal, that can be sensed for a greater interval of time. The detection spatial geometric parameters measured for a civil diver and described in this experiment have been projected into an hypothetic magnetometers array displaced on the sea bottom of the access way of the Duca degli Abruzzi basin, as shown in Fig. 7.

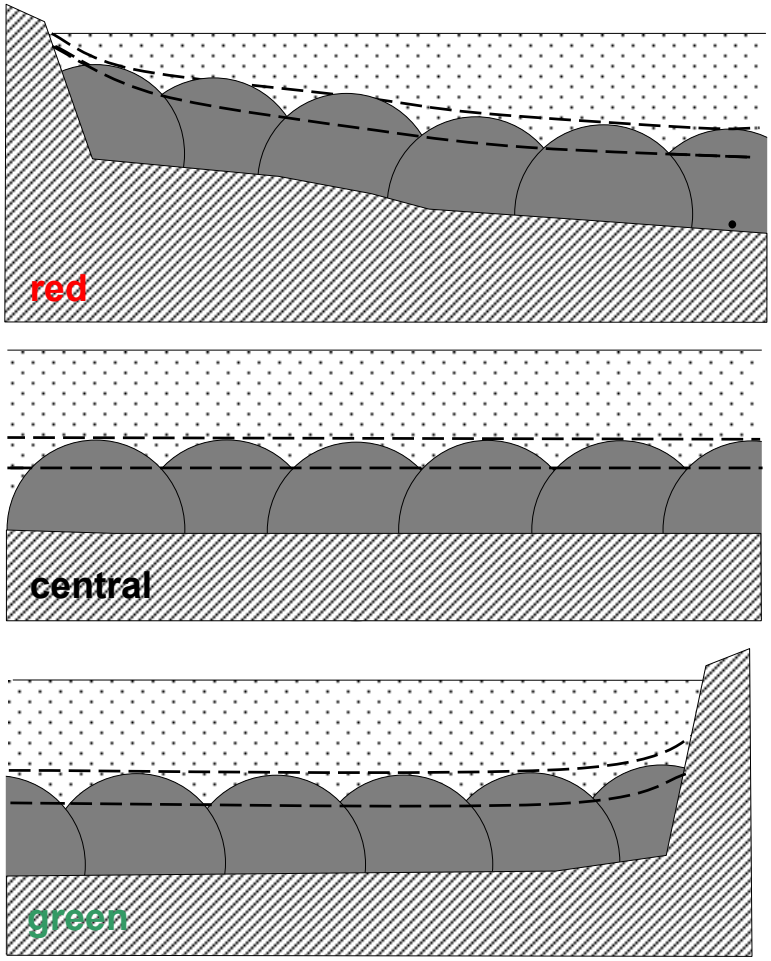

Fig. 7 - Model of magnetic coverage obtained by translation of MACmag performances for civil diver magnetic signature.

The dashed line nearest to the sea floor indicates the 100% detection section, the portion between the two dashed lines indicates the 75% confidence in detection zone, while the portion between the upper dashed line and the sea surface could not be observed by the MACmag subsystem. The zones painted more intense gray indicate the overlap of two different consecutive sensors: in these areas the de-correlation between signal and noise decreases: such condition of uncertainty originates from the automatic process described in Fig. 5. Applying the same principle of transfer, we will obtain the covering models for a military diver that swims towards the protected vertical surface. Fig. 8 shows the spatial effectiveness of the control system due to a military diver magnetic source; therefore the system can still detect and defence the periphery of the access channel near the seabed, where acoustic system works in greater stress conditions.

