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# Multi-passive coherent location radar system for detection range and range-doppler resolution in Tarakan

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Abstract — The presence of many radio frequency illuminators in an area provides an opportunity to be used as a transmission source for a passive radar system called a passive coherent locator (PCL). Unlike the active radar, the passive radar provides advantages such as low cost without an active transmitter, potential for broad range measurements, portable in construction, anti-detectable by active radar or electronic counter measures (ECM), etc. Just like other areas where there are many PCL in Tarakan such as FM radio transmission (RRI), many base-stations (BTS) from 4G-LTE network, digital TV transmission, access-point (AP) from wireless fidelity (Wi-Fi), and so on. This paper will present and analyze all of these PCLs which include predictions of performance and ambiguity function (AF). Performance prediction is related to range detection which provides information about target detection range, radar cross section, and range-velocity resolution. While AF analyzes the transmit waveform of all PCL which gives a limit of resolution to the range and Doppler of adjacent targets. The results of the evaluation and analysis of performance predictions show that FM radio transmission (RRI) has a range and velocity resolution of 1 km and 12 m/s, respectively and the detection range at a maximum SNR of 15 dB is around 4 km. While the results of the AF evaluation on the PCL obtained range and Doppler resolution of around 2.73 km and 500 Hz, respectively.

Keywords – ambiguity function, detection range, passive radar, passive coherent location, range-doppler resolution



## I. Introduction

There are many illuminators from radio frequency (RF) transmitters in an area, especially in urban areas. This provides an opportunity for the construction of a passive radar (PR) system that utilizes the RF illuminator which is called passive coherent location (PCL). It is known that compared to active radar, PR provides advantages in the form of low cost because without an active transmitter (Tx) which is only an antenna receiver (Rx), potential for broad range measurements, portable in construction, anti-detectable by active radar or electronic counter measures (ECM), *etc.* [1], [2].

Similar to other urban areas, Tarakan city, in Indonesia, has many PCL installed including FM radio transmitters (Pro-1, Pro-2, Pro-3 from RRI), transmitters on base-stations (BTS) on the 4G-LTE (Long Term Evolution) network, digital TV transmitters (TVRI, Trans-7, TV-One, *etc.*), access points (AP) on wireless fidelity (Wi-Fi) networks on campus, and so on. All of these RF transmitters have the potential to provide a source for the formation of PR which can simply be done with existing equipment in the antenna and wave propagation laboratories, especially those on campus. Various PCL conditions such as working frequency, transmit power, bandwidth, transmit waveform, *etc.* will provide variations in the measurement and detection capabilities of the detected target [1]. These measurement variations include variations in radar cross section (RCS), range resolution, velocity resolution, *etc.*

There are many studies that examine and implement various PCL as PR such as the study by [2]–[8] including the types of targets detected. The study conducted by [2] provides an overview of the potential of transmitters on many weather and meteorological

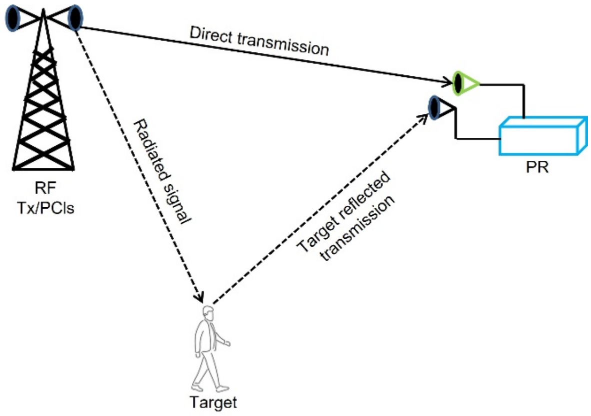


Fig. 1: PR configuration with PCLs from RF Tx.

radars in Oklahoma City, USA, to be used to detect wind conditions. Applications in PR with various PCLs such as monitoring human health using Wi-Fi signals by [3], detection of various types of targets on land by transmission from BTS on the global system for mobile (GSM) by [4], classification and detection of the human body by transmission from microwave wireless [5], supporting air traffic control of an aircraft at an airport with a navigation transmitter [6], determining the speed of targets for ships at sea with transmitters from global navigation satellite systems (GNSS) using long integration time by [7], [8], *etc*. From the literature [2]–[8] it can be deduced the fact that working frequency conditions and the type of radar greatly affect the type and size of detected targets.

