UDT 2019 – *Multistatic underwater protection sonar best patterns for harbour and larger critical environments*

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Abstract — This paper presents a modular multistatic sonar solution effective against low noise small index coastal underwater threats providing large detection coverage in order to give sufficient reaction time and improve tracking. Classical monostatic DDS would need impractical sonar numbers for a large critical zone. Various optimized, specific, patented patterns of multistatic sonar transmitters and receivers are shown to require significantly less numbers of Transmitters/Receivers than the equivalent monostatisc solution to cover the same secure barrier zone. . This paper gives parameters and choice criteria for the design of multistatic patterns and for the optimal collaborative arrangement of multiple patterns. It demonstrates optimized barrier length and thickness to ensure enough reaction time whatever threat path, assuming typical speeds through the barrier. Adequate disposition of transmitters and receivers allow both sharing receivers between patterns and partial or total cross-covering of the blanking zones of respective close bistatic dipoles. A practical example for complete harbor multithreat protection is given. Multistatic solutions show superiority and flexibility versus monostatic solution at pattern level and adequacy at system level, thus allowing large coastal critical zone protection solution against the more dangerous proliferating underwater new smart threats.

1 Introduction

1.1 Objective

The objective of this paper is to define multistatic sonar patterns of 1 TX (Transmitter) and nRX (n Receivers), their specific use and collaborative arrangements to secure detection in layered successive zones allowing early enough primo-detection and continuous possible tracking for reaction capability against various underwater worst threats attacking sensitive assets.

In order to protect a sensitive asset, a surveillance system shall comply with the time required to neutralize the threat. The reaction time shall be sufficient for all type of underwater threats. With a diver moving at an average speed of 1.5 knot, a secure solution is to have a primo-detection 15 minutes before the threat can reach the asset, which needs 700m range at 1.5 knot.

With propulsion aid called Diver Propulsion Device (DPD), the diver speed can be up to 3 knots, asking then 1400m for the same reaction time. With a fast Swimmer Delivery Vehicle (SDV) or a drone, the speed can be up to 6 knots. In this case, for the same primo-detection of 15 minutes the challenging detection range should be 2.8 km.

Threats considered here are low noise, making reliable passive primo-detection unlikely in strong ambient noise. The primo detection is performed here with powerful active sonar using multiple multistatic patterns. Their location depends on sensitive area to be protected and on the coastline shape in a given non homogeneous littoral environment. This is different, then, from open sea multistatic patterns, such as sonobuoys placement [1] for maximal homogeneous surface coverage whatever its shape or best statistical search game [2]. Multistatic wideband sonar is currently developing on networked mobile assets [3] increasing frigate operational advantage on submarines, with also possible bistatic helo/frigate cooperation [4].

A fixed detection coverage could be a surface [5], points to be detected [6] or a line barrier. The barrier shape is characterized by its distance to sensitive asset, its length for closing the area and thickness. The thickness is correlated with the need to detect the target continuously over a given time. Reaction can then be guided to stop the threat before it reaches the sensitive asset.

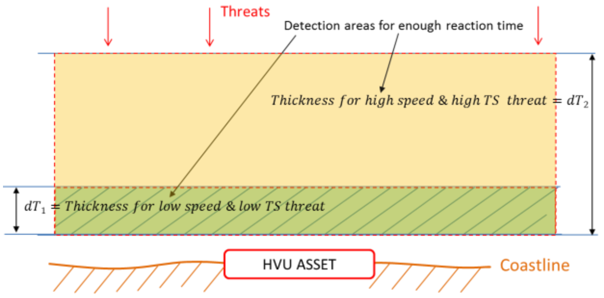

Fig. 1. Barrier needed thickness versus threat speed

1.2 Key results

Key results of this paper are multistatic 1TX/nRX detection patterns specific to secure fixed surveillance zone, from a global barrier chain up to a large surface. The overall solution shall deal with all kind of threat speeds, including long range for faster threats requiring multi-layered detection zones. This is shown to be achieved with significantly less numbers than collocated TX and RX of monostatic sonar solutions, and with less transmit timing constraints. Sharing of receivers between patterns, redundancy and blanking zone cross coverings offer supplementary significant multistatic advantage.

The 1TX/2RX shared chain defines the minimal barrier, doubling the efficiency of barrier “useful surface” of multiple monostatic sonars.