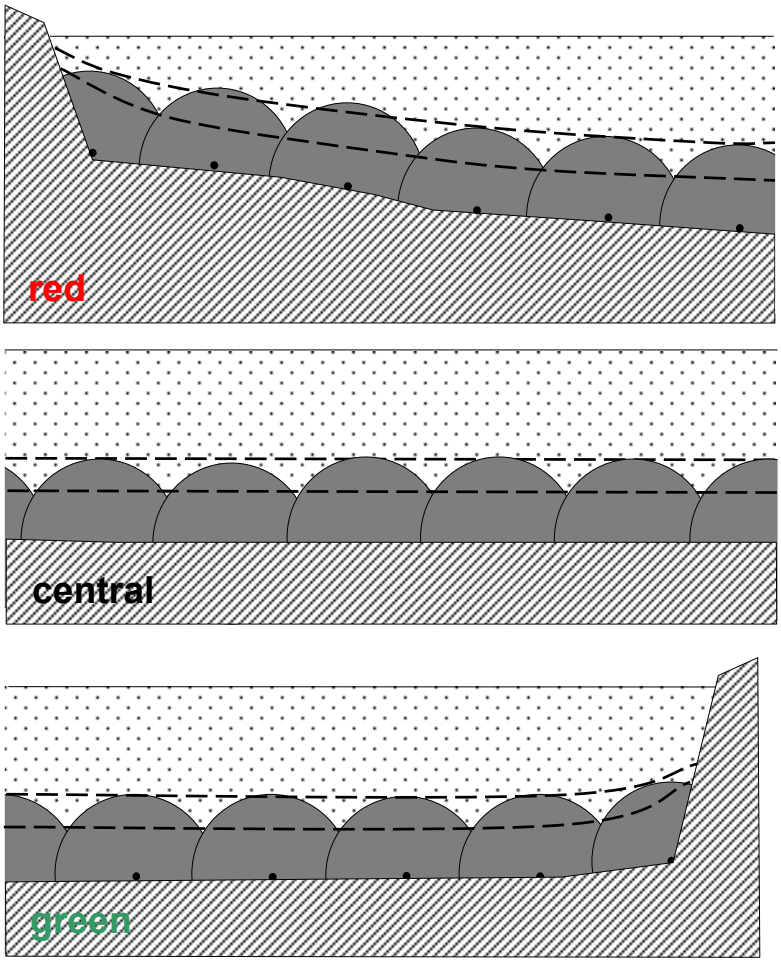

Fig. 8 - Model of magnetic coverage obtained by translation of MACmag performances for military diver magnetic signature.

To have a quantitative evaluation of the MACmag subsystem, we have produced a digital model of the Duca degli Abruzzi access channel section and its magnetic coverage (100% and 75% confidence, see Fig. 9). The digital model has been built by sampling the channel section in Fig. 8 with a network of pixels with a length of 50 [cm] and assigning the 100% value of effectiveness to the pixels in which the effectiveness value was 100% for at least the 80% of the pixel (block 1); the same procedure has been performed for block 2 (effectiveness equal to 75%). The areas borders have been interpolated with horizontal and vertical lines parallels to the interpolated profile of the sea floor, obtaining homogeneous blocks. This result, to the state of the art of the MACmag development, represents the magnetic component subsystem output, which has to be integrated with the acoustic response to obtain the final result.

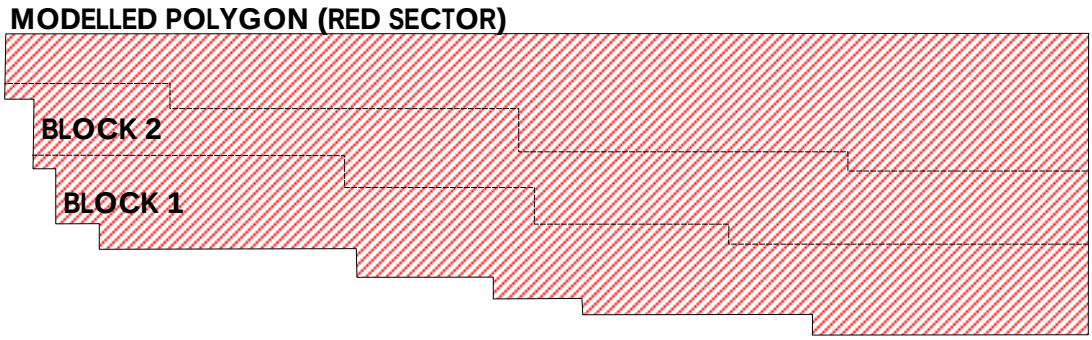

Fig. 9 - Digital model of magnetic coverage: Block 1 = 100%, Block 2 = 75% of effectiveness.

