PRESENTATION OF A REAL-TIME HIGH DATA RATE ACOUSTIC LINK BASED ON A SPATIO-TEMPORAL BLIND EQUALIZATION
The TRIDENT acoustic system

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Abstract: **There is no doubt about the growing interest in underwater acoustic communications. Among all existing applications, the objective of the Groupe d'Etudes Sous-Marines de l'Atlantique (GESMA) is to develop a sufficiently robust high data rate acoustic link, named TRIDENT. For that purpose, different kinds of information (text, images…) could be periodically emitted through the acoustic channel. A real-time receiver, based on a spatio-temporal blind adaptive decision feedback equalizer, developed and patented by ENST Bretagne was designed to cope with all perturbations induced by such harsh channels. Some sea trials were realized on June 2002. The first results are clearly convincing since most of the 48 sequences of 5 minutes are successfully demodulated by the DSP in real-time.**

This acoustic system allows the transmission to data rate from 8 to 25 kbps in horizontal configuration.

I- INTRODUCTION.

A real-time high data rate acoustic link is currently developed by GESMA. The objective of this project is to develop a solution allowing wireless communications since a vehicle towards surface. This acoustic link must be sufficiently robust to equip the mine hunting vehicles. Indeed, the evolving roles of underwater vehicles are currently constrained by the lack of reliable underwater communications.

The last years of this project were dedicated to up-stream studies. The aim was to choose the best receiver able to cope with multi-path and variability of the acoustic channel. A patented equalizer developed by ENST Bretagne was clearly well-suited for desired applications [1].

As a consequence, an acoustic link was developed in order to test the whole communication from the acquisition of useful data to the restitution. The emission part was realized by ORCA Instrumentation, a French company specialized in acoustic modems. The receiver was realized by ENST Bretagne. The heart of this receiver is a spatio-temporal decision feedback equalizer (DFE) able to identify and follow strong variations of underwater acoustic channel (UWA). The last edition of OCEANS gave some information about the integration of this receiver on a platform DSP (Digital Signal Processor) [2].

This paper is organized as follows. The second part gives some recalls about the SOC MI DFE. The two running modes of this receiver are described. The simplicity and modularity of such an equalizer are also presented. The third part presents an overview of this equipment called TRIDENT. Finally, two examples of the first results of the last sea-trials realized in June 2002 are presented.

II- SOME RECALLS ABOUT THE SOC-MI-DFE.

Let d[k] denote a zero-mean, with unit power σ_d^2, independent and identically distributed (i.i.d) sequence of discrete data. These data are transmitted through K channels h_i. In addition to the corruption of the channel, the received signals are sullied with Gaussian noise n_i [k] with variance σ_n^2. The received signals s_i [k] in this context SIMO (Single Input Multiple Outputs) can be written as:

$$s_i[k]=\sum_{l=0}^{N} d_{k-l}.h_i[l]+n_i[k] \quad i\in[1:K]$$

The expression of the optimal linear receiver which minimizes the mean squared error (MSE) is given by:

$$C_i(z)=\frac{\sigma_d^2.H_i^*(1/z^*)}{\sigma_d^2.\sum_{i=1}^{K} H_i(z).H_i^*(1/z^*)+\sigma_n^2}$$

The spectral factorization of the denominator of this expression gives then:

$$C_i(z)=\underbrace{\frac{\sigma_d^2.H_i^*(1/z^*)}{S_K.G^*(1/z^*)}}_{Bi(z)}.\underbrace{\frac{1}{G(z)}}_{A(z)+1}$$

where G(z) stands for the minimum phase polynomial

Usually, this linear equalizer (LE) is implemented as a transversal filter (FIR) in order to avoid instabilities. The optimal linear receiver thus consists of a filter A(z) common to each branch and a dedicated filter $B_i(z)$. A(z) is the reverse of a minimal phase filter. It is thus stable and realizable in recursive form. The separation of these two stages allows the LE equalizer to easily evolve towards the conventional DFE.

