Coastal Surveillance: Complex system of X-band and High Frequency Surface Wave Radars

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***Abstract-* In April 2009 Thales Air Systems signed an agreement with the French Aerospace Lab (ONERA) to industrialize and commercialize a High Frequency Surface Wave (HFSW) Radar, named Coast Watcher 200. Due to its capability of detection Over The Horizon (OTH), this radar offers, with the other coastal radars in X-Band, an efficient coverage of the Exclusive Economic Zone (EEZ). The aim of this paper is double. One aspect is focused the up to dated radar processing regarding the small target detection (often used in the illegal activities) in presence of sea clutter,. A new patented processing, called "*Kinematics Scan to Scan*", will be described. The other aspect is dedicated to the state of arts of the HFSW radar, used to the Early Warning (EW) missions. A focus will be brought about the tracking function in such radars. Processing will be illustrated on real trials realized in France. The radar complementarities should lead to the building of an operation maritime picture on the overall EEZ.**

I. Introduction

Recent events in the world show again the necessity of a reliable coastal surveillance system allowing to fight against piracy, illegal activities (fishery, immigration, …), good and drug smuggling,…. but also the necessity to get a very long range surveillance dedicated to the *Early Warning (EW)* missions.

From the *Territorial Water* surveillance (12 Nautical Miles) up to the *Exclusive Economic Zone* (EEZ - 200 Nautical Miles), the radar sensors stay the main actors for the non cooperative target detection and tracking.

Taking into account the range to survey and the radar characteristics (propagation conditions, waveforms,...), it seems obvious that a sole type of radar will not allow fulfilling all the requested missions. So, an association of X-Band high resolution and HFSW Early Warning radars is a good candidate for this surveillance.

That is why Thales Air Systems and ONERA work each on its side on sensor improvements to ensure a complete EEZ radar coverage in order to fulfill the operational missions

II. Interests of HF-Band and X-Band

Interest of HF-Band (3-30 MHz): One of the main interests of the use of HF-band is that signal will propagate over the horizon. As shown on Fig. 1, conventional radar (X-Band) is limited by the radio horizon (red line), for the Sky Wave HF radar (green line), the signal will be reflected on the ionosphere, for the Surface Wave HF radar (blue line), a surface wave will propagate along the sea surface.

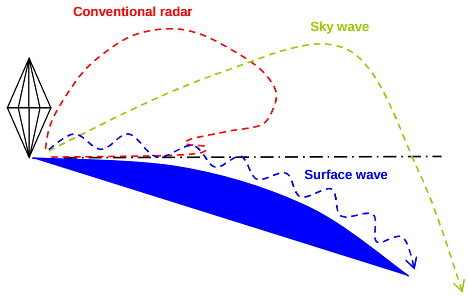

Figure 1. Sky Wave, Surface Wave signal versus conventional radar signal

Interest of X-Band (10 GHz): One of the characteristics of the X-Band radars is the availability to present High Range Resolution (HRR) and accuracy. HRR is often a solution to the problem of small target detection in presence of sea clutter, however this solutions leads to a high density of sea-spikes echoes. However, as HRR sometimes leads to high density of spikes, a tight regulation of false plots is needed in order to be able to control the tracking load and limit the number of false tracks.

III. X-BAND : KINEMATICS SCAN-TO-SCAN

1) Radar sea-spikes real data analysis: An example of raw recording data on X-Band pulsed radar with a range resolution of 5 m (range bin of 3 m) is given in Fig. 2. The display shows many sea-spikes echoes of received power higher than the echoes of boat. The small boat and the sea-spikes are point echoes and distinguishing sea-spikes from small target does not seem obvious using the range and azimuth information on one scan.

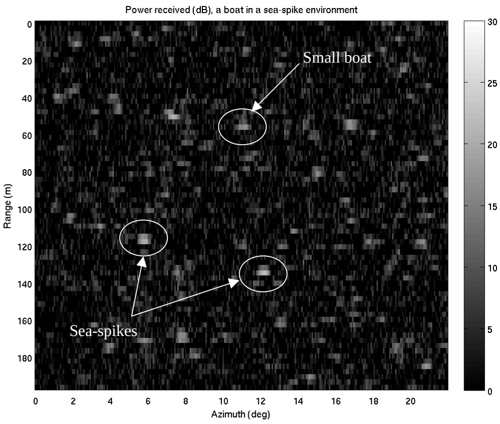

Figure 2. Raw data showing a azimuth range map of a small boat in a sea-spikes environment

However sea-spikes have an interesting property, their position decorrelates from one scan to the other if the scan duration is of a few seconds. On the contrary, the boat position is strongly correlated from one scan to the other. This property can be used to efficiently discriminate between small target and sea-spikes.

