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RESEARCH ARTICLE

Strategic method of determining parameter values in frequency modulated continuous wave radar for low noise floor over middle-long range

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Abstract

Heterodyne architecture has been frequently chosen to resolve the problem of dc offset in frequency modulated continuous wave (FMCW) radar. However, heterodyne FMCW radars use different local oscillators, resulting in uncorrelated phase noise (UPN) in beat signals. Therefore, the inherent leakage signal in the heterodyne FMCW radar also has UPN and raises the noise floor in the power spectrum. In this letter, we propose a strategic decision method for parameter values in the heterodyne FMCW radar to achieve a low noise floor over the middle-long range. In addition, we experimentally discover the relation between the UPN and the processing gain for the first time. Based on this relation, we devise an exact formula for the degree of improvement achieved due to the proposed strategic decision method. Experimental results confirm the devised formula and show that the proposed method significantly reduces the noise floor over the middle-long range.

KEYWORDS

frequency modulated continuous wave (FMCW) radar, noise floor, phase noise, processing gain, radar parameter, uncorrelated phase noise (UPN)

1 | INTRODUCTION

Frequency modulated continuous wave (FMCW) radar has been widely used for various purposes such as target detection, vital sign monitoring, motion recognition, radar imaging, altimeter, meteorological radar.[1-6]

There are two typical architectures in the FMCW radar, homodyne architecture and heterodyne architecture. Homodyne FMCW radar has a relatively simple structure and has range correlation effect (RCE) which reduces the magnitude of phase noise.[7] However, unwanted dc offsets not only saturate the amplifiers and the analog-to-digital converter (ADC), but also corrupt the baseband signals.[8]

Heterodyne FMCW radar has frequently been employed to resolve the problem of dc offsets.[9-12] However, as the heterodyne FMCW radar usually uses different local oscillators (LOs), it causes uncorrelated phase noise (UPN) and the RCE has little or no effect, which results in an increase in the noise floor.[10] When the configuration of the radar is monostatic or quasi-monostatic, the leakage signal, which is a drawback of the FMCW radar, becomes intensely strong and can worsen the noise floor rise.[11,12] However, in these configurations, it is unclear how the UPN of the leakage signal affects the noise floor, especially over the middle-long range, in the final signal processing result of the heterodyne FMCW radar. The noise floor over the middle-long range is particularly important in terms of radar sensitivity because the received power of a target is inversely proportional to the fourth power of the range according to the radar equation.

In this letter, through experiments, we clearly show the effect of the UPN of the strong leakage signal in the quasi-monostatic heterodyne FMCW radar on the noise floor. Then, based on these results, we propose a strategic decision method for parameter values in the heterodyne FMCW radar to reduce the noise floor over the middle-long range. In addition, we found for the first time how the commonly known processing gain (PG) theory works under the UPN. Considering this newly determined relation between the UPN and the PG, we devise an exact formula for the degree of improvement, namely the gain, achieved due to the proposed decision method. Experimental results prove that the devised formula works well and demonstrate that the proposed method enables us to achieve a low noise floor over the middle-long range without additional hardware parts by strategically determining the sweep period of the linear frequency modulated (LFM) signal and the sampling frequency.

2 | PROPOSED METHOD BASED ON EXPERIMENTAL ANALYSES

2.1 | Proposed idea

Figure 1(A) shows a block diagram of the heterodyne FMCW radar. When an LFM signal is transmitted through the antenna, it directly leaks into the receiver. The problematic beat signal of the leakage at the end of the baseband, $y(t)$, can be expressed as follows:

$$y(t) = A_{leakage}\cos\left(2\pi f_{beat\ leakage}t + \theta_{leakage} + \phi_{leakage}(t)\right), \tag{1}$$

where $A_{leakage}$, $f_{beat\ leakage}$, and $\theta_{leakage}$ are the amplitude, beat frequency, and constant phase of the leakage beat signal, respectively. $\phi_{leakage}(t)$ is the final UPN of the leakage beat signal, which is the consequential phase noise of the mixing with all the different LOs in the heterodyne FMCW radar.