The Acoustic Subsystem

The MACaco acoustic subsystem consists of a series of active acoustic sensors; these are deployed on the bottom of the area's entrance that should be protected. In this way the detection barrier is not invasive to the normal ship traffic, although it is able to provide a warning alarm to the intruders' passage. The active acoustic sensors use a medium frequency band to detect the threat. The sensors are omni-directional, so spherical propagation can be reasonably assumed. The following picture (Fig. 10) represents the acoustic performance of one sensor:

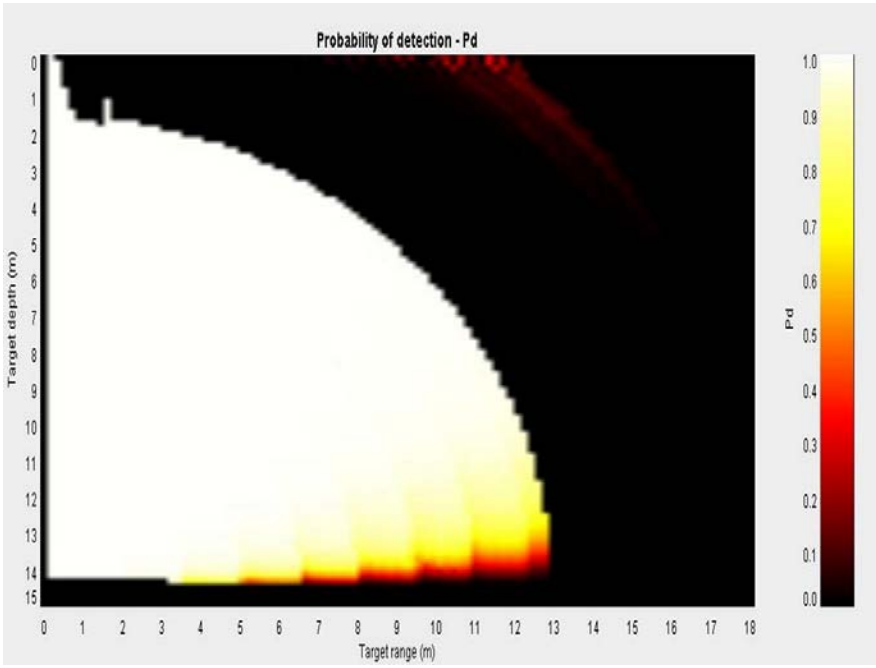

Fig.10 - Acoustic performance.

In the picture the sensor is positioned on the bottom left angle, so it is represented only half-sphere. Vertical axis is the depth water and horizontal axis the range, both expressed in meters. The detection volume is a sphere with a ray about the water depth. A double sensors line

composes the acoustic barrier. This is useful to discriminate alarms due to divers from alarms due to fishes, as well as to get indications for direction of the threat. The sensors number to be deployed is set as function of the scenario and in particularly of the stretch length to be surveyed. In order to protect a large volume of the stretch, the sensors must be spaced at a distance not greater than the water depth. In Fig. 11 is shown an example view of the acoustic barrier:

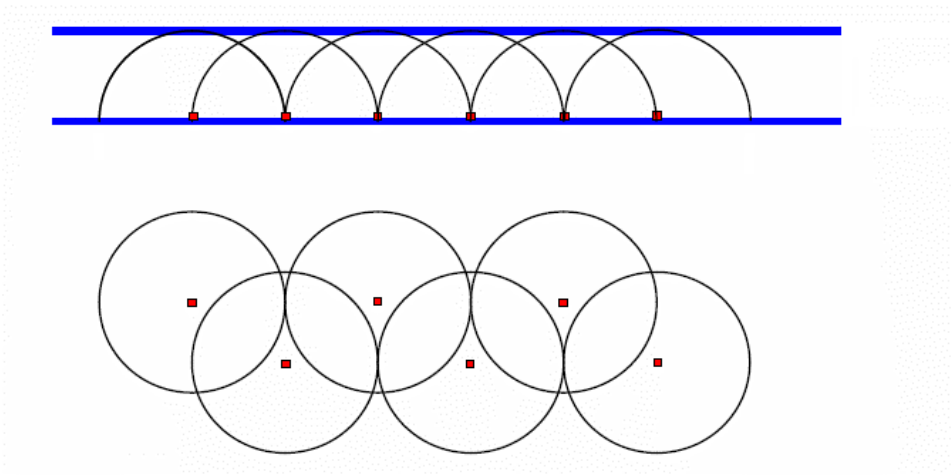

Fig. 11 - View of the acoustic barrier.