2) Kinematics scan to scan algorithmic description: The following algorithm is a special implementation of the patent [1]. The algorithm is located just after the detection and before the tracking as shown on Fig.3. The system until the detection measures for N scans the range and azimuth of a radar plot respectively named (r, θ).

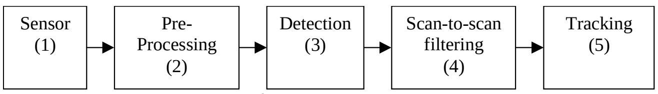

Figure 3. Position of the algorithm in the detection chain

The algorithm steps are summarized on Fig. 4. radar plot respectively named (r, θ). For each position and velocity hypothesis, a multidimensional is created (Fig. 4).

For each position and velocity hypothesis, a multidimensional tube is created (Fig.5). A tube is defined as a space-time delimited by intervals of (r, θ) and the derivative of (r, θ) named (V_r,V_θ) centered on hypothesis values. The interval of the tube on each dimension depends on the sensor accuracy.

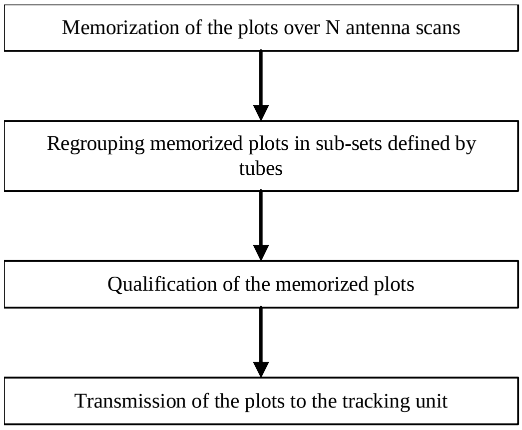

Figure 3. Algorithm procedure

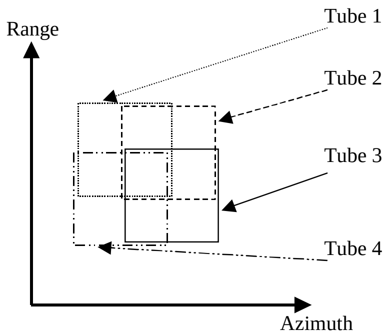

Figure 4. Four tubes of the (Range, Azimuth) overlapping procedure grid

The number of tubes is fixed and the union of all the tubes includes the entire target space and velocity interval considered. For a boat the velocity interval can be [-40m/s, +40m/s]. Moreover the tubes are created such that there are overlaps on both position and velocity dimensions in order to avoid the sampling side effects (Fig.4 and Fig.5).

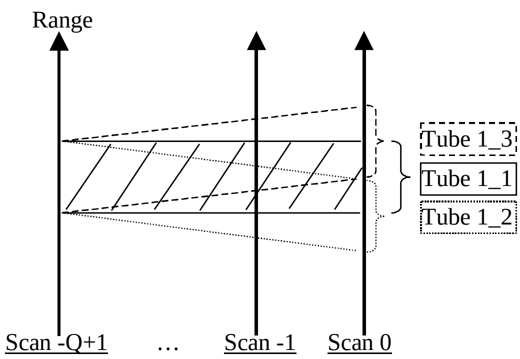

Figure 5. Three tubes (Range, time) overlapping grid

The presence of enough detection inside one of the tube during the filtering analysis (fig.7) means those detections do not have to be filtered out. For example a criterion of 3 presence of plots over N=5 scans gives already a good filtering. Those chosen detections can then be processed through the tracking sub-system (5) of Fig.3.

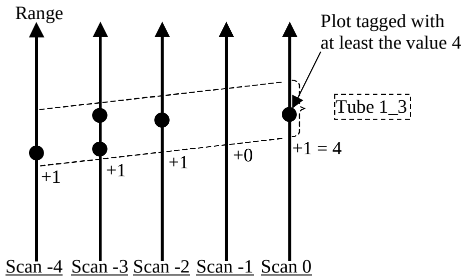

Figure 1: Summation of plot presence
on one of the tubes of the grid

3) Results on real data: The algorithm presented was extensively tested on different sea state conditions in the Atlantic Ocean and in the Mediterranean Sea. With this new algorithm, the number of false tracks for high sea-state is strongly reduced. The Fig. 8 illustrates the results in Sea State 5 (Fig. 3).