We conducted experiments to show how the UPN of the strong leakage beat signal in the quasi-monostatic heterodyne FMCW radar influences the noise floor. Figure 1(B) shows an experimental setup. The distance between the TX antenna and the RX antenna was 25 cm. The specifications of the radar are listed in Table 1. The listed parameter values, for which no strategic decision method is applied, are default values of the radar system. To clarify the noise floor, we took an average of 100 power spectra, which reduces the variance of the noise floor. Note that this averaging method is applied in all the power spectrum graphs in this study for the same purpose. Furthermore, we measured the power spectral density (PSD) of the UPN with a spectrum analyzer, Agilent Technologies E4440A.

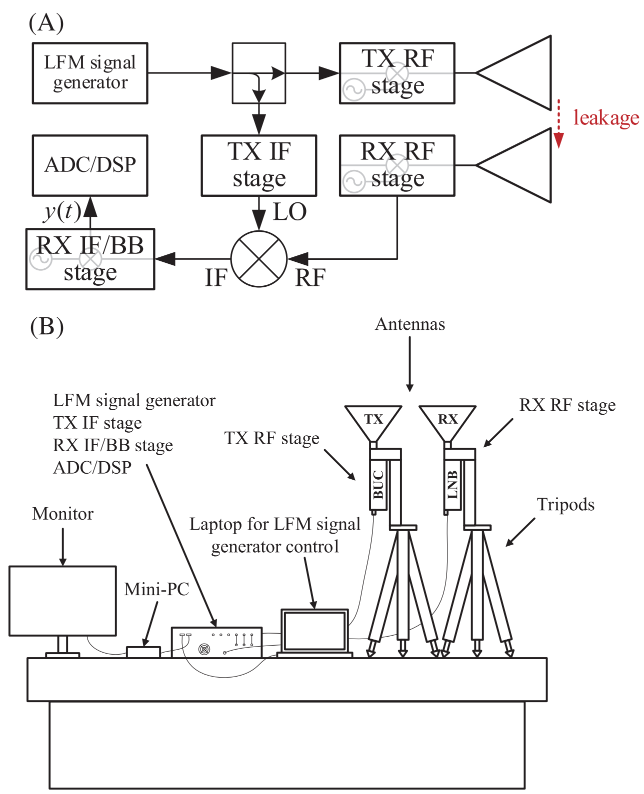

FIGURE 1 Heterodyne FMCW radar: (A), block diagram; (B), experimental setup. FMCW, frequency modulated continuous wave [Color figure can be viewed at wileyonlinelibrary.com]

The resulting power spectrum is shown in Figure 2(A). We overlaid the measured PSD of the UPN. Note that the intermediate part in the desired domain is approximately 0.4–0.5 F_s. Except for the intermediate part where the desired term and the image term collide, which slightly affects the noise floor, the measured UPN is well matched with the noise floor. This demonstrates that the UPN of the strong leakage beat signal dominates almost the entire noise floor, despite the presence of other noises such as thermal noise and quantization noise. The measured UPN is depicted in Figure 2(B). As the LOs in the heterodyne FMCW radar are phase-locked loop (PLL) based synthesizers, the measured UPN, which dominates the noise floor in the quasi-monostatic heterodyne FMCW radar follows the typical phase noise shape of the PLL. The characteristic of this phase noise shape is that the phase noise level decreases as the offset frequency increases.

We proposed an idea using the results from these experiments. A conceptual figure of the proposed method is presented in Figure 2(C). As the UPN of the strong leakage beat signal dominates the noise floor, we proposed to make especially low-level part of the UPN dominant in the noise floor. In this way, we can achieve a low noise floor over the middle-long range. The proposed idea can be realized by considering the well-known beat frequency-range relation in the FMCW radar, as follows:

$$f_{beat} = \underbrace{\left(\frac{2BW}{cT}\right)}_{\text{coefficient},\,\alpha} R, \tag{2}$$

where BW and T are the bandwidth and sweep period of the LFM signal, respectively. c is the speed of light, R is the range or distance of the target, and f_{beat} is the beat frequency. We strategically increase the coefficient in (2) to increase f_{beat} corresponding to R. Then, the value of f_{beat} corresponding to R becomes larger, thus the noise floor level at the same R corresponding to the increased f_{beat} becomes lowered according to the shape of the UPN. For an intuitive example, let us suppose that the beat frequency corresponding to 1800 m is 1 MHz and the beat frequency of the leakage beat signal is close to 0 Hz. If we double the coefficient in (2), the beat frequency corresponding to 1800 m becomes 2 MHz. Then, the noise floor at 1800 m is reduced by approximately 12 dB as the level of the UPN is changed from approximately −96 dBc/Hz to −108 dBc/Hz, which are the levels corresponding to 1 MHz and 2 MHz, respectively, in the graph in Figure 2(B). This can be done because it has been demonstrated that the noise floor is