The expression of the optimal nonlinear receiver gives:
For the forward filters P_i (z):

$$P_i(z)=\frac{\sigma_d^2.H_i^*(1/z^*)}{S_K.G^*(1/z^*)}$$

and for the feedback filter Q(z):

$$Q(z)=G(z)-1$$

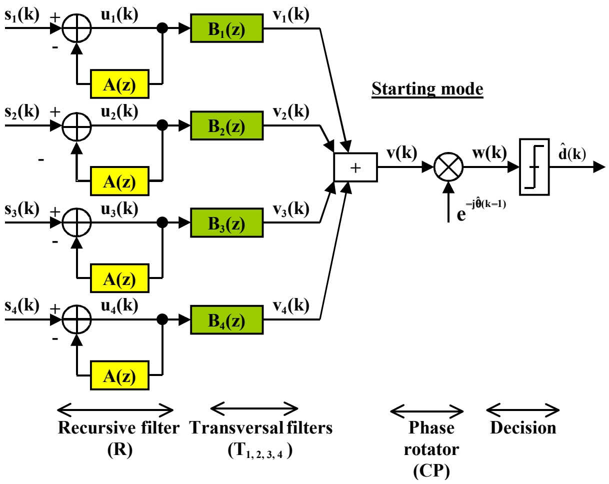

Fig. 1 : SOC MI DFE in its starting mode.

One can realize that the two structures are relatively similar. The only difference is given by the position of feedback filter either in front of the transversal filters B_i for the linear structure or around the decision device for the non-linear structure.

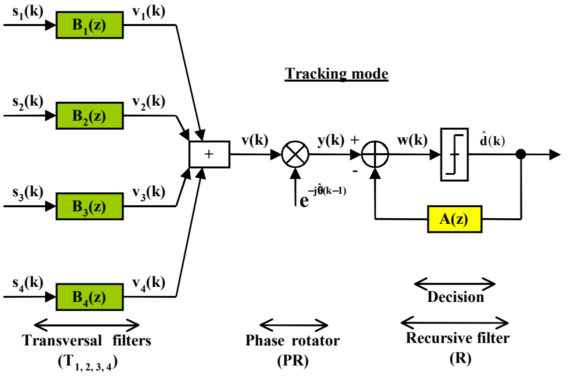

Fig. 2 : SOC MI DFE in its tracking mode.

Whatever the used structure, each stage is driven by a specific adaptive algorithm (blind in the starting mode and decision directed in the running mode). This receiver is then characterized by a great flexibility in use and an increased robustness. The various used algorithms are detailed in [4].

In this context, the bound of reachable performances of a DFE are:

$$EQM_{\min-DFE}=\frac{\sigma_n^2}{S_K}$$

By using the spectral factorization, one can show without difficulty the following relation :

$$\log(S_K)=T.\int_{-1/2T}^{1/2T}\log\Big(\sum_{k=1}^{K}\left|h_k(\nu)\right|^2.\sigma_d^2+\sigma_w^2\Big)d\nu$$

It appears since

$$\begin{aligned}
log(S_K) &= T.\int_{-1/2T}^{1/2T} log\Big(\sum_{k=1}^{K}\left|h_k(\nu)\right|^2.\sigma_d^2+\sigma_w^2\Big)d\nu\\
&> T.\int_{-1/2T}^{1/2T} log\Big(\sum_{k=1}^{K-1}\left|h_k(\nu)\right|^2.\sigma_d^2+\sigma_w^2\Big)d\nu\\
&> log(S_{K-1})\\
&\Rightarrow S_K > S_{K-1}\\
&\Rightarrow EQM_{\min-DFE(K)} < EQM_{\min-DFE(K-1)}
\end{aligned}$$

Consequently, the more sensors are used, the more theoretical performances are improved. From a practical point of view, adaptive algorithms impose a maximum limit on the number of used sensors. For example, the rhythm recovery can be hard to achieve when delay between too distant sensors exceed several symbol duration. A trade-off has to be found.

The main idea of this receiver is to combine the advantages of these two structures to define a decision feedback equalizer with an adaptive configuration. Thus, in period of convergence, the linear structure is selected in order to benefit from the stability and speed of convergence. When trust in decided data is sufficient, the structure turns into DFE by the evolution of the position of the recursive filter and all stages are then decision-directed. Usually, a measurement of the MSE is used to define the mode of the SOC MI DFE.

III- SYNOPTIC OF THE ACOUSTIC LINK.