The 1TX/4RX unshared allows a thicker redundant barrier with a good barrier shape.

The 1TX/6RX is a good pattern solution where large specific area detection is needed with strictly continuous detection for low threat index. It is an optimal surface pavement solution,

These and other multistatic patterns for protection are computed, sized and efficiency assessed in [7][8]

1.3 Context and solution added value

The protection of harbour, maritime asset or littoral sensitive areas from submarine threats uses heterogeneous sensors with complementary capabilities to counter different types of threats to be considered in the worst environment conditions and scenarios.

Thales has managed an experimental project for the surveillance of the strategic harbour of Fos-sur-Mer (Marseille, France). This project, called SECMAR (SECurity system in a critical MARitime area) was initiated by the French state and partially funded through the “Fonds Unique Interministériel” (FUI). The system combines detection from multiple type of sensors (sonar, radar, electro-optic, AIS receiver) [9] and includes an inshore surveillance and command centre that automatically detect surface and underwater threats thanks to an heterogeneous tracks fusion algorithm, associated with abnormal tracks behaviour analysis. The system was assessed during 6 months [10][11][12].

For an underwater threat, the performance fully relies on a sonar solution that provides alerts with very low false alarms.

The challenge is then to detect very silent threats in heavy ambient and traffic noises. The secure solution comes mainly with active sonar at least for primo-detection.

Numerous underwater protection monostatic sonar security systems have been developed since at least the early 1980s to address these threats in harbors and coastal areas. These products called DDS (Diver Detection Systems) are active sonar in the frequency range of 60 to 100 KHz, even if lower frequencies have been tried [13].

Combination of various sonar frequencies have also been tested for littoral surveillance allowing a layered approach for early alert of threat faster than a diver.

To get larger area coverage than with a single DDS, several overlapping DDS can be deployed, but at the expense to split bandwidth or transmission time in order to resolve interferences issue. Multiple monostatic sonars could be also used in bistatic but they should be closed enough and cannot receive while transmitting, then must have an alternate transmission strategy .

Monostatic sonars basically “blanks” receiving when transmitting. For example a pulse of 0.2 sec blanks echo reception up to 150m range, quite significant for a typical claimed detection of 600m on a closed circuit diver, and moreover 300m in practice in worse conditions.

Blanking area has also been analysed in multistatic [15]. Thanks to a distance of RX from TX in multistatic, a key improvement is achieved when the receiver simultaneously detects target echo and receives the much stronger but distant transmitter “direct blast” signal.

This processing we use is called “RX as TX” or “listen while transmit” and needed in CAS (Continuous Active Sonar) [16] or “High Duty Cycle” sonar [17].

It allows for example a transmit pulse of 2 seconds instead of less than 0.2 sec for monostatic DDS, giving a strong 10 dB advantage on sonar FOM (Factor of Merit). It gives also a decisive advantage with long Doppler codes adequate for low speed targets. Detection becomes then noise limited rather than reverberation limited.

Added value of this paper is to give specific multistatic protection pattern for barriers and large surface, taking advantage of “RX as TX” multistatic processing, and the way to dispose them collaboratively, sharing receivers and minimizing blanking zones. The challenge is to get enough reaction time for every possible threat speed.

Operational protection outcome is successful reaction assets from large, distant and long enough detection.

Reaction assets will be advantageously guided to manage threat if surveillance system brings continuous tracking.

2 Multistatic patterns

2.1 Barrier shape multistatic pattern

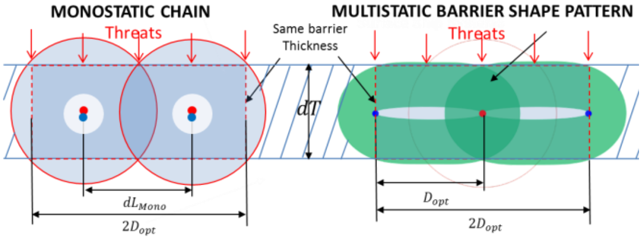

Fig. 2. 2TX/2RX Monostatic versus 1TX/2RX Multistatic pattern for same barrier length 2Dopt and thickness dT

Considering bistatism, the optimal Cassini oval of barrier type shape is oval such as TX/RX distance D_{opt} is [8]:

$$D_{opt} = \sqrt{8/3}\ R_{mono} \sim 1{,}63\ R_{mono}$$

➔ Thickness $dT_{Bistat} = 2R_{mono}/\sqrt{3}$

➔ Each Bistatic pair barrier Length: $dL_{Bistat} = D_{opt}$

That optimal Cassini oval barrier shape has identical minimal thickness at TX, RX, and mid TX/RX distance.

