W-band Noise Radar in Short Range Applications

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Abstract: *Noise Radar Technology (NRT) uses noise waveforms (continuous or pulsed) as a radar signal and correlation processing of the returns for their optimal reception. This paper is devoted to some possible applications of NRT in civil field, in particular to millimetre-wave radars, with comparison of the use of Noise W-band radar versus the more classical FM-CW or pulse compression solutions.*

1. Introduction

Noise Radar Technology (NRT) uses the noise waveform (continuous or pulsed) as a radar signal and correlation processing of radar returns for their optimal reception (Matched Filter/Ambiguity Function). This implies the use of both efficient *noise generators* and *digital correlation receivers* based on controllable delay lines or frequency-domain processors. Recent achievements in the field of Nonlinear Dynamics and Chaos provide new methods for generation of Noise Waveform (NW) with both wide bandwidth and high spectral density [1]. Integrated circuits have made available fast digital components required for digital correlators capable of processing NW radar returns in real time [1].

In principle, noise radar is realizing simultaneously optimal coherent reception of noise radar returns, high rate compression, independent control of velocity and range resolutions with both range and Doppler frequency measuring, no sidelobes in the ambiguity function, and no range ambiguity for CW and pulse waveform. Furthermore, noise radars show high resistance against EM interference and the possibility to use simultaneously many radars within the same area [2]. Nevertheless, there are drawbacks in NRT; perhaps the most significant one is the limited exploitation of the power amplifier/oscillator: the average transmitted power in a Noise Radar may be some *10 dB* lower than in a FM-CW or Pulse Compression radar using the same power amplifier; this is due to the need to maintain most of the dynamic range of the noisy transmitted waveform.

Both theoretical and experimental investigations [3] are still needed to fully exploit the capabilities of NRT and the affordability for design of *W-band* noise radar systems ($94 \div 95$ *GHz* with a bandwidth wider than 2 GHz available) as primary radar in civil applications such as SMGCS and debris search on runway/speedway and/or security such as anti-intrusion and railway ground transportation safety.

2. Noise radar waveforms

In range/velocity processing of radar returns, the optimal reception (MF) for the signal $s(t)$ is characterized by the *ambiguity function*: $\chi(\tau,\nu)=\int_{-\infty}^{+\infty} s(t)\, s^{*}(t+\tau)\, exp(-j2\pi\nu t)\, dt$, that permits to define the accuracy and the resolution of the range and velocity measurements [7], [9]. For practical applications the Range/Doppler sidelobes should be less than a value as low as *-40 dB* or more. Using a *rectangular* pulse of length *T* there are no range sidelobes, but there are poor performances in range resolution, high Doppler sidelobes and finally inefficient spectral use. Range resolution will be reached using pulse compression while permitting an acceptable velocity resolution by means of coherent pulse train. In *noise radar* the processing is based on the correlation: $C(T_0,T_r)=\int_0^T s(t-T_0)s(t-T_r)\,dt$ where the transmitted (reference signal) $s(t-T_r)$ is a stationary random process of noise with spectrum width *B*, $s(t-T_0)$ is the received signal by a target at range $R_0=cT_0/2$ and T is the time extent of the measurements (integration time). When $T_r=T_0$ a peak correlation is received. The range resolution is $\Delta r=c/2B$ and the number of the independent samples is $N=BT$. Due to the limited time T, for different realizations of noise, $C(T_0,T_r)$ fluctuates around its average limiting the possible sidelobes suppression. The *expected value* of $C(T_0,T_r)$ and its *variance* has been evaluated in [5] where the average Peak to Sidelobe Ratio is evaluated equal to *N*.

For the range/Doppler processing of noise radar, the transmitted waveforms can be mainly obtained (a) directly from the noise source, (b) with a pseudo-random numbers generator followed by D/A conversion, [4], (c) as a Phase (or Frequency) Modulated, PM/FM signal by noise [6]. In the case (a) if $s(t)$ is a realization of duration *T* of a narrowband stationary noise process with spectrum width *B* and autocorrelation function $R_0(\tau)$, the *ambiguity diagram* (in range *r* and Doppler velocity v_D) is evaluated as [2]:

$$|\chi(r,v_D)|^2=\left\{\left|R_0\left(\frac{2r}{c}\right)\right|^2\right\}\left\{\left|(T-|2r/c|)\frac{\sin\left[2\pi v_D/\lambda\left(T-|2r/c|\right)\right]}{2\pi v_D/\lambda\left(T-2r/c\right)}\right|^2\right\} \qquad (1)$$