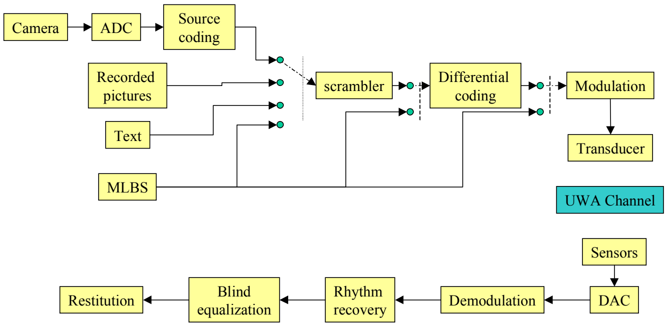

Fig. 3 : Description of the acoustic system TRIDENT.

Fig. 3 depicts a conceptual schematic of the acoustic system TRIDENT. A low-rate mode is first used to fix all parameters of the expected high data rate communication. Moreover, this low data rate acoustic link is able to evaluate the quality of the channel, to give an estimation of signal to noise ratio (SNR) and to draw a snapshot of the impulse response. A graphical user interface (GUI) was developed especially for this application. Among parameters which could be fixed, one can select:

- The kind of information. TRIDENT is able to transmit some useful data (CCD camera), text, recorded pictures, MLBS[1] and voice soon;
- The kind of transmission. Digital information could be scrambled, and differential encoded. Resulting information are then modulated with 2, 4 or 8-PSK.
- The data rate up to 25 kbps chosen by the number of samples per symbol duration (from 2 to 16).

Two bandwidths will be available in the next version of TRIDENT. The first one goes from 30 to 40 kHz with an emitted level of approximately 185 dB@1µPa\1m. The second one will cover frequencies from 10 to 30 kHz.
Emitted signal is received on a 4-sensors antenna, each of them placed wherever on the antenna.

The core of the receiver platform is an acquisition card with a Texas Instruments DSP (TMS320C3201). Most of the processing is written in assembler language in order to reduce the processing time. One can save more than 90 % of time between a same function written either in C-language, either in assembler.

Only amplification is realized in an analogical way. After that, each input signal is synchronously sampled. Demodulation, rhythm recovery and equalization are then performed using digital processing. Demodulation are made easily by sampling every signal at a clock frequency 4fo, fo denoting the carrier frequency. That is why symbol duration T was chosen in such a way that the product fo.T is integer. Timing recovery is performed with the GARDNER algorithm [5].

After that, T-spaced equalization can be realized. Decided data are then decoded and displayed into the GUI.

IV- RESULTS OF THE FIRST SEA-TRIALS.

The first sea-trials were realized in the bay of Brest during June 2002. Acoustic transmissions were performed on two ranges, 300 and 1000 meters. 300 meters long stand for a distance where UWA channel is characterized by a harsh structure of multipath. 1000 meters long correspond to the nominal range for desired applications.
Fig. 5 illustrates the procedure of sea trials on two stations, respectively 300 and 1000m on the bay of Brest. The system TRIDENT is buried at sea and recovered once a day. The emission part is placed approximately at 7 m depth. The antenna is deployed since the BEE Langevin. The space between hydrophones is 2m (around 50 acoustic wavelengths). The first hydrophone is deployed at 7m depth (approximately 3m below the ship's draught).

Fig. 4 : TRIDENT sub-surface equipment.

An order concerning the type of transmission to be received is beforehand transmitted by the low data rate acoustic link (chirp modulation). Once received, the equipment TRIDENT carries out the emission of required information.
Visualization of the transmitted signals showed more or less deep fading, responsible of most of the noted errors. Approximately, 48 shots of 5 minutes were thus transmitted.
The platform of reception TRIDENT processed in real-time received data and thus displayed decoded information.

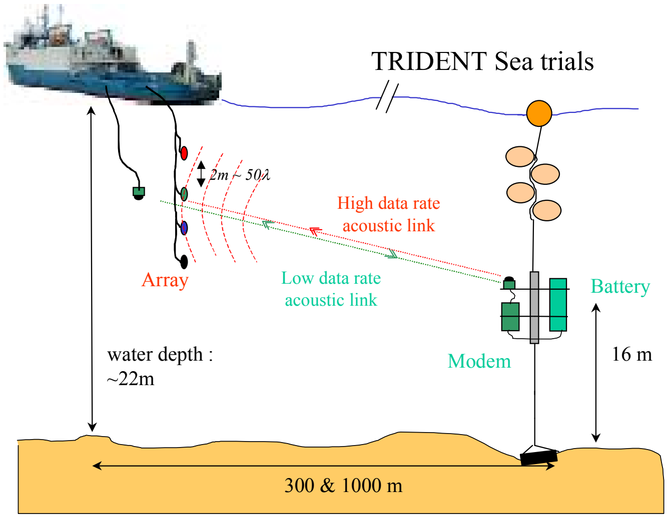

Fig. 5 : Illustration of the sea-trials.

