Passive Bistatic Radar (PBR) for harbour protection applications

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Abstract—**In this paper we investigate the feasibility of using Passive Bistatic Radar, PBR, to provide security for a harbour area. There have been numerous publications on the suitability of passive radar for air surveillance applications. However, this paper focuses predominantly on maritime applications. We investigate the ability of passive radar to detect, track, and eventually manage, marine vessels (boats). The paper includes a case-study of the Livorno Harbour in Italy. Livorno has been chosen as it represents a busy maritime hub. Simulations are provided to determine the theoretical radar performance, which are then compared with experimental results from a DVB-T-based passive radar. It will be shown that passive radars represent a viable solution for harbour protection applications.**

I. INTRODUCTION

A number of nations and organisations have an interest in investigating the potential of bistatic and passive bistatic radar to act as a security sensor for the protection of special areas. The special areas, designated sanctuary zones, of particular focus in this investigation are important harbour areas. Harbour protection sensors, therefore, should be capable of detecting ground-based, marine-based, and airborne targets.

Other works have shown the relevance of passive radar for air and ground surveillance of targets. However, the primary objective of this work is to investigate the use of passive radar for monitoring marine traffic (ships, etc.) in the proximity of a harbour. It is not always feasible for port authorities to invest in an expensive infrastructure of primary radars. Therefore, cost-competitive passive radars utilising illuminators of opportunity may provide a better means to manage vessel traffic within a harbour. This can include the monitoring of potentially malevolent operators, such as illegal fishing vessels, hazardous cargo transporters and smugglers. Furthermore, multiple passive sensors could be networked to extend radar coverage and improve target localisation.

II. THE HARBOUR AREA

For this work, the harbour of Livorno (Leghorn), Italy, has been taken as a realistic case study to assess the capability of passive radar to monitor harbour traffic. Livorno (Fig. 1) has been chosen as it presents a favourable scenario, not only for the presence of various targets (including petroleum tankers), but also for different kinds of illuminators of opportunity.

Fig. 1. Livorno Harbour

Livorno is one of the busiest harbours in Italy. This is evident from the number of shipping routes in Fig. 2. All of the shipping routes from Genoa, in the north of Italy, to the south of the Mediterranean Sea, pass in front of Livorno, yielding an abundance of potential targets.

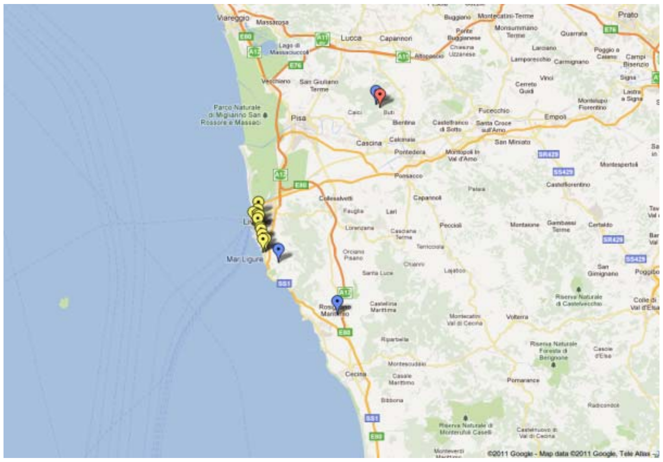

Fig. 2. Google Map image of the Livorno region of Italy. The map shows transmitters of opportunity near Livorno. Blue: FM radio, Red: DVB-T, Yellow: UMTS.

III. PASSIVE RADAR

The principles of passive radar have been comprehensively covered in textbooks such as [1] and [2]. However, in this section only the particular specifications of the PBR used in this work will be described.

To demonstrate the value of passive radar for harbour protection applications, an experimental trial was conducted at Livorno using a DVB-T passive radar demonstrator situated at a site along the coast.

The radar demonstrator was based on a flexible, low-cost, Software Defined Radio (SDR) concept (a USRP board). The system consists of a reference and surveillance channel, for the reception of the reference signal and target signal, respectively. Low-cost Yagi-Uda antennas were used with a gain of 18 dBi and a half-power-beamwidth (HPBW) of 20°. Following the antennas and RF front-end, analogue-to-digital converters (ADCs) with 12-bit resolution sampled the DVB-T signal at 64 MS/s. The DVB-T channel of interest during the experiment had a carrier frequency centred on 818 MHz.

