Radar Waveforms for A&D and Automotive Radar
White Paper

This White Paper provides a detailed review of radar waveforms for Aerospace and Defense and commercial radar systems, as well as commercial radar sensors such as those used in automotive safety applications. Waveforms such as pulse and pulse-Doppler signal, continuous wave and frequency shift keying waveforms are described.

It also shows continuous waveform trends designed for specific needs and application differences of continuous wave radar compared to pulse radar systems.

Note:

This document is an update to the original white paper by Steffen Heuel, 2013.

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1 Abstract

The history of radar goes back more than 100 years and is now widely used in both defense and commercial applications. Today's modern radar systems use highly specialized and innovative technologies to meet the growing industry demands.

With the rapid advances across the entire spectrum of radar and electronic warfare technology, the capabilities of test and measurement systems must be continuously enhanced. Identification, targeting, control, and self-protection systems are becoming ever more complex and integrated. More computational complex waveforms and signal processing applied by high-end Digital Signal Processors (DSP) and Direct Digital Synthesis (DDS) are now widely in use. Also, Active Electronically Scanned Array (AESA) antennas increase signal processing due to necessary beamforming techniques.

Automobiles are increasingly being equipped with radar sensors that support drivers in critical situations, helping to reduce the number of accidents (Figure 1). Radar makes it possible to quickly and precisely measure the radial velocity, range and azimuth angle of multiple objects. For this reason, the automobile industry is increasingly using this technology in advanced driver assistance systems (ADAS). Rohde & Schwarz offers T&M solutions for generating, measuring and analyzing radar signals and components to ensure trouble free operation of these sensors.

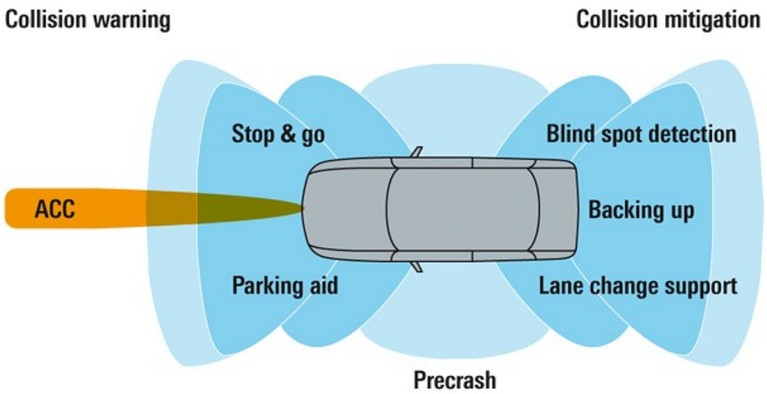

Figure 1. Automotive radar is rapidly expanding to offer greater vehicle safety.

For a system designer, all these new techniques play an important role. Next to the selection of the radar waveform, test and measurement accuracy are critical in the development and launch of a new radar system. New radar designs need to ensure that all hardware components as well as software parts work in the desired manner and under all considered conditions. This creates specific measurement needs and tasks for the measurement equipment. Therefore a technical understanding of waveform design is fundamental.

To reduce design uncertainty, test solutions are required with the performance, precision, and insight to solve these advanced design challenges. Rohde & Schwarz

solutions are at the leading edge of performance, capability, and ease of use to deliver confidence and test integrity of complex radar designs.

This white paper describes different Continuous Wave Radar waveforms in more detail, addresses future waveform trends and the different aspects to Pulse Radar systems.[1] It explains the broad variety of radar and radar waveforms for civil and military applications for successful selection or development of future radar systems.

[1] Along with the application note 1MA127 “Overview of Tests on Radar System and Components” Rohde & Schwarz provides a general overview of different military and commercial radar systems in the white paper 1MA207 “Introduction to Radar System and Component Tests”.

2 Radar Waveforms

In general terms radar enables the measurement of range, radial velocity and echo signal power for all objects in the observation area. Determining these object parameters simultaneously and in multiple target situations is a technical challenge for the design of the radar system, radar waveform and signal processing.

Both in civil and military applications, waveforms with great performance and flexibility in the measurement and resolution of multiple target situations are desired. However, each civil application like automotive applications as Adaptive Cruise Control (ACC), Blind Spot Detection (BSD), Active Pedestrian Safety [4], or military applications such as navigation, surveillance or missile guidance systems satisfy specific needs. Radar covers all needs by a broad variety of system designs using specific carrier frequencies, bandwidths, transmit durations, waveforms, antennas and much more.

Next to range and radial velocity measurement, radar allows determining azimuth and elevation angle. While the latter mainly depends on the antenna design, range and radial velocity measurement including resolution, accuracy and ambiguity depend on the designed waveform and system parameters. The next chapters describe range measurement, radial velocity measurement and simultaneous range and radial velocity measurement using pulse radar and different kinds and combinations of continuous wave radar.