There is also a lot of literature on the use of various PCL as PR such as FM radio transmission [9]–[11], digital TV transmission [12], [13], BTS from cellular networks [14], [15], AP from Wi-Fi [16]–[18], *etc*. In generally these studies see the PCL as a passive radar from the performance of its ambiguity function (AF) which is usually in the form of range-Doppler resolution without involving the size of the RCS and its detection range as investigated by [10]–[14] and [16]–[18] or even limited to determining the RCS and detection range without considering the waveform properties of the PCL type as reported by [9] and [15].

Based on literature such as [19], [20] that to determine the detection range of two adjacent targets, comprehensive knowledge of the waveform properties of a transmission signal from PCL is required, especially in the form of range resolution which is a function of modulation bandwidth, carrier wavelength, and antenna dimensions. Besides that, it also requires a doppler resolution that is able to distinguish adjacent targets based on their velocity. According to the study [21] that for PCL where Tx and Rx are not aligned, it is more likely to evaluate and demonstrate these resolutions using AF of various waveforms for range resolution and doppler for detection performance [21].

This paper exploits the potential and opportunities of Tx RF as a PCL in the Tarakan area, Indonesia from a variety of available types including FM radio transmitters (Pro-1, Pro-2, Pro-3 from RRI), transmitters on BTS on 4G-LTE networks, digital TV transmitters (TVRI, Trans-7, TV-One, *etc*.), APs on Wi-Fi networks on campus, *etc*. The things presented in this paper are completer and more comprehensive when compared to previous PCL studies from passive radars, namely performance predictions related to RCS and target angle vs. working frequency of PCL, range-Doppler resolution vs. target angle, and its detection range. While the waveform properties are presented in the AF of all PCL as a function of time delay (range) and doppler frequency (velocity) to evaluate the range and Doppler resolution. In the future, it is hoped that the performance prediction and AF can help and provide recommendations for radar designers to develop PR with RF transmission sources, *i.e.*, other PCLs, especially according to the size of the detected target RCS.

## II. Research Method

Principal model of PCL as a PR system and some parameters that show the performance of all PCLs such as RCS, range-Doppler resolution, range detection, signal waveform and properties. The PCL principal model provides an illustration and configuration of a PR system with various PCLs in order to obtain systematics and steps for calculating and evaluating the desired performance parameters for these PCLs. This is followed by giving expressions to determine the PR performance for various PCLs as mentioned above.

### *A. Basic Principles of PCL in PR Systems*

The following is an illustration of the basic principles of using PCL as PR presented in Fig. 1 There are many Tx sources of RF called PCL which can be FM radio transmissions, digital TV transmissions, base stations from cellular networks, APs from Wi-Fi [16]–[18], *etc*. This PCL transmits waveforms with transmission power, operating frequency, bandwidth, and other important parameters to space. The transmitted signal finally goes to the Rx antenna on the PR which has a broadband working frequency range which is called direct transmission. However, there is also a transmission signal to the Rx antenna from the PR that previously hit a certain target, which is called target reflection transmission. Based on these two transmissions, the signal processor then performs a cross ambiguity function (CAF) to obtain delay and Doppler frequency information from the target which will be further processed to obtain range, velocity, including resolution. Besides that, RCS will also be taken into account regarding the type of target and even how close the two targets can be identified.

The steps for forming the AF start from the PCL beam signal received by the Rx antenna and then fed to the spectrum analyzer (SA). Furthermore, SA feeds the down conversion signal to intermediate frequency

(IF). Then by the digitizer card, then the signal is converted into a base-band signal which is stored on the PC. Finally, the signal is processed using a signal processing application such as Matlab to obtain AF as a function of time delay ( $\tau$) and Doppler frequency ($f_d$) presented in a three-dimensional (3-D) plot, AF with $\tau = 0$, and AF with $f_d = 0$. Parameters that are measured and evaluated in AF include range resolution, Doppler resolution, peak sidelobe level (PSL), and peak to sidelobe ratio (PSLR).

*B. Parameter-parameter Kinerja PR*

The following provides a description and expression of the PR performance parameters for various PCLs such as RCS, range-Doppler resolution, range detection, signal waveform and properties.