Eq. (1) is plotted in *Figure 1* for rectangular noise $R_0(2r/c)=\sin(2\pi Br/c)/(2\pi Br/c)$ with $B=500\ MHz$, $T=5\ ms$, $\lambda=3.15\ mm$ (95 *GHz*). In the case of PM the autocorrelation is evaluated in [6]. In real time applications, correlation processing puts severe requirements on the speed of the signal processors [5], [6]. To cope with this problem binary or low bit ADC are used with a degradation in sidelobe suppression because of the reduced dynamic range and the non linear characteristic of the A/D steps. These simplified techniques, however, are less and less important today because of available high speed A/D convertors and fast processing tools (DSP, FPGA, ASIC).

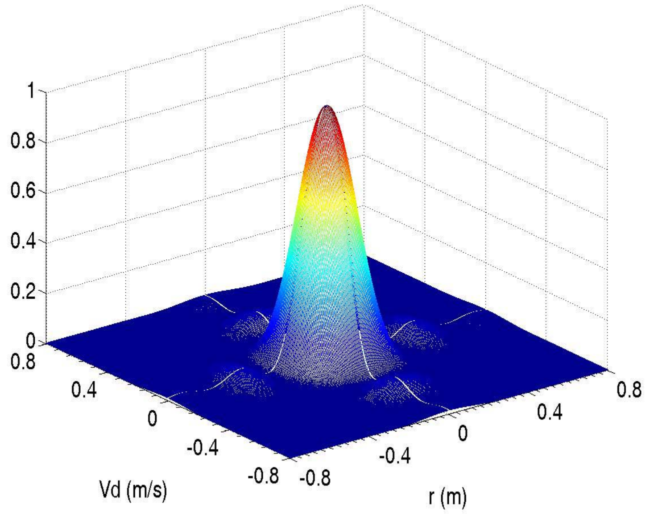

Figure 1. – Ambiguity Diagram of noise.

3. Some civil potential applications

The noise radar technique combined with modern coherent signal processor (time-frequency, wavelets, …) allows very high accuracy and resolution in both range and radial velocity. Current real-time signal processors state of the art (based on most recent powerful FPGA and DSP devices) makes NRT extremely attractive in terms of performances compared to other CW Radar techniques as, for instance, the widely known FMCW radar.

Table 1 shows a comparison between FMCW and NRT techniques.

Table 1 – Noise Radar versus FMCW

	FMCW	NRT
Range Accuracy	Affected by frequency modulation linearity, transmitted signal bandwidth and target velocity.	Affected only by transmitted signal bandwidth.
Doppler Accuracy	Affected by observation time.	Affected by observation time.
Ambiguity Function	Target range estimation is affected by target velocity: if only one target is present in the scenario, there are techniques that allow to estimate target velocity and make range error correction to achieve the real target range.	The ambiguity function is nearly ideal thumbtack, so both target range and velocity parameters can be estimated at once (according to the bandwidth and observation time selected) using a bank of correlators.
Sensitivity	Affected (as function of the range) by leakage effect, power source phase noise performance, FFT side lobes.	Affected by leakage effect (at the zero range) and by correlation side lobes.
Power Source	Mostly based on low-power solid-state devices that (according to low phase noise and good linearity requirements) may often require expensive modulators (typically VCO) with unfavourable cost-effectiveness.	Mostly based on low-power solid-state and very reliable low cost devices containing noise diodes (IMPATT technology), already used widely for receiver testing. High power tubes are available for longer ranges.
Signal Processing	Target Range and Velocity parameters are calculated by using standard FFT processing with coherent pulse trains.	Target Range and Velocity parameters are calculated by means of 2D Correlation Filtering. Often one-bit correlation processing is acceptable with significant reduction in computational burden [5].
LPI, ECM, ECCM, CESM	Inherent low probability of intercept (LPI) but the transmitted waveform is continuously repeated and subject to countermeasures.	Inherent LPI and superior electromagnetic compatibility: NRT transmitted signal does not show up as an intentional signal.
Spectral Efficiency	Mutual interference may easily occur between two FMCW that occupy the same transmission spectral band providing significant performance losses.	Mutual interference between two noise radar that occupy the same transmission spectral band is negligible, since the signal from one radar will not correlate with the other's references.

Current noise radar technology is now mature for short-range sensing (typically < *3 km*) for both military and civilian applications. Some possible NRT civil applications at millimetre wave are shown in Table 2 with a suggested configuration and the relative parameters.