The acoustic sensors are connected by a serial link. The acoustic data, from each sensor, are sent to the acoustic processor ashore through a fiber optic cable laid down on the bottom. Also the power required by the sensors is supplied through the cable. The prototype tested in the Italian Navy Base was composed of 6 sensors (Fig. 12).

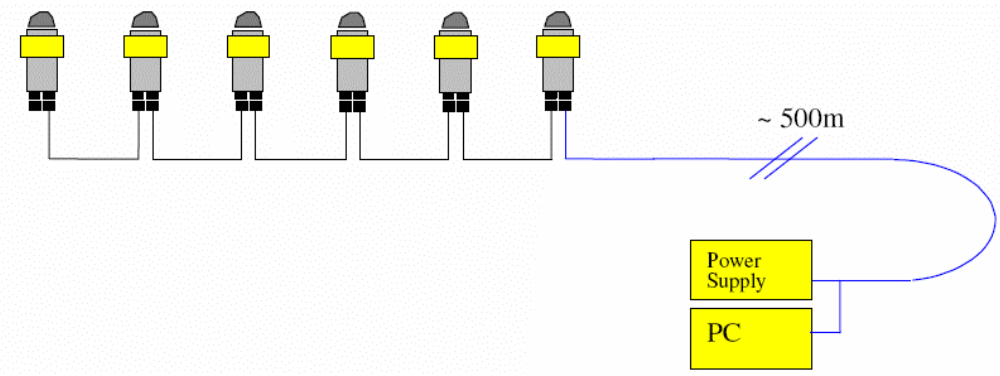

Fig. 12 - Connection between sensors.

The limit performances of the acoustic sensors of the prototype barrier have been evaluated by means of numeric simulations. Assuming SS8 (worst case) for the ambient noise, we observe from Fig. 13 that reverberation is always prevailing respect to noise, in case of flat bottom.

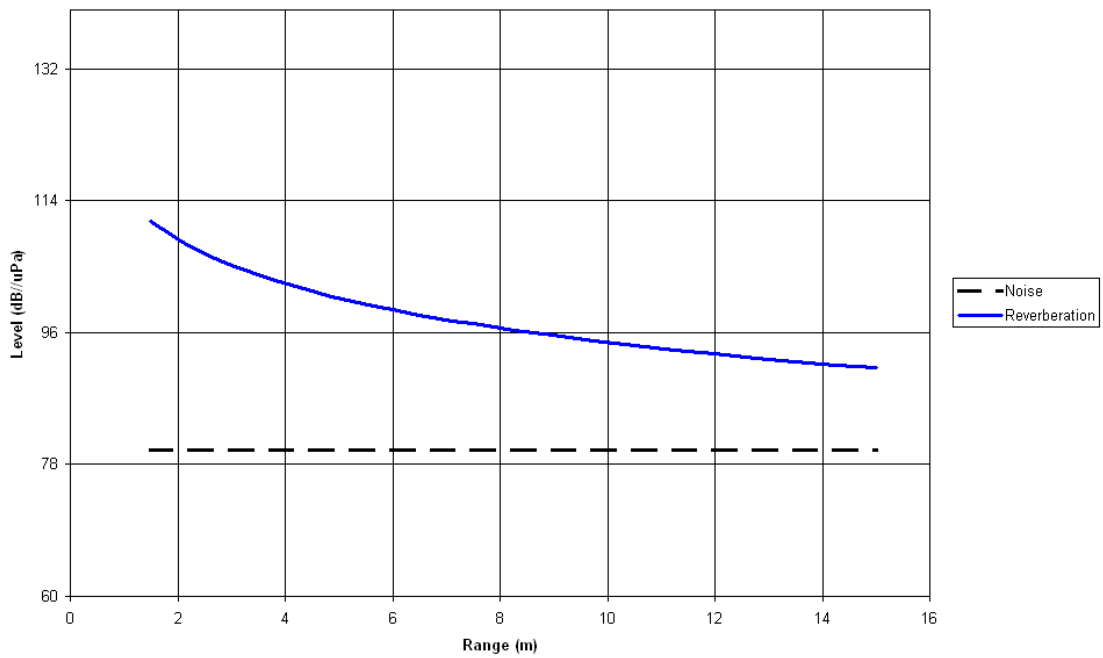

Fig. 13 - Reverberation.