*1) RCS Target from PR*

The RCS of the target on the PR is dictated by the physical area of the target ($A$) and the working frequency of the PCL expressed in its propagation wavelength ($\lambda$) [19], [22]. Through CAF, RCS of a target will be obtained which is expressed by

$$\sigma = \frac{4\pi A^2}{\lambda^2} \tag{1}$$

While the angular width of the signal scattering from the target which has a dimension of length d is expressed by

$$\theta = \frac{\lambda}{d} \tag{2}$$

Based on (1) it appears that the RCS is largely determined by the working frequency of the PCL. According to the proposed PCL in Tarakan, the FM transmission will have a large target detection relative to other PCLs.

*2) Range-Doppler Resolution and Range Detection*

Range resolution is a measure of how close the range between two adjacent targets can still be distinguished. Based on the PCL type of RF Tx, the range resolution is determined by the size of the bandwidth ($B$) of the transmitted waveform and the angle between the direct transmission and the target reflected transmission ($\phi$) [22] which is expressed by

$$\Delta R = \frac{c}{2B\cos(\phi/2)} \tag{3}$$

where c denotes the speed of light in a vacuum ($c \approx 3 \times 10^8 m/s$).

The resolution that differentiates between the velocities of two adjacent targets is determined by the integration time ($T$) of the RF PCL transmission. The velocity resolution expression is expressed by

$$\Delta v = \frac{\lambda}{2T\cos(\phi/2)} \tag{4}$$

Based on (3) and (4) it can be seen that the resolution of range and velocity are mutually independent where the range resolution is very dependent on the magnitude of B. Meanwhile, the velocity resolution is determined by $T$, where the greater the $T$, the more difficult it is to identify and detect the target. Therefore, there needs to be an appropriate setting to provide the right $B$ and $T$ values so that adjacent targets can be detected correctly. To determine the detection range of the target on the PR, it is expressed by the signal-to-noise ratio (SNR) obtained from the bistatic radar equation [22], i.e.

$$SNR = \frac{P_r}{P_n} = \frac{P+tG_t}{4\pi r_t^2}\frac{\sigma}{4\pi r_r^2}\frac{G_r\lambda^2}{4\pi}\frac{L}{kT_0BF} \tag{5}$$

where SNR is determined from the ratio between power Rx ($P_r$) and noise power ($P_n$), $P_t$ is the transmit power, $G_t$ denotes the antenna gain Tx, $r_t$ and $r_r$ are the range from Tx and Rx to the target, respectively, $G_r$ is the antenna gain Rx, L is the system losses, $k$ is the Boltzmann constant ($1.38 \times 10^{-23} J/K$), $T_o$ is the noise reference temperature, and F is the noise figure on Rx.

Table 1: Transmission Signal Parameters of PCLs in Tarakan

| PCL | Frequency | Bandwidth | Tx Power |
|---|---|---|---|
| Pro-1 RRI | 97.9 MHz | 220 kHz | 10 kW |
| Pro-2 RRI | 107 MHz | 220 kHz | 10 kW |
| Pro-3 RRI | 88.8 MHz | 220 kHz | 5 kW |
| BTS 4G-LTE | 2.3 GHz | 200 kHz | 100 W |
| TVRI | 546 MHz | 6 MHz | 10 kW |
| AP Wi-Fi | 2.4 GHz | 20 MHz | 100 mW |
| Trans-7 | 522 MHz | 6 MHz | 10 kW |
| TV-One | 618 MHz | 6 MHz | 10 kW |

Based on the real values in Table 1 which correspond to the PCL conditions of RF Tx, the detection range in (5) can be evaluated and its performance predicted. For illuminators in the form of audio broadcasting such as RRI Pro-1, Pro-2, and Pro-3 in Tarakan, they use FM transmit power of 10 kW, 10 kW, and 5 kW at working frequencies of 97.9 MHz, 107 MHz, and 88.8 MHz, respectively. For BTS on 4G-LTE cellular networks operating at a frequency of 2.3 MHz with a transmission power of 100W [23]. TVRI, Trans-7 and TV-One operate at 546 MHz, 522 MHz and 618 MHz, respectively with a transmission power of 10 kW each. While the AP on the Wi-Fi network installed on the UBT campus has a transmit power of 100 mW at a working frequency of 2.4 GHz and a bandwidth of 20 MHz.