Table 2 – Possible civil applications of NRT

Applications	Suggested configuration	Parameters
Railways Foreign Object Detection (FOD) to automatically detect debris and other hazards on high speed railways.	(A) *Very Short Range* (*tens* of *m*). $\Delta r = 15\ cm$ Remind: steady/slow targets	$B = 1\ GHz$ $T = 4\ \mu s$ $D = 10\ cm$ $G_t = G_r = 38dB$ $N = 4 \cdot 10^3$
Automotive Traffic Monitoring (highways and critical tunnels, car collision alerts, …).		
Perimeter Surveillance Radar to protect ports, harbours and big ships against intruders or swimmers.	(B) *Short Range* (*hundreds* of *m*). $\Delta r = 30\ cm$ Remind: steady/slow targets	$B = 500\ MHz$ $T = 8\ \mu s$ $D = 1\ m$ $G_t = G_r = 46dB$ $N = 4 \cdot 10^3$
Wire Detection Radar and Obstacle Avoidance for Helicopters navigation support.		
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Airport Foreign Object Detection Radar to automatically detect debris and other hazards on runways and airport areas.		
Airport Traffic Surveillance Radar (in miniradar network or SMR gap filler), with targets from zero to medium speed (*100 km/h* and resolution about *36 km/h*).	(C) *Medium Range* (*many hundreds* of *m*). $\Delta r = 3\ m$	$B = 50\ MHz$ $T = 160\ \mu s$ $D = 1\ m$ $G_t = G_r = 46dB$ $N = 8 \cdot 10^3$
Legenda – Δr : range resolution; *T*: integration time; *D*: antenna diameter; *N*: number of signal samples		

Other civil applications are: Concealed Weapon Detection Trough Clothing (Passive Millimetre Wave Camera for passengers security scanning); Buried Object Detection (non metallic land mines, human bodies, …). SAR for Mini-UAV (for search and rescue, detection of structural changes in manmade and natural objects). Other, military, applications can be: Battle Surveillance Radar, Seeker for missile guidance, Tracking Radar for fire control.
Using the radar equation for *CW* Radar in clear atmosphere [8]:

$$SNR = \frac{P_{CW} T G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4 \cdot k \cdot T_0 \cdot F \cdot L} \tag{2}$$

where $P_{CW} = 10\ mW$ is the assumed average power for the transmitter, while for the antenna gain we consider, for *Very Short Range* a small antenna ($D = 10\ cm$, $G_t = G_r = 38\ dB$), and for *Short* and *Medium Range* a shaped antenna ($D = 1\ m$, $G_t = G_r = 46\ dB$); $F = 9\ dB$ is the noise figure, $T_0 = 290\ °K$, $L = 3\ dB$ is the loss, $\sigma = 1\ m^2$ is the *RCS* of targets, the *SNR* (*dB*) versus *Range* (*m*) has been evaluated in the cases (A), (B) and (C), see Figure 2. Of course the detection (specially in case C) will strongly depend on rain and other propagation effects.

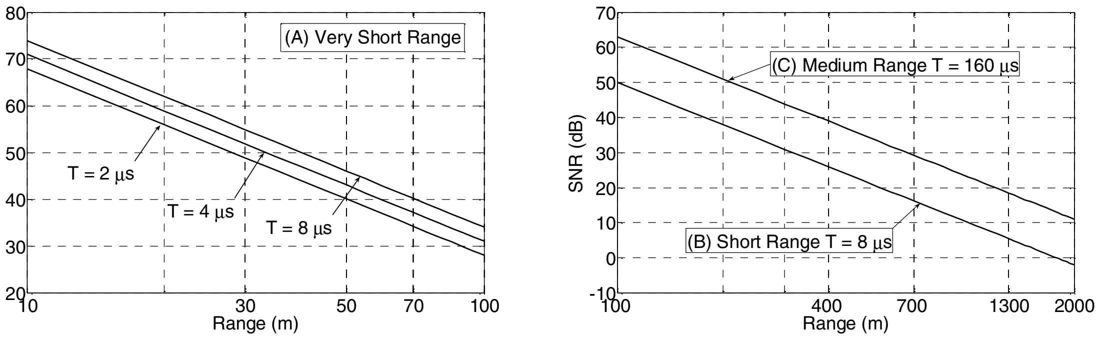

Figure 2 - SNR (dB) versus Range (m). (A)Very Short Range, (B) Short Range (C) Medium Range.

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