Now we can compare monostatic barrier length for that same thickness: $dT = dT_{Mono} = dT_{Bistat}$

Monostatism length is also $dL_{Mono} = dL_{Bistat}$ as:

$(dT_{Bistat}/2)^2 + (dL_{Mono}/2)^2 = \mathbf{R}^2_{\mathbf{mono}}$

$(dL_{Mono}/2)^2 = 2/3\mathbf{R}^2_{\mathbf{mono}} \Rightarrow dL_{Mono} = D_{opt} = dL_{Bistat}$

A bistatic pair of optimal TX/RX distance D_{opt} brings then the same barrier length than one monostatic of same minimal barrier thickness. Both have then the same barrier "useful surface", minimal thickness of a threat passing through multiplied by barrier length.

Multistatism by definition processes at least two RX with same TX, the barrier detection shape is then exactly two times Cassini ovals, same thickness but double length:

$dT_{Multistat} = 2R_{mono}/\sqrt{3}$ & $\boldsymbol{dL_{Multistat} = 2D_{opt}}$

1TX/2RX multistatic pattern barrier length is exactly double versus bistatic pair, and then equivalent of a chain of 2 monostatic sonars of same barrier thickness in Fig 2.

Barrier "useful surface" of 1TX/2RX optimal barrier shape multistatic pattern gives same "useful surface" as two monostatic sonars using 2TX/2RX then more material.

Moreover a key advantage of RX distant from TX in multistatism is to allow RX as TX long pulses (Cf § 1.3).

2.2 Multistatic versus monostatic barrier chain

Now a strong advantage of multiple multistatic pattern schemes versus multiple monostatic sonars appears when multiple multistatic patterns are adequately chained sharing at least one receiver, example with 1TX/2RX:

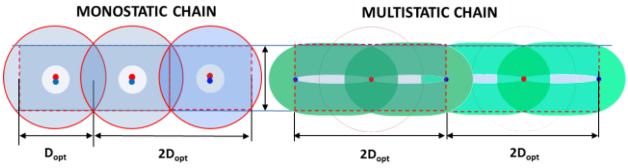

Fig. 3. Multistatic chain of 1TX + 2sharedRX doubles the one monostatic length $\boldsymbol{D_{opt}}$ by adding only 1TX+1RX

This 1TX/2RX shared multistatic barrier pattern is the most simple but very length efficient barrier chain adding a $2D_{opt}$ barrier extension with twice less material than 2TX/2RX monostatic sonars for the same barrier length.

Sharing receivers in a multistatic chain is more natural and easy than in multiple monostatism, without being stopped during TX transmission.

Multistatism is also more flexible as it can allow inside a pattern to adapt each bistatic pair RX distance from same TX, either because a specific environmental constraint from coastline or bottom depth. With monostatism you add for that each time 1TX/1RX instead of 1 RX only

2.3 Extending barrier pattern thickness

If the previous 1TX/2RX barrier is not thick enough, the 1TX with 4RX non shared has also a good barrier shape.

Its thickness is 2 Rmono and Length 2,7 Rmono [8] which remains attractive in terms of cost per « useful surface area» as soon as RX cost is less than 1,3 times the TX one, which is the case with at least a factor of 2 or 3..

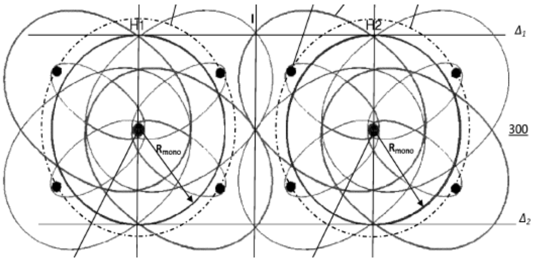

Fig. 4. 1TX/4RX double pattern with a thicker barrier shape

In addition of this thickness and material cost advantage per surface unit versus monostatism, it brings RX redundancy, cross covering of blanking zones, most of the time 2 if not more concurrent receptions with 2 different Doppler with no possible nulling for the target.