It is assumed that the target detected when using (5) has a uniform RCS so that the target can be detected at delay (range), Doppler frequency (velocity), and angle using conventional processing approaches. Meanwhile in Rx, noise and interference levels are an integral part of detection performance. Noise is uniformly distributed. The effective value of the noise figure used depends on the signal and noise environment. For example, for rural and suburban environments, the noise level is low, while for high-frequency environments, such as cell-phone transmission and TV broadcasts, the effective noise figure is less than 25 dB [22]. Generally in PCL systems that direct transmission is used as a reference which is juxtaposed against the target reflected transmission to obtain processing gain. The effective bandwidth is obtained from the received signal. The integration time depends on the time in which the target echo becomes coherent.

*3) Signal Waveform and Properties*

According to [19] that the range-Doppler resolution is a principal parameter that is determined from the waveform properties of a radar system. For PCL from PR, the parameter does not depend on the signal controlled by the radar designer. Usually the Doppler-range resolution is determined and evaluated from the AF for the RF Tx signal from the PCL. A case example from a study reported by [22] is that FM broadcasts with a frequency between 88–108 MHz and a bandwidth of around 75 kHz have a resolution range of around 1–2 km.

AF is the output of a matched filter which is expressed by

$$\left|AF(\tau, f_d)^2\right| = \left|\int_{-\infty}^{\infty} \varphi(t)\varphi*(t+\tau)e^{j2\pi f_d t}dt\right|^2 \quad (6)$$

where $\varphi(t)$ is the signal of the direct transmission and $\varphi(t+\tau)$ is the signal of the target reflected transmission originating from the PCL of an RF Tx. Computation on (6) produces a three-dimensional (3-D) plot on the x-axis as the time delay, the y-axis as the Doppler frequency, and the z-axis as the magnitude of AF.

## III. Result

This section provides some calculation and evaluation results of the performance parameters listed in Section II.B including RCS, range-Doppler resolution, range detection, signal waveform and properties.

### *A. RCS Target and Scattering Angle*

Evaluation of the effect of working frequency on the RCS and the width of the signal scatter angle is determined based on (1) and (2), respectively. If it is assumed that there is a target, for example a car with physical dimensions $A = 6m^2$ and $d = 3m$, the effect of all PCL operating frequencies will be obtained as shown in Figs. 2 and 3.

### *B. Range-Doppler Resolution and Detection Range*

The range and velocity resolution for all PCL listed in Table 1 were evaluated using (3) and (4) and the results were obtained as shown in Figs. 4 and 5. Evaluation of the detection range is calculated using (5) with parameter values according to the PCL conditions

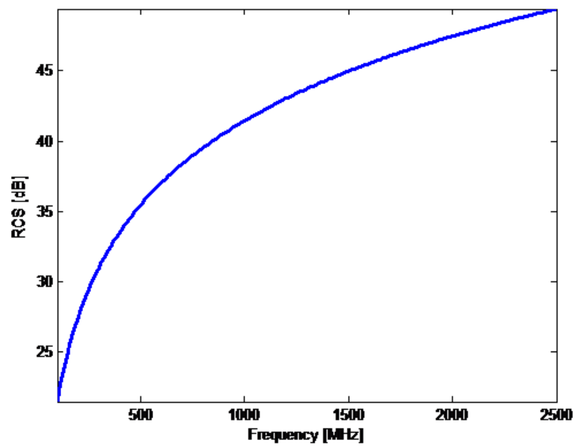


Fig. 2: RCS as a function of the operating frequency of the PCL.

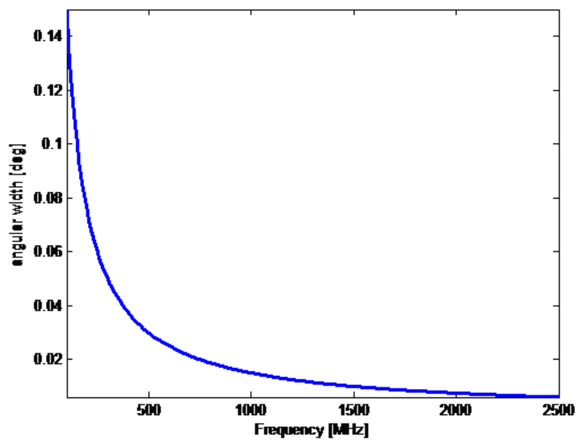


Fig. 3: Angular width as a function of working frequency of PCL.