Among 48 signals available, two examples are chosen to illustrate performances of the TRIDENT system.

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[1] Maximum Length Binary Sequence

The first example shows some results about a transmission of recorded pictures. Symbols (differential coded and scrambled) are transmitted using a Q-PSK modulation and a bit rate of 14 kbps. The distance between transmitter and receiver was about 1000m and the depth around 22m.

The different parameters of the SOC MI DFE equalizer are the following: transversal filters had 17 taps among which 5 are reserved for the casual part. The recursive filter is filled with 35 coefficients. This length has to fit with the duration of estimated impulse response.

Fig. 6 shows the evolution of the estimated mean square error (MSE) of the SOC MI DFE for 1 sensor (either with sensor 1 or sensor 3), 2 sensors and 4 sensors. 4 minutes (more than one and a half million of symbols) of transmission are also successfully demodulated which proves once again the robustness of this receiver. Even if estimated MSE are relatively low whatever the number of sensors used, one can note that performances of the SOC MI DFE with one sensor (named in that case SADFE) can greatly fluctuate according to the position of the sensor. This variation is drawing with sensor 1 (dash line) and sensor 3 (dash dot line). The interest of using multiple sensors clearly appears in that case providing more stability and sufficient safety margin. The gain brought by 4 sensors can reach more than 7 dB.

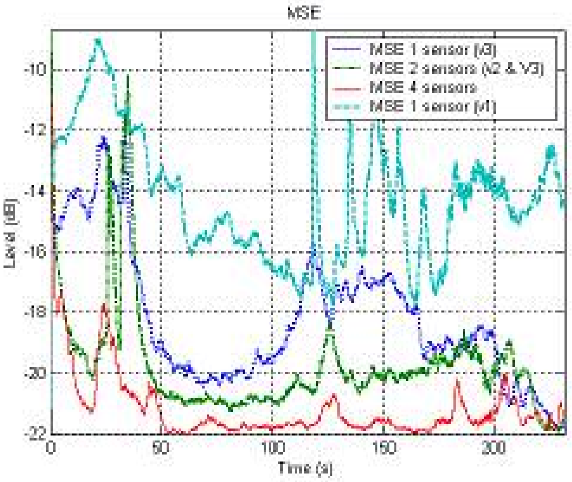

Fig. 6 : Evolution of the MSE for 1, 2 and 4 sensors.

Fig. 7 depicts constellations taken from 150 to 153 seconds of the different signals processed in real-time by the DSP (after digital demodulation and rhythm recovery). The first line corresponds to the SADFE equalization on sensor 3. The second line shows input constellations of sensors 2 and 3. The third line presents constellations given by 4-sensors equalization. The right column draws output constellations given in the different cases (respectively with 1, 2 and 4 sensors).

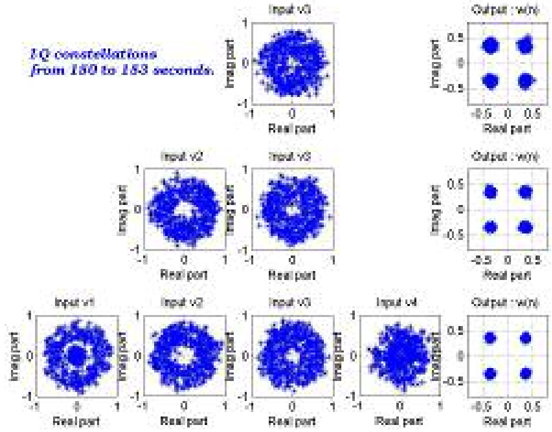

Fig. 7 : I-Q constellations of the SOCMIDFE for 1, 2 and 4 sensors (DSP processing).