2.4 Multithreat pattern with multilayers

An additional advantage of multistatic pattern is that still using same TX, a second distant layer of RX can be added with adequate distance for distant detection of a significantly faster threat, plausibly with higher TS index.

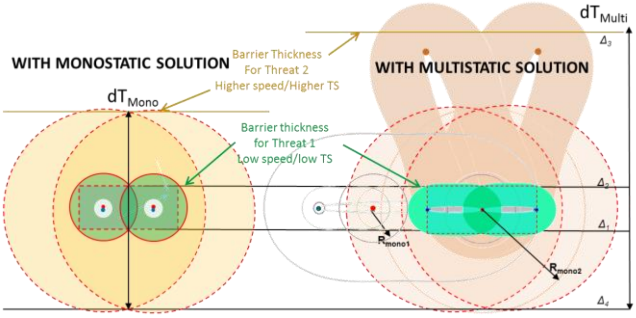

Fig. 5. Comparison of monostatic and multilayer multistatic barrier chains detection areas for 2 types of threats.

Slow threat previous detection scheme is in green. Fast threat detection is red dashed line limited for both monostatic and multistatic previous pattern.

By adding now 2 additional RX shared to each multistatic pattern forming then a second distant layer, we obtain a significantly thicker brown $2dT_{Multi}$ barrier than monostatic dT_{Mono} orange one.

When extending barrier, this new 1TX/4RXshared multilayer pattern adds only 1TX/2RX per added pattern.

Monostatic chain adds 2TX/2RX then more material for same added barrier length, but less thickness :

- For low speed/index threat, multistatism doubles barrier length $2\boldsymbol{D_{opt}}$ adding only 1TX/1RX (Cf §2.2)
- Adding distant layer for higher speed/index threat is possible with multilayer multistatic pattern adding globally 1TX/2RX shared per same doubled length
- Monostatism needs 2TX/2RX for same $2\boldsymbol{D_{opt}}$ double barrier length, where multistatism brings a better detection Thickness $\mathbf{dT_{Multi}}$ versus $\mathbf{dT_{Mono}}$ pattern with only 1TX/2RX, then less material.

Even one multistatic pattern brings flexible multithreat protection, allowing flexible scaling of distance of at least 1 RX dedicated for faster threat than close RX for divers.

2.5 Surface multistatic patterns

A remarkable particular case of surface patterns is the 1TX/6RX hexagonal deployment, especially when tuned

6 RX exactly at R_{mono} distance from TX. (Fig 7A of [8]):

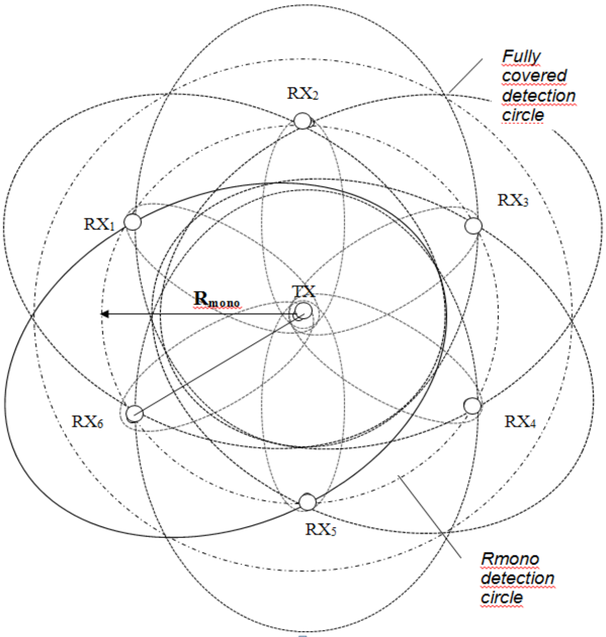

Fig. 6. Detection coverage for hexagonal 1TX/6RX pattern with specificity of RX deployment at Rmono distance of TX.

Specific property of such hexagonal pattern tuning is that:

- any point inside R_{mono} circle is at least with 2 RX detection, very advantageously for Doppler detection if not redundancy
- there is no blanking zone around receivers inside that circle as Cassini ovals of neighbouring patterns cross exactly at their neighbouring receivers.
- It remains only very small blanked circle around TX of compressed pulse size for RX as TX processing
- Such RX as TX processing allows much longer pulses than monostatism

This hexagonal pattern is very adequate for large surface coverage by sharing all receivers with up to 6 similar hexagonal patterns forming a widely used paving.