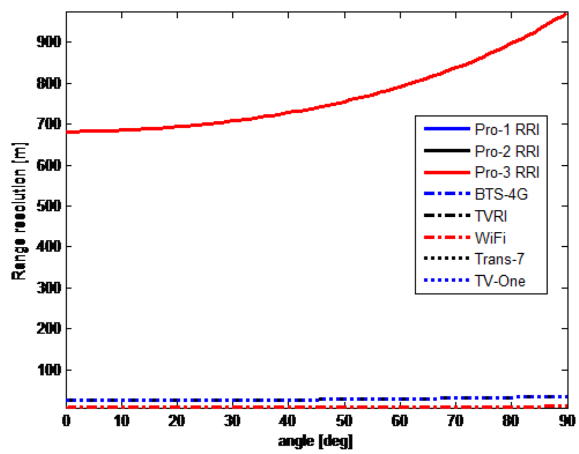


Fig. 4: The resolution range as a function of the angle $\phi$ of the PCL at Tarakan.

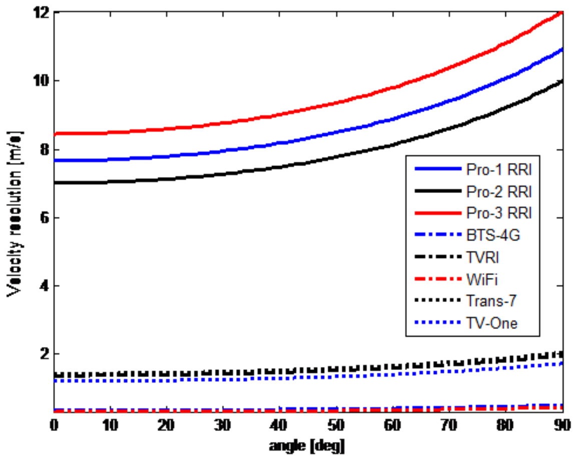


Fig. 5: The velocity resolution as a function of angle $\phi$ from PCL in Tarakan.

in Table 1. Performance prediction in the form of detection range generated by each PCL in SNR is obtained by assuming the Tx and Rx antennas are omnidirectional, $\sigma = 1m^2$, integration time 0.1 s, $F = 25$ dB, $L = 5$ dB, and $T_o = 290$ K. Starting from the illuminator, i.e., RRI radio (Pro-1, Pro-2, and Pro-3), BTS on 4G-LTE, TVRI, AP on Wi-Fi, Trans-7, and TV-One which is presented in Fig. 6 where the interval range Tx and Rx to the target, namely $r_t$ and $r_r$, is 0–30 km.

### *C. Ambiguity Function*

Evaluate the AF properties using (6) with $f_c$ data from each PCL as listed in Table 1. Shown in Figs. 7(a)-(d) are presented AF of the RRI FM Pro-1 transmission. Next for Figs. 8(a)-(g) provides AF of Pro-2 RRI, Pro-3 RRI, TVRI, Trans-7, TV-One, BTS 4G-LTE, and AP Wi-Fi transmissions. As is the case with Fig. 7(b) then Fig. 8 shows AF with normalized magnitude.

## IV. Discussion

This section reviews all the results that have been presented in Section III.

### *A. Impact of Working Frequency of PCL on Target RCS*

It appears at Figs. 2 and 3 that the higher the operating frequency of the PCL, the larger the size of the RCS which scatters the reflected signal to the PR but has a smaller signal scattering angle ($\theta$). This shows that the ability of PCL with low frequency will have a high probability of target detection because of the large scattering angle as reported by [19]. Based on evaluations (1) and (2) of the working frequency data of all the PCL listed in Table 1, the RCS is 16.82, 17.59, 15.98, 44.25, 31.75, 44.62, 31.36, and 32.83 in dB, respectively. While the signal scatter angles are 1.02, 0.93, 1.13, 0.04, 0.18, 0.04, 0.19, and 0.16 in degrees, respectively.

### *B. PCL Performance on Range-Doppler Resolution and Range Detection*

The range resolution shown in Fig. 4 is determined by $B$ and the angle between the direct transmission and the target reflected transmission $\phi$ where FM radio broadcasts on Pro-1, Pro-2, and Pro-3 have the largest range resolution, which means that it is possible that the distance between two adjacent targets around 35 - 1000 m can be predicted to be detected properly. This is not the case for other PCLs, i.e., 4G-LTE BTS and Wi-Fi APs, which have a distance tolerance between two adjacent targets of under 35 m. Meanwhile, the velocity resolution presented in Fig. 5 is determined by the integration time and working frequency of the PCL waveform transmission signal. Shown in Fig. 5 that generally PCL type BTS 4G-LTE and AP Wi-Fi are suitable for detecting two adjacent targets with a velocity of up to $0.43ms^{-1}$. Meanwhile TV broadcasts such as TVRI, Trans-7 and TV-One can detect two adjacent targets with a velocity of up to 2 ms-1. Furthermore, for RRI FM radio broadcasts on Pro-1, Pro-2, and Pro-3 can distinguish two targets with a maximum velocity of $12ms^{-1}$.