TABLE 1 Specifications and parameters of the heterodyne FMCW radar

Parameters	Values (default)
Radar configuration	Quasi-monostatic
System architecture	Heterodyne
Operating frequency	14.35–14.50 GHz
Transmit power	2 W
Antenna	Corrugated horn
Antenna gain	16 dBi
Sweep bandwidth (BW)	150 MHz
True range resolution	1 m
Sweep period (T)	1800 μs
Sampling frequency (F_s)	5 MHz
Maximum unambiguous range (R_{max})	4500 m
Window function	Hann

Abbreviation: FMCW, frequency modulated continuous wave.

dominated by the UPN of the strong leakage beat signal. Note that the absolute level of the noise floor and the PSD of the UPN are not the same, but the difference between the noise levels in both graphs is the same.

There are two ways to increase the coefficient. One is to increase BW, and the other is to decrease T. However, increasing BW requires broadband RF parts. If the radar system is already designed or even built, then the system must be redesigned and rebuilt. Therefore, we strategically decrease T to obtain a high coefficient. However, as the maximum unambiguous range, R_{max}, is reduced when T is decreased, we increase the sampling frequency, F_s, to maintain R_{max}. The increase of F_s augments the computation over the same amount of time. Having said that, we can reduce the noise floor by only adjusting the parameter values, T and F_s, without additional hardware parts.

2.2 | Relation between UPN and PG

The PG, which is also called the fast Fourier transform (FFT) gain, should be considered when T or F_s changes. As the number of samples, N, for the FFT increases with the increase in T or F_s, the signal-to-noise ratio (SNR) should be improved by $10\log_{10}N$.[13] In this study, we revealed the actual relation between the UPN and the PG through the experiments.

Figure 3 shows the relation between the UPN and the PG as T changes. Note that we plot only the desired domain henceforth, because the mirrored domain is not used in practice. We fixed the default F_s and decreased T. Figure 3(A) shows that the SNR is reduced by $10\log_{10}N$ as T decreases. If the commonly known PG theory works, the SNR should be reduced by approximately 3 dB, as reducing T by half will also reduce N by half. To confirm this, we adjusted the graphs for $T = 1800$ μs and $T = 450$ μs by 3 dB. As shown