It is also adequate for a point-like sensitive area such as maritime petrol extraction site, and is more efficient than a centered monostatic solution with strong power counter balancing short pulse and platform noise constraints.

3 Multithreat protection zones example

3.1 Sensitive Area example

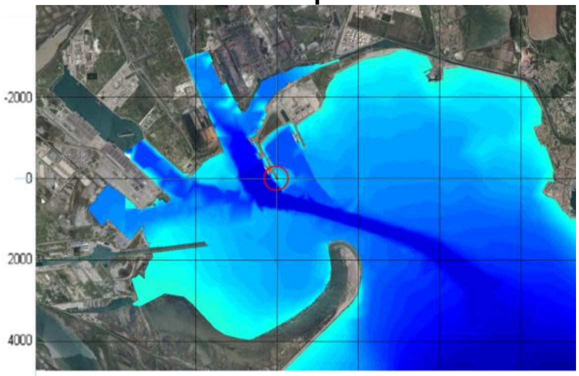

Fig. 7. FOS sur mer underwater approach with 2000m grid

FOS Petrol station in FOS sur mer harbour near Marseille is a quite strategic asset (SECMAR project [9]).
Objective is to protect it from external threats underwater approach, assessed with enough primo-detection time before threat can access the red circle entrance point, whatever realistic threats speed.

3.2 Modelling Hypotheses

Our multistatic littoral specific model takes in account:

Environment:

* Water depth slope is locally linearized for each pattern or even for each TX/RX pair.

* Worst yearly bathycelerimetry, clearly the negative gradient around summer, which we measured.

* Threats Target Strength range from worst -25dB for Closed Circuit divers around 1 knot with no aid or 1,5 knot max. TS=-15dB for 2/3 knots DDS, 4/6 knots for diver surrounding vehicles up to 4/6 knots, TS=-5dB for fast big SDV or drones at 6/8 knots in such water depths.

* Traffic and ambient noise is clearly strong, Sea state 6

Characteristics of Thales multistatic sonar product:

*Medium frequency omnidirectional transmission above human audible sounds, much lower than classical DDS.

* Long pulses Doppler codes can be up to 2 sec length

* Very high RX rejection of array and processing of the distant TX pulse allowing the "RX as TX" feature

* Capability of Noise limited detection rather than reverberation limited even on low speed targets

3.3 Zone 1 for close protection

Objective is continuous detection form external approach of smallest index TS=-25dB threats. We obtain a secure 700m (in red) then 15 minutes time for those threats, and 1100m (in green) whatever target track if TS = -15 dB. Multistatic pattern shape allows RX optimal placement so as to both surround central point and entrance closing.

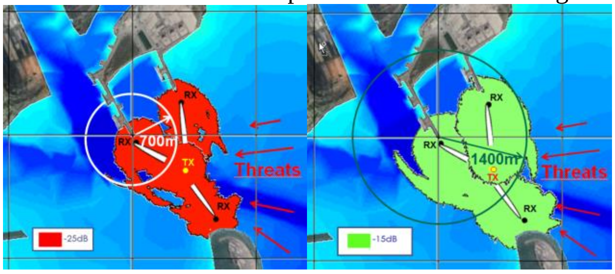

Fig. 8. Multithreat 1TX/3RX detection pattern area & thickness Lowest RX on bottom closes entrance even for smallest threat. Protection thickness for Red TS = -25 dB, Green = - 15 dB

3.4 Comparison with Monostatism

Multistatic detection surface for TS = -15 dB threats can be compared with monostatics using the same receiver and transmitter, and same environment conditions.
If easy isothermal bathycelerimetry condition allows Rmono=1380m, it is only 530m with our negative gradient worst case. A typical 50ms pulse length is compared with 200ms not better from inherent blanking and plausible reverberation.
If we want same continuous detection with Rmono radius circles then overlapping, we need 5TX/5RX when multistatic detection smart shape allowing both close protection and just entrance alert is only 1TX/3RX