Seen in Figs. 6(a)-(c) FM radio transmissions such as RRI (Pro-1, Pro-2, and Pro-3) have the farthest range coverage or are called long range compared to other RF transmissions. It also appears that the coverage range from PCL after FM radio is followed by TVRI, Trans-7, TV-One, BTS LTE-4G, and AP Wi-Fi. The operating frequency factor ($f_c$) is proportional to the detection range where the $f_c$ on RRI FM radio has the farthest detection range. This is in line with study [9] where a passive radar based on FM transmission has a large range coverage and also improves the accuracy of the position of the target. However, that does not mean that other PCLs do not have an advantage which is related to the size of the RCS of the detected target as described in Section III A.

On Figs. 6(a)-(c), the area covered in the FM RRI transmission (Pro-1, Pro-2, and Pro-3) for a maximum SNR of 15 dB reaches an area with a range of about 4 km. For digital TV transmission (TVRI, Trans-7, and TV-One) for a maximum SNR of 15 dB it reaches an area with a range of about 2.5 km as shown in Figs. 6(d)-(f). Meanwhile, for BTS 4G-LTE transmission and AP Wi-Fi in Figs. 6(g)-(h) has a detection range of up to 500 m and below 50 m, respectively. The coverage range for 4G-LTE BTS with an SNR of around -29.8 dBm is in accordance with what was reported by [23].

Evaluate Figs. 7(a)-(b) shows AF with normalized magnitude side and top views, respectively. For the condition of the Doppler frequency $f_D = 0$, the range resolution will be obtained as shown in Fig. 7(c) where the time delay is $\pm 1.82ms$, the resolution range is around 2730 m. It can also be seen that the PSL is