The receiver was located at the "CSSN-ITE G. Vallauri" institute in Livorno. The illuminator of opportunity was the Monte Serra transmitter and the baseline separation between the two sites was 32 km, with the primary area of surveillance being the sea in front of Livorno. The experimental scenario is shown in Fig. 3

Fig. 3. Experiment scenario geometry.

IV. THEORETICAL PERFORMANCE OF A PBR FOR HARBOUR PROTECTION

As part of this feasibility study, simulations have been performed to estimate the bistatic radar coverage out into the sea around Livorno. These simulations have been performed using both Matlab and a bistatic radar Mission Planning Tool (MPT) developed at Fraunhofer-FHR, which includes digital terrain data of the region of interest.

For both simulations and the experimental trial, the Monte Serra DVB-T transmitter was used as the illuminator of opportunity. The relevant system parameters are outlined in Table 1.

Table 1. DVB-T passive radar system parameters.

Parameters	Values		
EIRP	40 dBW		
Tx position	Latitude: 43.74719°	Longitude: 10.55498°	Height (AMSL): 900 m (incl. 120 m mast)
Livorno Harbour (Rx position)	Latitude: 43.5295°	Longitude: 10.3079°	Height (AMSL): 2 m
Rx-Tx baseline	32 km		
Frequency	818 MHz		
DVB-T bandwidth	7.61 MHz		
Noise figure Rx	5 dB		
System loss	5 dB		
Integration time	0.5 s		
Assumed bistatic RCS (for boats)	30 m^2		

To properly utilise a passive radar it is important to characterise, as well as possible, the parameters of the transmitter. In addition to the signal properties, it is critical to know the azimuth and elevation patterns. The Monte Serra transmitter is an 8-bay DVB-T antenna, with an omni-directional azimuth pattern. The elevation pattern has been simulated in Fig. 4 and shows the HPBW to be approximately 8°. It should be noted that vertical beam tilt has not been included in the simulated pattern, as the focus of this paper has been to demonstrate radar performance for detecting vessels on the sea-surface (the elevation pattern of broadcast transmitters is usually directed towards the users on the ground). O'Hagan in [3] provides a broader analysis of the elevation properties of common illuminators of opportunity.

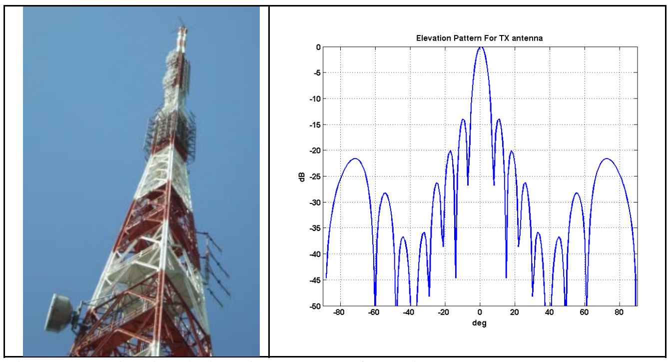

Fig. 4. Simulated elevation pattern of an 8-bay DVB-T antenna.

By utilising the system parameters in Table 1, the expected coverage capability of the passive radar demonstrator has been estimated using the MPT, which includes level 1 Digital Terrain Elevation Data (DTED). The coverage map relative to the Monte Serra DVB-T transmitter and a receiver located at Livorno Harbour is shown in Fig. 5. The ability of the MPT to indicate regions with poor coverage caused by terrain masking should be noted. The more intense colours (i.e. the more black) indicate those areas of highest altitude.

For the coverage simulation, the receiver antenna has been approximated as omni-directional in azimuth, except for a 20 dB null directed towards the transmitter.

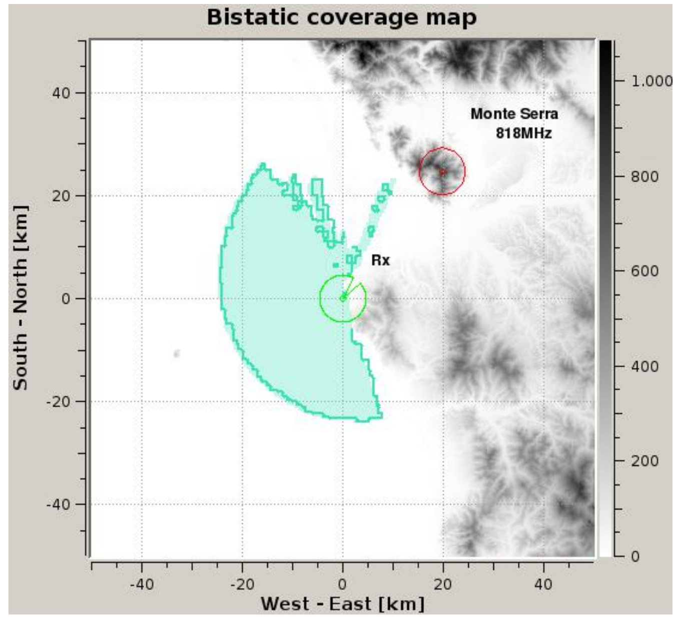

Fig. 5. Passive radar coverage map plotted on DTED level 1 terrain.