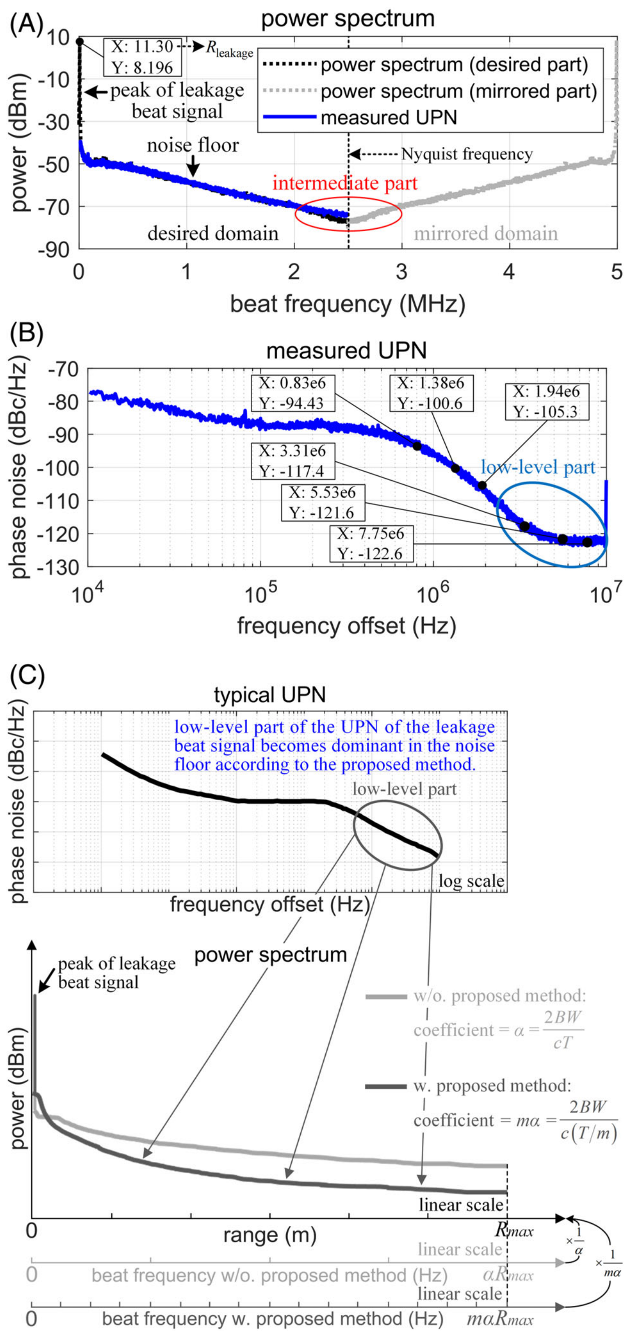

FIGURE 2 UPN and the proposed idea: (A), influence of the UPN of the strong leakage beat signal on the noise floor; (B), measured PSD of the UPN on a log scale; (C), conceptual figure of the proposed idea. UPN, uncorrelated phase noise [Color figure can be viewed at wileyonlinelibrary.com]

in Figure 3(B), the adjusted graphs are overlapped well, which indicates that the UPN follows the commonly known PG theory when T changes.

In contrast, a different phenomenon occurs in the relation between the UPN and the PG as F_s changes, which is shown in Figure 4. We fixed the default T and increased F_s. If the commonly known PG theory works, the SNR should be improved by $10\log_{10}N$, as increasing F_s raises N. However, the results show that the SNR does not change as F_s changes,

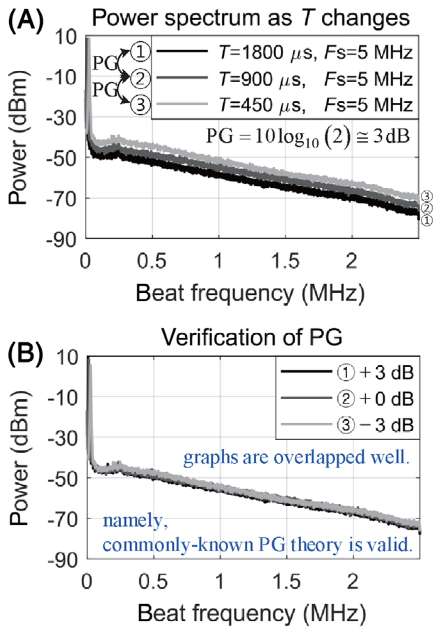

FIGURE 3 Validity check of the commonly known PG theory as T changes: (A), power spectra as T changes; (B), level adjustment of power spectra in Figure 3(A) [Color figure can be viewed at wileyonlinelibrary.com]

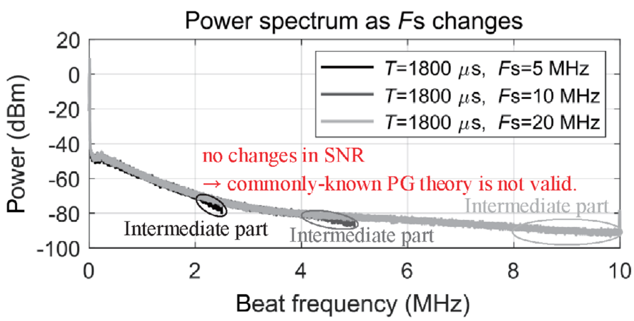

FIGURE 4 Validity check of the commonly known PG theory as F_s changes [Color figure can be viewed at wileyonlinelibrary.com]

which indicates that the commonly known PG theory does not work and no PG occurs at all.

These results can be discussed as follows. The proposed method can lower the noise floor by reducing T so that the low-level part of the UPN becomes dominant in the noise floor. Furthermore, the proposed method can compensate the reduced R_{max} as it increases F_s. Thus, if the commonly known PG theory worked even in the experiments for Figure 4, the loss due to the reduction of T would be canceled out by the gain due to the increase in F_s, and there would be no need to consider the PG when we apply the proposed method. However, as shown in Figure 4, because the commonly known PG theory does not work for the UPN when F_s changes, there is no compensational gain for the loss due to the decrease in T. Therefore, when the proposed method is applied, T and F_s should be strategically determined by considering the loss due to the reduction in T.