This means that even in the most severe conditions, the performances of the prototype are limited only by reverberation. Based on the above results, Signal Excess (SE) vs. target range has been computed (see Fig. 14). The acoustic performance, in terms of Pfa and PD, are satisfactory for all operating depths with exceeding 20 dB even at 15 m depth.

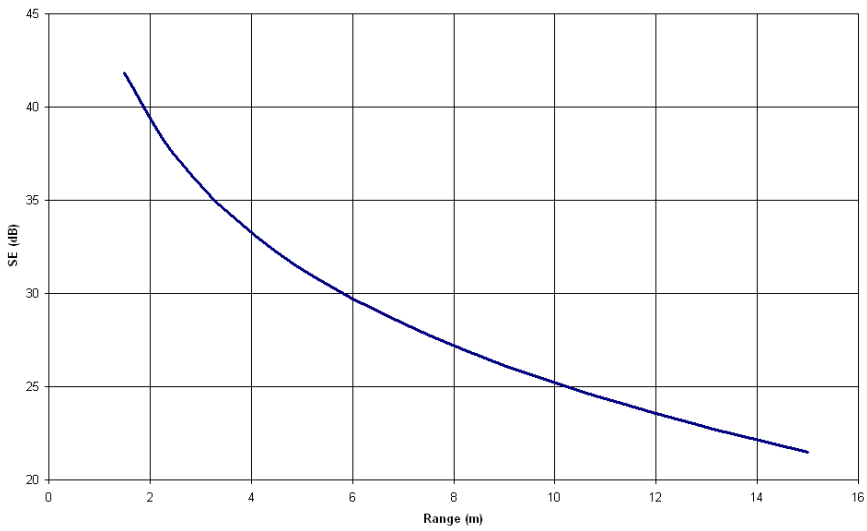

Fig. 14 - Signal excess.

In the HPT08 context, the acoustic barrier was tested through the random transit of commercial and stealth divers as well as little surface units. During the trials, the barrier task was to provide early detection of threats. The system, conceived as explained above, is effective. Both

commercial and stealth divers could be detected as well as little surface units. One sample of the experimental results is shown in the following picture (Fig. 15):

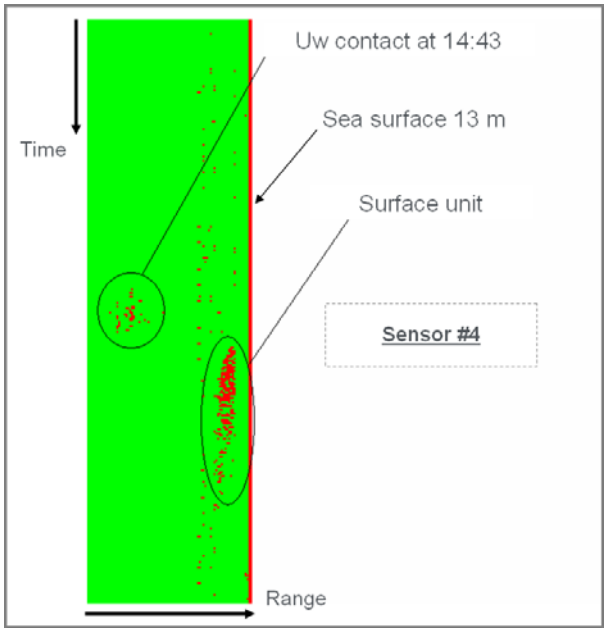

Fig. 15 - Acoustic detection.

The vertical axis represents time. The figure displays a time-history of 5 minutes of echo returns; each return being represented by the horizontal lines, while time-history flowed downwards. The water column is represented on the horizontal axis. The echoes start from the sea bottom (on the left side) and arrive to the surface (on the right side). In this case a diver, approximately half depth in the water column, is detected as well as an inflatable boat above water. When the bottom of the sea is rising (for example near to the piers) the effect of reverberation appears at lower distances than the bottom depth. In this case, the performances of the acoustic barrier are well reduced and it is advisable to use complementary magnetic sensors.