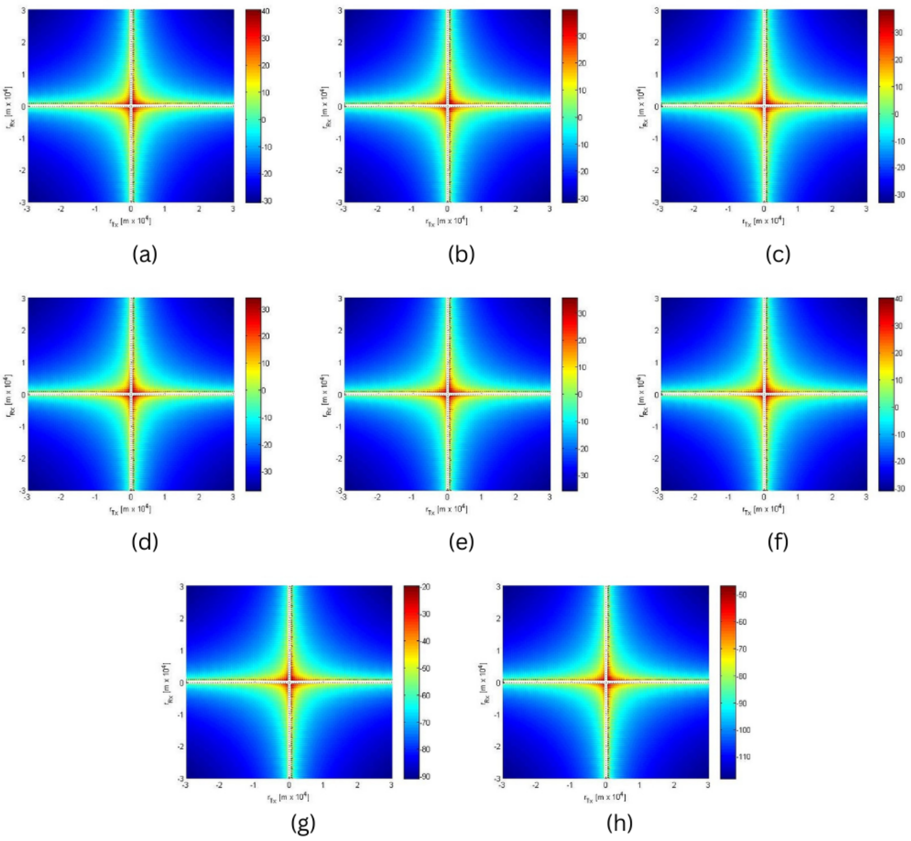


Fig. 6: The detection ranges for PCL in Tarakan are: (a) Pro-1 RRI, (b) Pro-2 RRI, (c) Pro-3 RRI, (d) TVRI, (e) Trans-7, (f) TV-One, (g) 4G-LTE BTS, and (h) AP Wi-Fi.

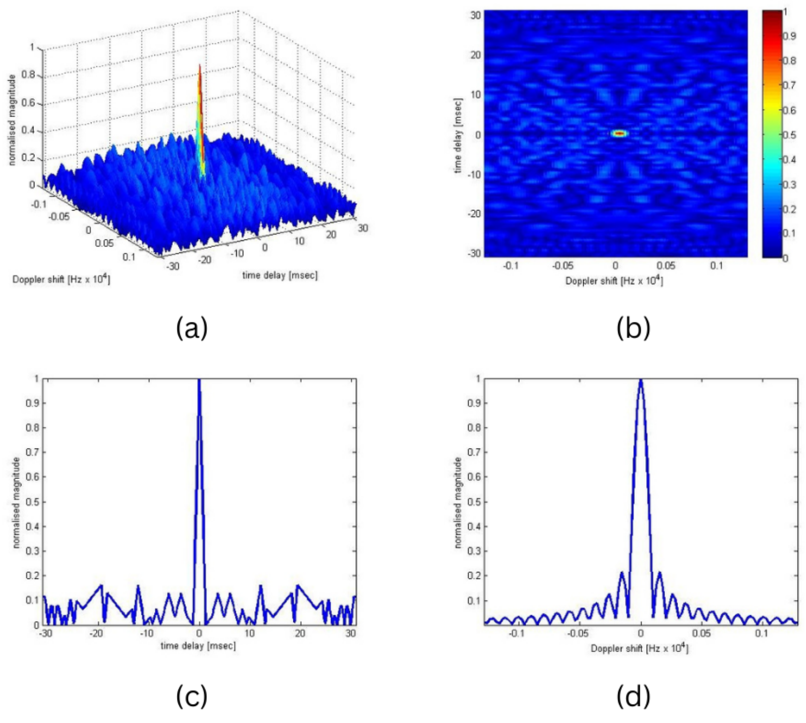


Fig. 7: Ambiguity function for a passive radar with FM Pro-1 RRI transmission with: (a) side view and (b) top view as a function of time delay and Doppler frequency, (c) condition $f_D = 0$, and (d) condition $\tau = 0$.