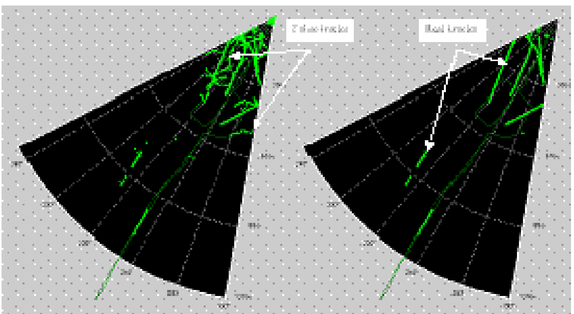

Figure 8. Tracks initialized for a sea-state 5, without scan-to-scan processing (left) and with dynamics scan-to-scan processing (right)

The Fig. 9 and 10 respectively illustrate operational maritime picture and small target detection using the “Kinematics scan-to-scan” algorithm. Small targets and large targets are detected and tracked.

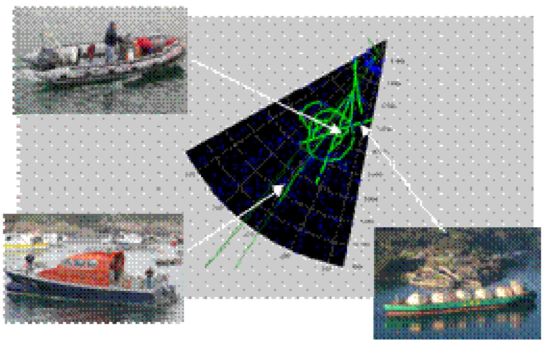

Figure 9 : Operational Maritime Picture

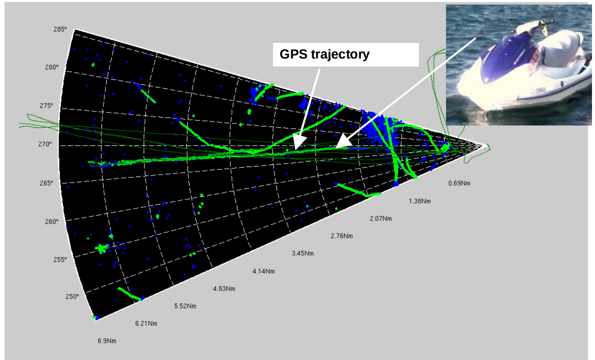

Figure 10 : Example of small target detection : Jet ski.

IV. HF-Band : State of the Art

ONERA has got a large competence with the French MoD (Direction Générale de l’Armement) support in the High Frequency radars. From 1996 to 2006, ONERA has developed and experimented a Sky Wave radar: the Nostradamus radar System. This radar system is a set of around 300 bi-cone antenna elements distributed over the arms of a three-branch star, with a buried infrastructure to shelter the transmission and reception electronics. Nostradamus allows the detection and the tracking of aircraft flying at great distances beyond the horizon. After this experience, ONERA has built a High Frequency Surface Radar in France.This HFSW radar has been deployed in Biscay Bay and is available since Early 2007. The radar is located in DGA trial center.

1)Materiel Architecture: Initially composed of one bi-conical antenna in transmission fed by a power amplifier (2 kW – CWrms) and a network of 16 antennas in reception, the radar has slowly evaluated in the time towards a more powerful configuration composed of three bi-conical antennas in transmission, three power amplifiers (2 kW – CWrms) and 32 antennas in reception (Fig. 11).

Figure 11 : Upgraded receiving system with 32 antennas

Figure 12 : New transmission system with three antennas

The next step of this evolution will be an increase of the power of the three amplifiers in order to increase the power budget and to limit the blind range.

In opposite to the X-band radar, the radar range cell is wider and directly linked to the radar bandwidth, transmitted frequency and length of the receiving phase array.

The Fig.13 gives the relations between these three parameters.