This figure illustrates in the same way the gain brought by multiple sensors judging by the output constellations. The main interest of this figure is to show the evolution of input constellation according to samples of different symbols selected by the rhythm algorithm. Samples are clearly chosen in order to minimize a MSE of Gardner error. As a consequence, a sample kept in SADFE equalization could be rejected in SOCMIDFE equalization. That is why a ring structure as the input constellation of the sensor 3 in 1-sensor equalization can be relatively different in the 4-sensors processing. One can note some usual structures of input constellations typical of inter-symbol interference (ISI) in the 4 sensors processing.

Finally, with 4-sensors equalization, data are decoded and send to the GUI which displays received picture. Fig. 8 illustrates one example of an emitted and received picture respectively on the left and right side. Available recorded pictures are representative of sonar processing picture, or drawings.

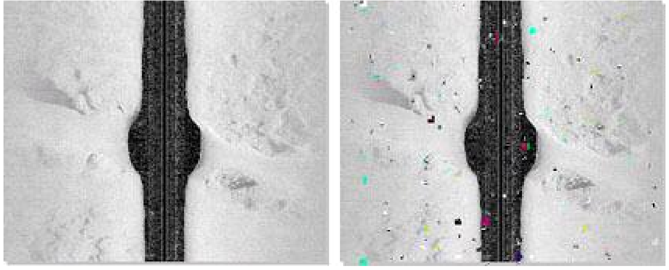

Fig. 8 : Example of an emitted (left side) and a received (right side) picture.

Decoded picture present some errors during JPEG packet decoding. This result could be improved with some channel coding.

From a general point of view, this equipment is clearly able to transmit high data rate information over a long duration.

The second example correspond to a transmission of Q-PSK modulation with a bit rate of 17.5 kbps. The kind of information are MLBS without coding and scrambling. This type of information is useful to draw estimated impulse response. The distance between transmitter and receiver was about 300m and the depth around 20m.

The different parameters of the SOC MI DFE equalizer are the following: Transversal filters had 17 taps among which 13 are reserved for the casual part. The recursive filter is filled with 35 coefficients.

The plots in Fig. 9 and Fig. 10 display the evolution of magnitude of different taps every 800 symbols and for a file duration around 3 minutes. The length of the recursive filter is representative of the length of the impulse response as mentioned in part II-. In that case, three main paths appear on the first twenty taps. Fading could explain the variation of magnitude of the main path during the second minute of transmission.

The different levels of the transversal filters show some tap values of the first filter twice greater than those of the last two sensors filters. Transmission loss and acoustic propagation could explain this variation of power.

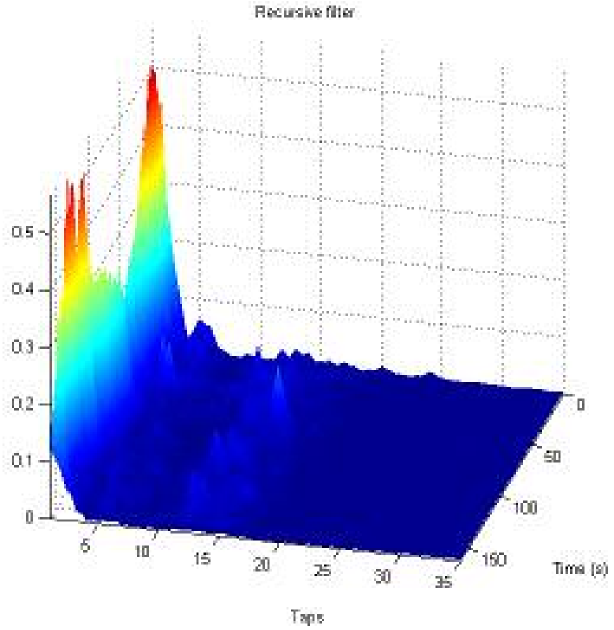

Fig. 9 : Evolution of the magnitude of recursive filter taps during transmission.

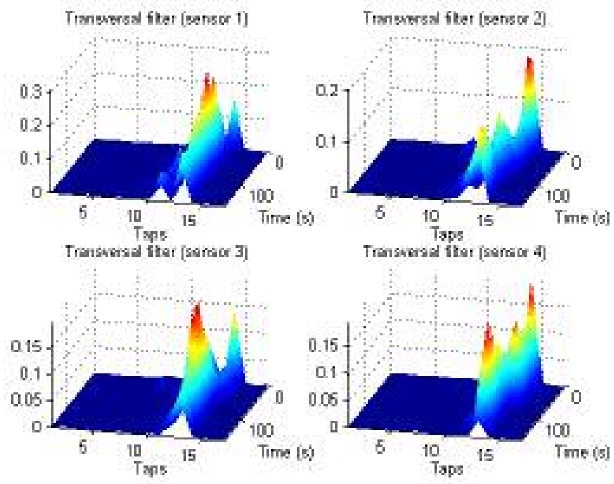

Fig. 10 : Evolution of the magnitude of transversal filters taps during transmission.