The Synthetic MAC (Magnetic-ACoustic) System

In order to obtain the effectiveness' areas overlap of the two subsystems, we have built the model in Fig. 16. In this scheme the effectiveness' area of each acoustic sensor have been transposed to the magnetic model, obtaining an horizontal effectiveness section of the MACaco subsystem, which highlights the decrees of the controlled area of the acoustic system in connection with the proximity to the sea bottom and/or to the docks.

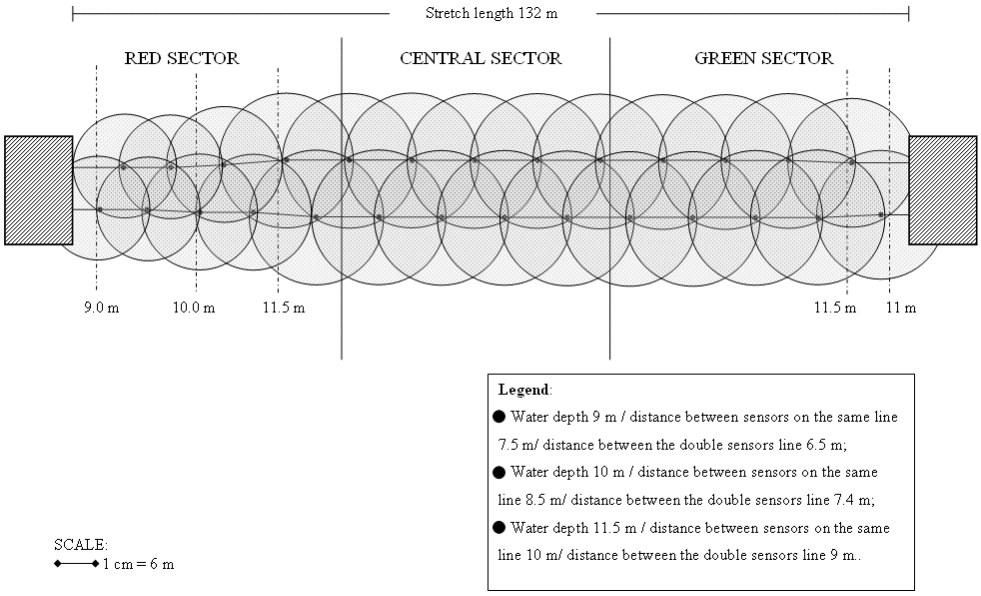

Fig. 16 - Model of acoustic coverage (horizontal section of the access channel).

Projecting the vertical surface of each sector on a general model we obtain the integrated vision of the attended performance of the MAC System (see Fig. 17).