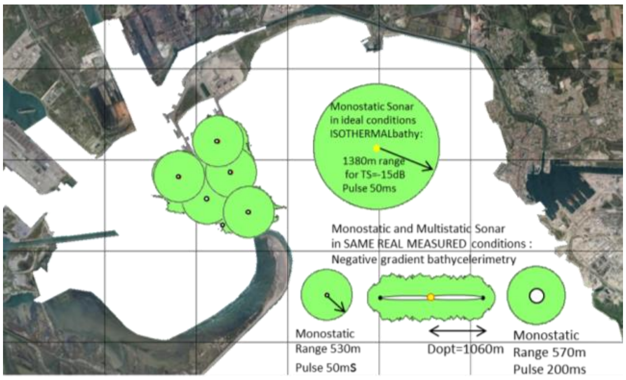

Fig. 8. Monostatic range for worst and best bathy condition. For same worst case bathy, monostatic continuous coverage needs 5TX/5RX when Multistatic solution is 1TX/3RX

3.5 Zone 2: Faster medium size threats coverage

More dangerous threats would be medium size keeping TS = -15dB low, but faster than aided divers, then up to maximum 6 knots, such as DPD(Diver Propulsion Device), small SDV or drones. Range becomes 2800 m being 4 times 700m of 1,5 knot max unaided diver speed.

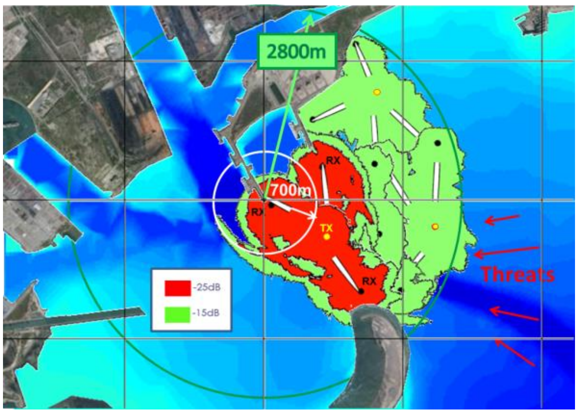

Fig. 9. External coverage radius is 2800m adding 2TX/6RX Hexagonal type patterns allow a large flexible pavement.

Two partial tuned hexagonal type patterns (§2.5) are added, with some RX not needed. A wide 2800m primo-detection and continuous tracking for all threats of index >TS= -15dB arriving from outside sensitive area. As stated in §2.2 patterns have blanking zones partly cross covered by bistatic close neighbours.

3.6 Successive 3 zones multithreat solution

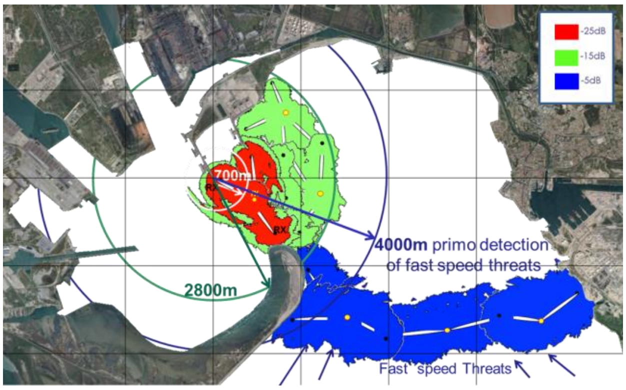

Fig. 10. Multizone multistatic specific patterns deployment with quite wide range of primo-detection distance versus threat index for enough reaction time even on fast targets.

The adequate pattern for long barriers is the 1TX/2RX shared chained pattern (Cf §2.2). Tailoring it with 2RX instead of 1 along closest coastline of FOS allows 4000m protection from FOS station critical point. Even for a very fast littoral threat at 8 knots, bigger with then TS = -5dB we obtain 10 minutes primo-detection time before this worst speed threat reaches sensitive point to protect.

4 Lessons learnt

During past years, a prototype versus §3 targeted solution was developed and used for several at sea trials. It was composed of a sectorial reduced power transmitter, a specific panoramic reduced gain receiver module and a multistatic sonar processing.

Objectives were achieved proving the key essential specific capabilities, including RX as TX processing. The figure below shows continuous detection and tracking including inside the direct blast-blanking zone (inside the isotime ellipse that corresponds to 0.6s pulse length, i.e. 1500*0.6/2=450m sound travel wayback).