Fig. 11 shows the evolution of the estimated mean square error (MSE) of the SOC MI DFE for 1 sensor (dash line), 2 sensors (dot line) and 4 sensors. 3 minutes (more than one and a half million of symbols) are successfully demodulated. Estimated MSE are more stable than in the previous example. MSE bound goes from 10 dB in the 1 sensor case to 16 dB in the 4 sensors case. As a consequence; the gain brought by 4 sensors can reach more than 6 dB. Performances seem to be less good even if the range was reduced. Once again, spatial diversity provides a safety margin.

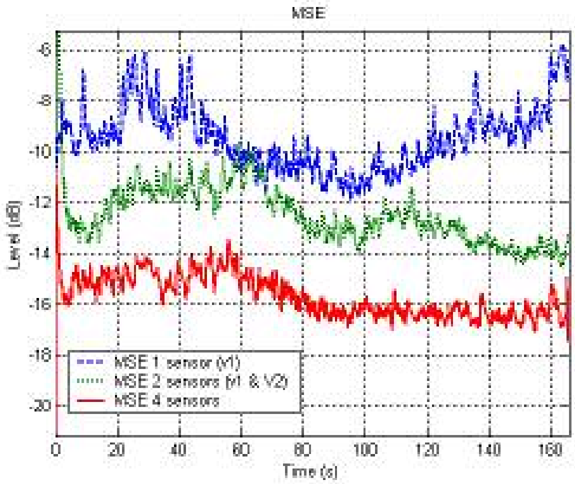

Fig. 11 : Evolution of the MSE for 1, 2 and 4 sensors.

Fig. 12 depicts constellations taken from 70 to 73 seconds. As Fig. 7, the first line corresponds to the SADFE equalization (on sensor 1 in that case). The second line shows input constellations of the first two sensors. The third line presents constellations given by 4 sensors equalization. The right column draws output constellations given in the different cases (respectively with 1, 2 and 4 sensors).

As mentioned above, the structure of multipath seem to be more difficult at the range of 300m than at 1000m. The ring structure of the constellations in the previous example could be representative of a relatively simple structure (one or two main paths) even though the blurred constellations are more representative of a very harsh UWA channel.

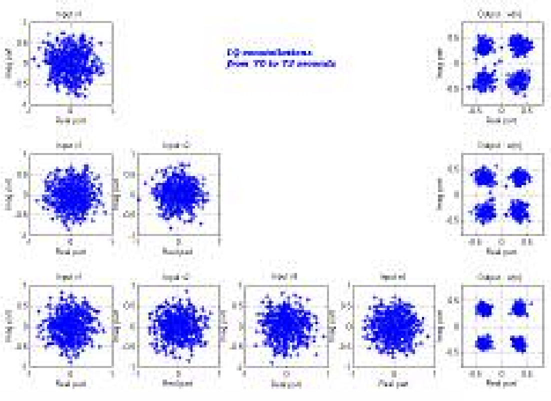

Fig. 12 : I-Q constellations of the SOCMIDFE for 1, 2 and 4 sensors (DSP processing).

V- CONCLUSION.

In this paper, a real time acoustic link developed by GESMA, ENST Bretagne and ORCA Instrumentation is presented. Based on a patented blind equalizer, this system, named TRIDENT, showed some interesting performances in terms of MSE, Bit Error Ratio (BER) and convergence speed. Most of the transmitted sequences were successfully demodulated during several minutes. The robustness and adaptability of its receiver is clearly shown.

Interest of spatial diversity is confirmed. Even if mono sensor equalization exhibits a good behavior, spatio-temporal equalization offers a safety margin and an improved stability.

As a result, evolution of this system could be either the integration of channel coding or iterative procedure. For that purpose, some theoretical points needs further works.

These first sea trials will be followed by other evaluations whose aim will be the evaluation of Doppler immunity. The TRIDENT equipment will be carried out by a ROV in order to test a typical mine hunting mission.

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