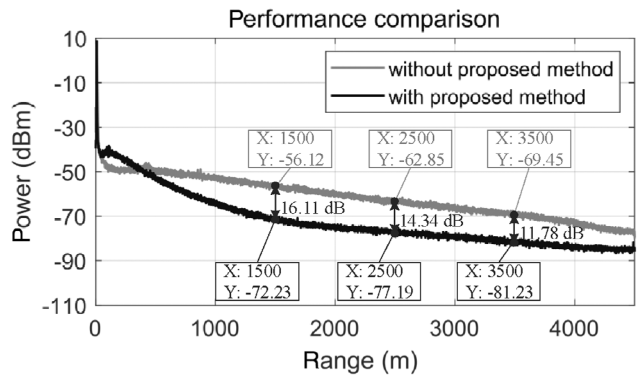

FIGURE 5 Performance of the proposed method

Considering these analyses, we devised the exact formula for the total gain due to the proposed decision method as follows:

$$\begin{aligned} G(R) = [\{ & S_{\phi\phi}\left(\frac{2BW}{cT_{default}}(R-R_{leakage})\right) \\ & -S_{\phi\phi}\left(\frac{2BW}{cT_{decision}}(R-R_{leakage})\right)\} \\ & -10\log_{10}\left(\frac{T_{default}}{T_{decision}}\right)] \quad (\mathrm{dB}), \end{aligned} \tag{3}$$

where $S_{\phi\phi}$ is the PSD of the UPN, and $R_{leakage}$ is the range value corresponding to $f_{beat\ leakage}$ in (1), which can be easily measured by the peak-searching. Through (3), we can expect the total gain of the proposed method at a certain range, R, by substituting the known parameter values, that is, BW, c, $T_{default}$, and $R_{leakage}$, and the parameter value to be determined, that is, $T_{decision}$. Conversely, we can also determine the $T_{decision}$ that results in the desired gain by using (3). Then, we increase F_s by the ratio of $T_{default}/T_{decision}$ to compensate the reduced R_{max}.

3 | RESULTS AND DISCUSSION

Considering the aforementioned analyses, we strategically decided $T_{decision}$ to be a quarter of the default value so that the low-level part of the UPN became dominant in the noise floor. Then, we set F_s at four times the default value to maintain the reduced R_{max}. Finally, we plotted the power spectra without and with the proposed method. In Figure 5, the range was calculated using (2), and only the desired domain, which is from 0 to R_{max}, was plotted, as we mentioned earlier. As shown in Figure 5, the noise floor over the middle-long range is significantly reduced owing to the proposed method. Referring to the markers in Figure 2(B) and the known parameter values, BW = 150 m, $c = 3 \times 10^8$ m/s, $T_{default}$ = 1800 μs, and $R_{leakage}$ = 11.30 m from Table 1 and Figure 2(A), we expected several representative gain values as follows. G(1500 m) ≊ [$S_{\phi\phi}$(0.83 MHz) - $S_{\phi\phi}$(3.31 MHz) - 6] = 16.97 dB, G(2500 m) ≊ [$S_{\phi\phi}$(1.38 MHz) - $S_{\phi\phi}$(5.53 MHz) - 6] = 15.00 dB, G

(3500 m) $\approxeq$ [$S_{\phi\phi}$(1.94 MHz) - $S_{\phi\phi}$(7.75 MHz) - 6] = 11.30 dB. Then, we can verify (3) by comparing the expected gain values with the actual gain values measured in Figure 5. As shown in Figure 5, the expected gain values and the actual gain values are almost the same, and the errors are within 1 dB. Therefore, we can use (3) to estimate the gain due to the proposed method accurately or to decide the parameter values, T and F_s, to achieve low noise floor at the middle-long range.

4 | CONCLUSION

This letter demonstrated the effect of the UPN of the strong leakage signal in the quasi-monostatic heterodyne FMCW radar on the noise floor. Furthermore, the relation between the UPN and the PG has been revealed for the first time. Based on these analyses, the strategic decision method for the parameter values to decrease the noise floor over the middle-long range has been proposed, and the exact formula for the gain of the proposed method has been devised. The experimental results show that the proposed method greatly lowers the noise floor over the middle-long range. Additionally, the validity of the devised formula has been verified. The proposed method is a simple and powerful way to reduce the noise floor over the middle-long range by strategically adjusting the sweep period and the sampling frequency without requiring additional hardware parts.

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