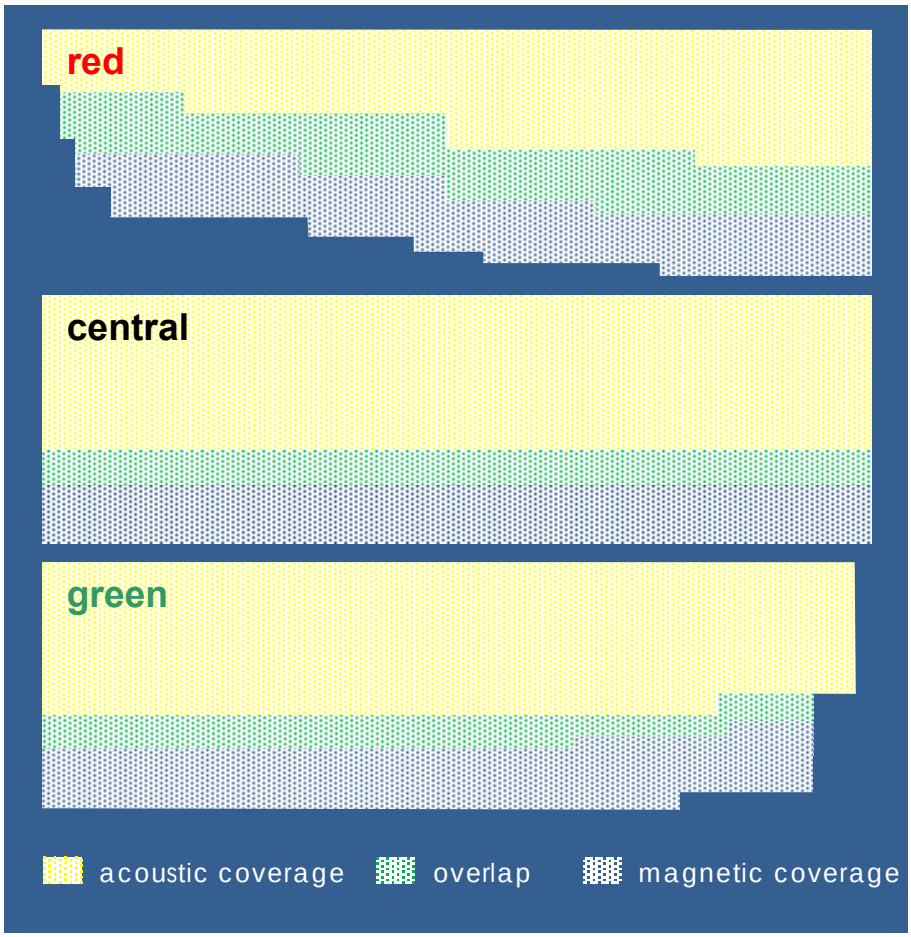

Fig. 17 - Model of MAC System performance – Vertical sections of the three sectors.

Figure 17 shows that the magnetic component (blue zone) works with greater effectiveness in the proximity of the sea bottom, where the confidence of the acoustic system (yellow zone) decreases, while, vice versa, near the sea surface the acoustic subsystem completely protects the magnetic component, out of reach. The integration is completed considering a third zone (green zone) in which the two systems overlap each others, making this layer of water subject to a dual control.

Conclusions

In the field of detecting fleeting underwater cinematic sources (i.e. malicious divers) the performances of detection systems based on a single sensor class often results to have low confidence. For example, high performance of acoustic systems in the volumetric control is strongly reduced to effectiveness nearly zero in proximity of docks and seafloor, in particular if it is morphologically irregular or if there is a wreck on the sea floor. All this objects behave like acoustic reflectors that become active also in calm sea condition. On the contrary, auto-referred magnetic systems, based on the geometric concept of spatial stability noise-target, supply excellent performances in proximity of the sea bottom, also in case of irregular morphology, but its effectiveness decreases with the increase of the distance from the sentinel sensors. So, the acoustic subsystem is a typical volumetric observer, while the magnetic system is a typical peripheral observer. The integration between the two subsystems into a dual observation magnetic-acoustic MAC System allows a high confidential covering barrier of the water section to be controlled, preserving the best features of the two single approaches.

Bibliography

Faggioni O., Gabellone A., Hollett R., Kessel R.T., and Soldani M., *Anti-intruder port protection "MAC (Magnetic ACoustic) System": advances in the magnetic component performance*, CD-ROM Proceedings of 1st WSS Conference, August 25-28, Copenhagen, Denmark, 2008.

Kanasewich E.R., *Time Sequence Analysis in Geophysics*, The University of Alberta Press, Edmonton, Canada, 1981.

Faggioni O., Soldani M., Gabellone A., Maggiani P., and Leoncini D., *Development of anti intruders underwater systems: time domain evaluation of the self-informed magnetic networks performance*, in Corchado E., Zunino R., Gastaldo P., and Herrero Á. (Eds.), *Proceedings of the*

International Workshop on Computational Intelligence in Security for Information Systems CISIS 2008, Springer-Verlag, Advances in Soft Computing, vol. 53, pp. 100-107, Berlin Heidelberg, Germany, 2009.

Gabellone A., Faggioni O., Soldani M., and Guerrini P., *CAIMAN Experiment*, CD-ROM Proceedings of UDT Europe 2007 Conference, June 5-7, Naples, Italy, 2007.

Gabellone A., Faggioni O., Soldani M., and Guerrini P., *CAIMAN (Coastal Anti Intruder MAgnetometers Network)*, CD-ROM Proceedings of RTO-MP-SET-130 Symposium on NATO Military Sensing, March 12-14, Orlando, Florida, USA, 2008, NATO classified.