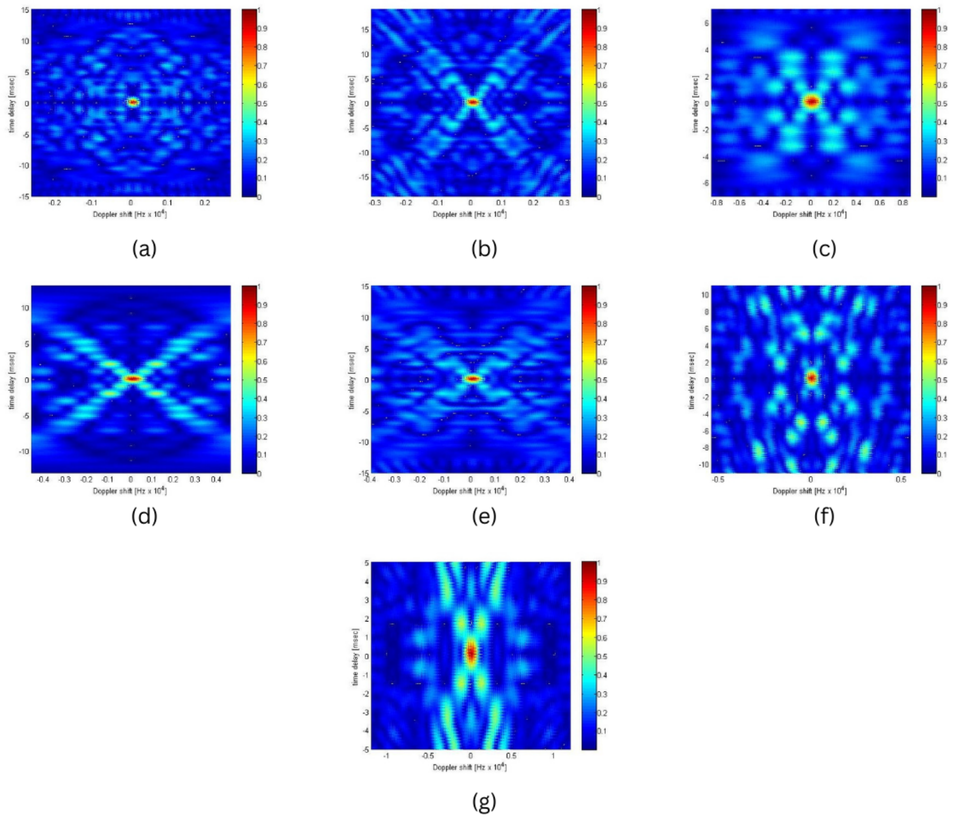


Fig. 8: Ambiguity function is shown above as a function of time delay and Doppler frequency for passive radar with transmission of: (a) Pro-2 RRI, (b) Pro-3 RRI, (c) TVRI, (d) Trans-7, (e) TV-One, (f) BTS 4G-LTE, and (g) AP Wi-Fi.

0.11 and the PSLR is 9.09. While in Fig. 7(d) where the time delay $\tau = 0, f_D = \pm 0.05104 Hz$ is obtained.

In the Doppler frequency condition $f_D = 0$, time delays for Pro-2 RRI, Pro-3 RRI, TVRI, Trans-7, TV-One, BTS 4G-LTE, and Wi-Fi AP will be obtained i.e.: $\pm 2.61, \pm 1.67, \pm 1.35, \pm 1.24, \pm 1.39, \pm 1.16$, and $\pm 1.07$, respectively in ms, so that the resolution ranges are obtained i.e.: 3915, 2505, 2029.5, 1860, 2085, 1740 and 1605 in m, respectively. It can also be seen that the PSL was 0.23, 0.32, 0.27, 0.27, 0.16, 0.17, and 0.08, respectively, so that the PSLR was 4.35, 3.13, 3.71, 3.71, 6.25, 5.88 and 12.5, respectively. For AF with the condition $\tau = 0$, the $f_D$ is $\pm 0.04 \times 104, \pm 0.12 \times 104, \pm 0.02 \times 104, \pm 0.06 \times 104, \pm 0.01 \times 104, \pm 0.14 \times 104$, and $\pm 0.07 \times 104$ in Hz, respectively.

Looks from Figs. 8(a)-(g) obtained the smallest range resolution by Wi-Fi AP transmission. Meanwhile, the smallest Doppler resolution is achieved by TV-One transmission. For the largest PSLR obtained by AP Wi-Fi transmission with PSL and SLL are 1 and 0.08, respectively. To detect targets with small RCS that are close to each other, it is recommended to choose PCL in the form of Wi-Fi AP transmission.

## V. Conclusion

This paper has presented performance predictions and waveform properties of several PCLs in Tarakan such as RRI FM radio (Pro-1, Pro-2, and Pro-3), digital TV (TVRI, Trans-7, and TV-One), BTS on 4G-LTE, and AP from Wi-Fi. Performance prediction provides RCS, angular width, range-Doppler resolution, and range detection in SNR of each PCL where FM RRI radio has the farthest range coverage. FM broadcasts have a range resolution of up to 1 km and Wi-Fi APs have a range resolution of under 35 m. For BTS 4G-LTE and AP Wi-Fi, it is suitable for detecting two adjacent targets with a velocity of up to $0.43 ms^{-1}$. The detection range for RRI FM radio and digital TV is from 2.5 to 4 km. While the waveform properties are presented as the AF of the PCLs which are presented as a function of time delay and Doppler frequency which provide range resolution, Doppler resolution, peak sidelobe level, and peak to sidelobe level ratio. The smallest range resolution is achieved by AP Wi-Fi transmission and the smallest Doppler resolution is achieved by TV-One transmission. It is hoped that this performance prediction and ambiguity function can help and provide recommendations for radar designers in developing passive radars with other RF transmission sources, especially according to the size of the detected target RCS.

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