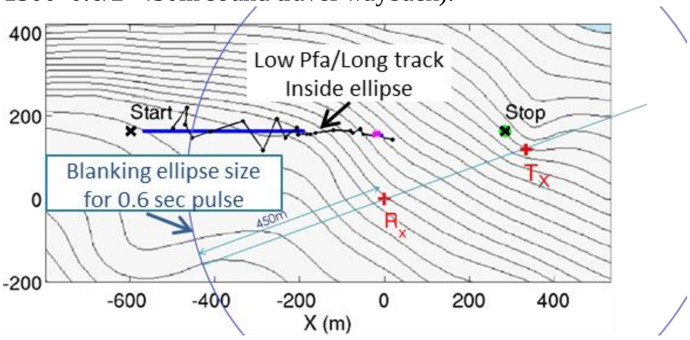

Fig. 11. At sea result with a 0.6sec pulse detecting inside ellipse

It confirms the capability to get automatic and long distance target detection after tracking in large zone and with very low false alarm rate.

Performance was assessed against a wide range of underwater threats such as open and closed circuit divers with or without civil or military underwater vehicles, and also an unmanned drone.

All the threats have been detected and tracked at expected range, in a noisy shallow-water environment, close to a coast line where water depth was between 10 and 50 m. Most advanced active processing algorithms have been implemented, which take benefit from Thales long standing experience in the field. The results achieved at sea confirm the capability to detect during transmission “RX as TX”.

It allows long pulses without blanking zone constraint which provides high Doppler resolution and high processing gains at the receivers.

Detection of a moving target becomes then noise limited rather than reverberation limited even in coastal shallow water environment [18].

5 Conclusions, future

- Specific Multistatic patterns are given, optimising “useful” surface area, defined as detection length multiplied by minimal thickness of threat incoming, for enough reaction time of continuous detection, with much **less TX+RX numbers** than monostatism

- Some patterns can **cross-cover blanking zones**

- A 1TX/nRX pattern can be designed “**multithreat”,** having different RX distances and angles from TX for a **secure and flexible detection area of different threat speeds** then different Target Strength index.

- Patterns arrangement can be **chaining for barrier or surface paving**, **sharing or not receivers,** also **adapting to environment** anisotropy.

- **Monostatic solutions require impractical material numbers,** with interference problems, more blanking zones, without RX as TX advantage.

- The presented example of Multistatic pattern arrangement provides 3 **successive layers** for each successive threat speeds and index with **continuous detection for reaction:**
  - 700m for 1,5 knot threat of TS= - 25dB
  - 2800m for 6 knots threats of TS = -15 dB
  - 4000m closing barrier for 8 knots / -5dB threat with early alert of large area entrance

Multistatic is the multithreat and large protection solution of choice, with minimal TX/RX material.

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6 Author/speaker biographies

Dr. Louis Raillon was born in Paris in 1954. He received Supelec MEng in 1976 , MSc in 1977, and PhD degree from Paris UPMC in 1979 in Probability & Applications. He worked for 37 years in Thales France and Australia, on sonar studies, design, development, sea trials assessment, leading performance modelling. As technical director of surface ship sonar segment, a challenge was to convince international key sonar experts or Navies top users of Thales innovative solutions for Captas in Norway, UK, France, Italy. He won the Thales gold innovation award in 2005 and developed sonar technical intelligence for Thales with French DGA interest, instigating many technico-operational future sonar system studies and this multistatic surveillance project as System Design Authority. He published many papers, international presentations and 5 patents, last 2 ones on multistatism surveillance. He created LRC consulting since 2017 retirement and is currently external consultant for Thales DMS/UWS.

Dr. Michel Fouquet was born in Marseille in 1958. He received a PhD thesis in automatic and signal processing in 1985. From 1985 to 1988, he worked on sonar research and development for the french DGA underwater detection laboratory. He joined Thales in 1989, where he headed the software team in charge of submarine sonar processing development. In 2004, after being technical leader of a European Union funded project on massive parallel processing, he joined the sonar product line as bid technical manager. In this position, he has defined sonar solutions on almost a hundred projects in various underwater warfare areas, facing international competitions and collaborating with industrial partners and navies. Since 2014, he acts also as program manager for the development of sonar system for underwater coastal protection.