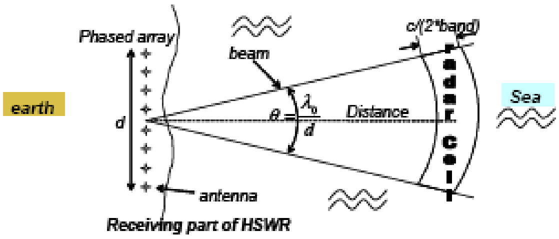

Figure 13 : Radar Cell

So, at 400 km, this radar cell is around 40 km*5 km. In such conditions, it is a true challenge to detect and to track surface targets with stable accuracy.

1)Detection: Three phenomena act upon the target detection performances : the Sea clutter (Fig. 14), the Ionospheric clutter and the propagation losses.

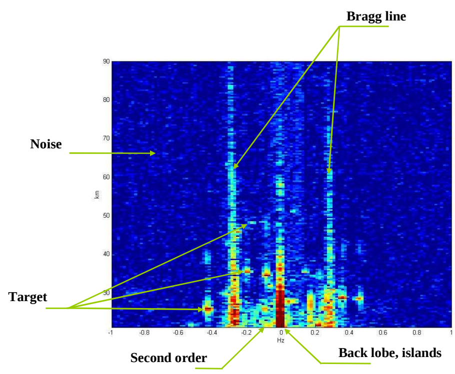

Figure 14 : Typical Sea spectrum

The sea clutter spectrum is represented by well know “Bragg Lines”. These lines are due to the interaction of the radar wave with the sea waves. These interactions respectively create the *First Order Bragg Lines* and the *Second Order Bragg Continuum.* The position of the First Order in the spectrum is linked to the transmitted frequency. In order to limit the target detection misses in these areas, at least, two frequencies must be transmitted to translate the lines positions in the Doppler spectrum and powerful algorithms must be developed to detect the closest of these lines.

The Ionospheric clutter (Fig. 14) is due to the reflection of the radar wave on the ionosphere. According to the radar location, period of time in the day and the transmitted frequency, its influence is more or less perceptible.

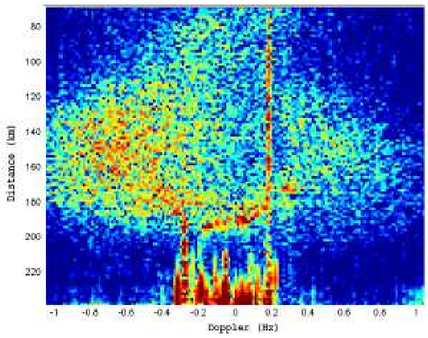

Figure 14 : Example of Ionosperic clutter in France

In this example, the challenge is to maintain the detection. One of the way is to adapt in real time the best waveform and the integration time from the measurements done by the radar.

The Propagation losses are also depending on the radar location and present a large variation between day and night. To illustrate this phenomenon, the Fig. 15 shows a measurement realized in France, over 48 hours (abscissas). The steer angles are given in degrees (ordinates). The propagation losses can vary on 20 dB (from blue to red levels).

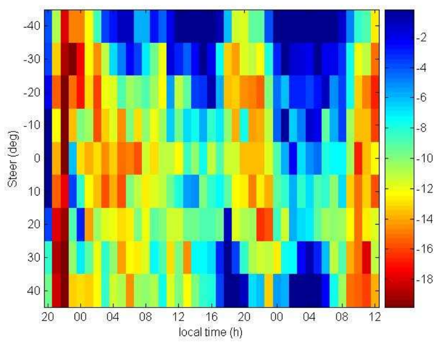

Figure 15 : Propagation losses – Strong variations

From these three illustrations, several conclusions can be done on the detection: in HFSW radar, specific signal processing and accurate environment knowledge are required to detect and extract targets from various clutters. Over more the detection at long range (200 Nm), due to the losses increase and their strong variations, leads to transmit large power to ensure radar power budget to ensure large surface target detection. In fact, at these ranges it seems unrealistic to want to detect small targets.

2)Tracking: Once the detection elaborated, the tracking is the second problem to solve. The radars of new generation impose a full automatic tracking including both initiations and track maintenance.

Even if the initialization criteria can be very simple typically p/q (i.e. p detections over q rotations), its application in a HFSW radar is a true challenge taking into account both the radar accuracies (several hundred meters) setting the tracking windows and the rate of the updated information.

Even if the use of the Doppler information includes in the plot is an invaluable help to limit the false associations at this level, specific algorithms must be developed to take into account this information.