Fig. 5 shows that the PBR demonstrator is capable of detecting 30 m^2 targets at a range of about 30 km from the harbour with an 11 dB minimum SNR for the detection threshold. The 11 dB detection threshold provides a high confidence of true detection. Future work will look at the detection threshold which is actually needed to give an acceptable false alarm rate with the relatively small number of resolution cells in the system. It should also be noted that the baseline distance of 32 km provides adequate Direct-Signal Interference (DSI) isolation to avoid receiver saturation. The residual DSI has been suppressed using conventional adaptive filter routines, thereby unmasking the targets of interest.

Another important feature of the geometry of passive radar for harbour protection is that the mode of operation is often in an over-the-shoulder configuration. That is, the transmitter is normally behind the receiver and the targets normally reside along the extended baseline in the pseudo-monostatic region. In this region, the bistatic radar operates in a similar manner to an equivalent monostatic radar (centred at the receiver site) in terms of system resolution performance. This is an important consideration as bistatic range resolution depends on the relative positions of the transmitter, receiver and target. To better evaluate the radar resolution within the considered scenario, a specific map is shown in Fig. 6. The bistatic range resolution regions are plotted on a Cartesian map centred on the receiver (hottest colours equates to the best/finest resolution).

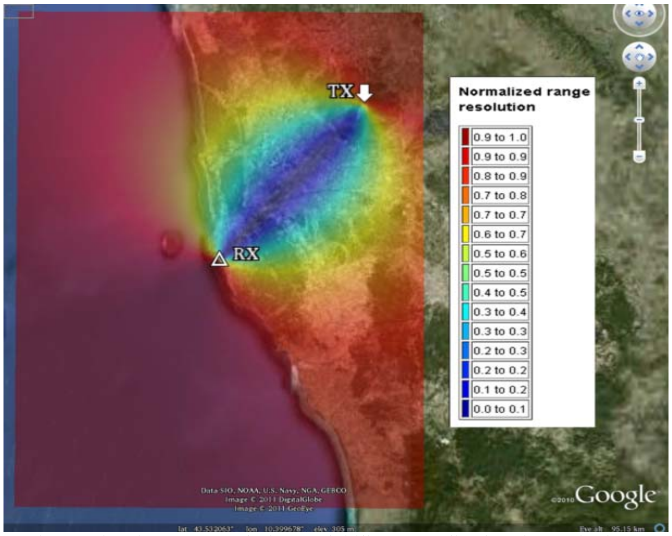

Fig. 6. Bistatic range resolution variability normalised to the equivalent monostatic range resolution. The finest resolution corresponding to the monostatic case is approximately 20 m.

V. Experimental Results of a PBR for Harbour Protection

The surveillance area during the acquisition is shown in the photo in Fig. 7, where the target of interest has been highlighted with a circle. The target in this case is a large boat approximately 170 m long. The director elements of the surveillance channel Yagi antenna are visible at the top of the photo.

Fig. 7. Surveillance area during the acquisition.

To estimate the expected Doppler frequencies in a bistatic scenario, the following equation is used:

$$f_d = \frac{1}{\lambda}\left[\frac{\vec{r}_1 \cdot \vec{v}}{|\vec{r}_1|} + \frac{\vec{r}_2 \cdot \vec{v}}{|\vec{r}_2|}\right] \qquad (1)$$

where $\vec{v}$ is the target velocity vector, $\vec{r}_1$ is the transmitter to target velocity vector, and $\vec{r}_2$ is the target receiver velocity vector.

In Fig. 8 the expected Doppler frequencies for ships departing from the nearby harbour are shown.

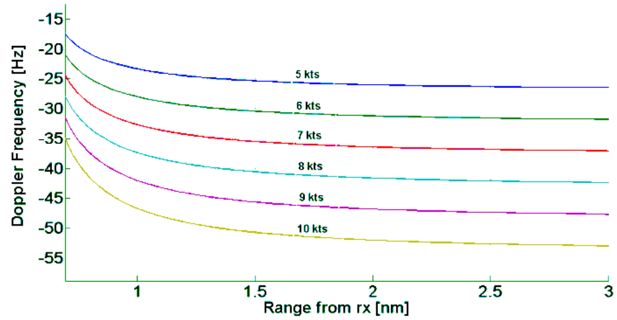

Fig. 8. Expected Doppler frequencies for ships departing from the nearby harbour (receding from receiver).

Within the confines of a harbour, assumed here to be 0 nm to 3 nm, and assuming a vessel speed of between 5 kts and 10 kts, the asolute Doppler frequency will lie between -20 Hz and -60 Hz.

A pre-processing technique based on NLMS (Normalised Least Mean Squares) filtering has been used in order to reduce the DSI in the surveillance channel. The Cross-Ambiguity Function (CAF) obtained after pre-processing is presented in Fig. 9.

The echo relative to the ship is clearly visible at a range of about 2.1 nm with a negative Doppler frequency equal -32 Hz (i.e.: about 6.5 kts). It should be noted that the target echo is actually formed by two main peaks at the same Doppler frequency. The strongest peak is further from the radar than the weaker and they correspond to two scattering structures on the same target, a large bow and another, slightly smaller, stern structure. The two main peaks visible in the CAF can be directly associated with the two main scattering structures of the measured target (see Fig. 10). The target length of around 170 m is in accordance with the distance of the two main target peaks in the CAF (around 160 m).

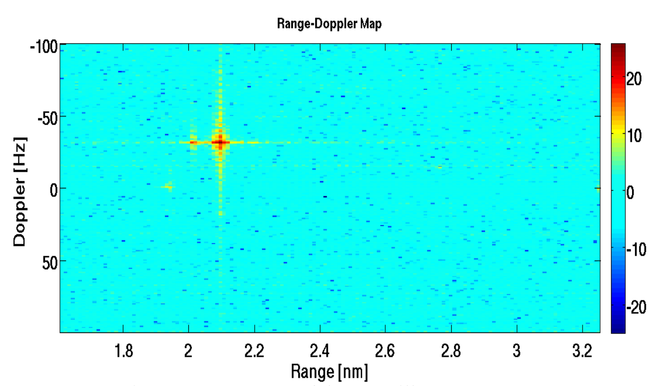

Fig. 9. DVB-T CAF of the surveillance area.

The signal to noise ratio (in Fig. 9), although clearly substantial, is well below what would naively be expected for a vessel of this size at this range. The monostatic RCS of such a ship could be assumed to be of the order of 10000 m^2, in which case a free-space extrapolation from the coverage prediction in Fig. 5 would suggest that the signal to noise ratio would be more than 60 dB. The difference is most probably due to the effects of low-elevation multipath over the sea, which will be very significant at long wavelengths and low sea states, and which was not included in the calculations which produced Fig. 5.

Fig. 10 shows the target of opportunity corresponding to the target in the CAF in Fig. 9. This vessel is typical of the marine traffic in the vicinity of Livorno.

Fig. 10. Target of opportunity corresponding to the measured target in Fig. 9.

VI. ANALYSIS AND CONCLUSIONS

In this preliminary investigation the feasibility of passive radar for harbour protection applications has been demonstrated. The work has focused on the busy harbour of Livorno and has provided site-specific simulations of the environment. It has been found that it is theoretically possible to detect targets in the order of 30 m^2 to ranges in excess of 40 km from the harbour. This offers detection ranges which are comparable with a monostatic marine radar and which may be useful for generating a general vessel-management scheme.

For the experimental trial, only targets of opportunity were available from which to derive an evaluation of system performance. A close-in harbour surveillance area has been defined as between 0 nm and 3 nm (from the harbour). The result in Fig. 9 has shown that the DVB-T system has detected a large vessel which has been confidently identified as a large ship approximately 170 m long which was seen at a range of about 2 nm. Future work will compare the signal to noise ratio seen on the target with what would theoretically be expected.

This work has demonstrated the feasibility of employing (potentially) cost-competitive passive radars to secure harbours. However, future research is required to refine system performance. Currently research is ongoing to investigate the impact that bistatic sea clutter has on radar performance.

Based on the results presented here, a future trial has been planned with updated hardware and greater system dynamic range. Furthermore, a range of calibration targets (boats of various size) will be measured during the trial and one key priority is to determine detection performance against small boats in moderate sea states.

REFERENCES

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[3] D. W. O'Hagan, "Antenna elevation analysis of common illuminators of opportunity", 3rd PCL Focus Days, FHR, Wachtberg, May 2011.