Due to the updated rate, the steady state of the Kalman filter is generally slow to get and these HFSW typical characteristics must be also managed both at the track level but also for the display of the full operational picture. The Fig. 16, Fig 17 and Fig 18 show the same operational picture with a time separation respectively of half an hour and three hours.

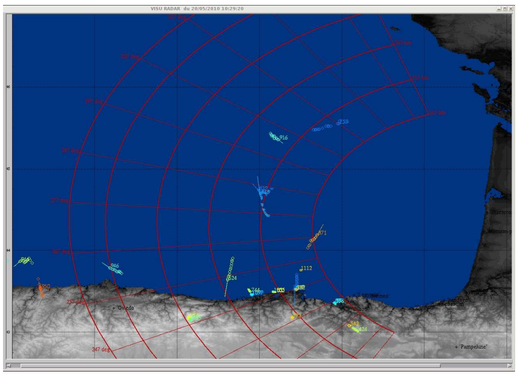

Figure 14 : Operational picture around 10h 30

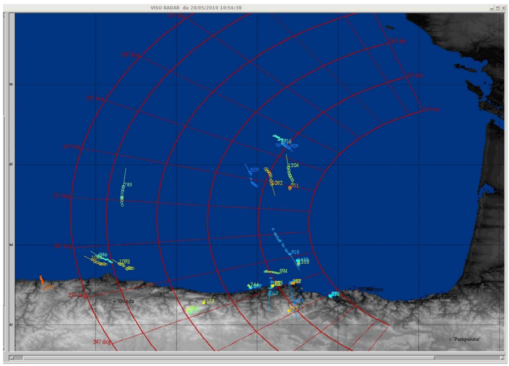

Figure 15 : Operational picture around 11h00

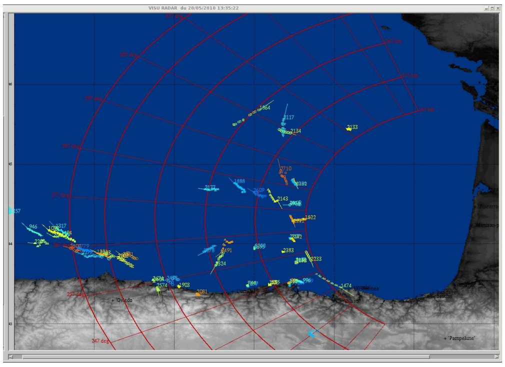

Figure 16 : Operational picture around 13h30

These three operational pictures shows clearly tracks tracking over 200 Nm (last circle is set at 400 km) in Biscay Bay. In particular, the target number 946 initiated around 10h30 is tracked up to 13h30. The radar, working in a mode “long range”, explains the large blind range around 165 km. The correlation between radar tracks and AIS has not been yet matched. This correlation will be done in some areas where the AIS information is available, generally close to the coasts. In particular, around Oviedo (Gijon harbour) in Spain, AIS station are installed and AIS information available.

V. Conclusion : Operational concept

From these short analyses, we can draw several lessons about the operational concept. Both radars are complementary; X-Band radars are dedicated for the detection of small targets generally close to the shores with a good accuracy. We have implemented a specific processing to limit the false alarm and provide excellent small target detection and tracking. HFSW radars are dedicated to Early Warning missions. Even if the maximum range is influence by environmental conditions, OTH function is always available. In the intermediate area, the tracks from the both radars should be merged at Command and Control Center level. At the sensor level, each radar could make a designation to the other one, helping it in the track initiation process. The Fig 17 gives an illustration of the radar coverages for an implementation in the South of France.

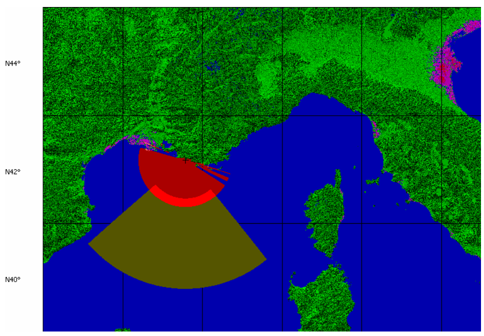

Figure 17 : Example of X-band and HF-band Coverages

ACKNOWLEDGMENT

Thales Air Systems and ONERA would like to thank DGA for DGA for the support in the HFSW radar development and the DGA Essais de missiles for the logistical support.

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