Driven by automotive radar future waveform trends will allow even greater unambiguous measurements of range and radial velocity with high accuracy and shorter observation time. These trends may also contribute to A&D radar systems.

3 Range Measurement

Range is measured using the physical law of signal propagation time τ between transmit and receive signal[2]. This section gives additional information about certain waveforms widely used in radar.

3.1 Pulse Radar

A waveform to measure range is a single pulse which is transmitted, reflected and again received by the radar. Measuring signal propagation time τ of the transmitted single pulse, range R can be determined where c is the speed of light, Equation 3-1.

$$R = \frac{c}{2}\tau$$

Equation 3-1: Range Measurement using Signal propagation time.

Figure 3-1 shows the general functionality of a pulse radar system using a pulse width T_p and a pulse repetition interval T_r.

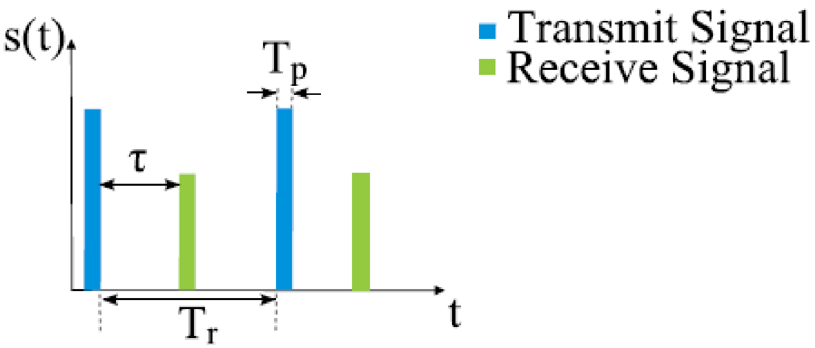

Figure 3-1: Radar Principle.

Radar systems are characterized in terms of resolution, accuracy and ambiguity for each domain measured. Range resolution ΔR is described as the minimum difference in range for which two targets can be separated by the radar. In case of two targets which are closer to each other compared to range resolution these targets cannot be resolved as their radar echo signals overlap, as shown in Figure 3-2.

The two receive echoes P_{r1}, P_{r2} overlap where the radar will either detect the strongest target or detect a mixture of both. The radar echoes P_{r3}, P_{r4} can be resolved as two targets.

[2] Please reference white paper 1MA207 "Introduction to Radar System and Component Tests" for more information on this subject.

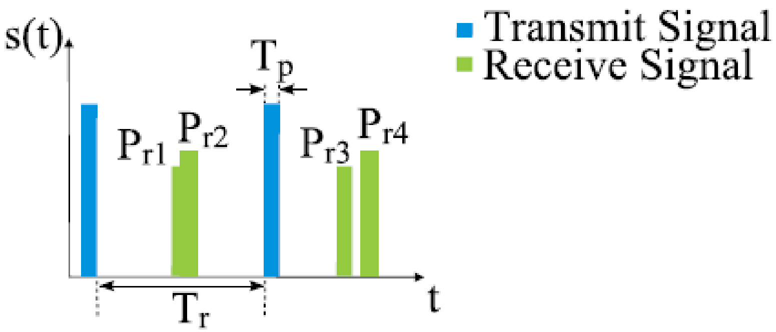

Figure 3-2: Range Resolution.

Range resolution is determined by duration of a single pulse T_p Equation 3-2. Systems with very short pulses have high range resolution which requires large bandwidth.

$$\Delta R = \frac{c}{2} T_p$$

Equation 3-2: Range Resolution.

While range accuracy is determined by the signal to noise ratio of a radar echo signal, unambiguous range R_{max} describes the maximum range that can be detected. In case of equal radar signals transmitted consecutively, echo signals which arrive later than in the corresponding receive period cannot be assigned to the original pulse timing. The maximum unambiguous range of a pulse radar system depends therefore on the pulse repetition interval T_r, Equation 3-3.

$$R_{max} = \frac{c}{2} T_r$$

Equation 3-3: Unambiguous Range

3.2 Pulse Compression Radar

Next to pulse repetition interval, maximum range of a pulse radar depends on the average transmit power. Using a given pulse repetition frequency (PRF) maximum range can be extended by higher transmit power. However, an increased transmit power has higher demand on hardware. Additionally radars transmitting pulses with high power are easier to locate for others. An alternative to power amplification is the extension of pulse duration. This causes on the other hand degradation in range resolution. Using pulse compression technique pulse duration (and therefore average pulse power and maximum range) can be extended by keeping the advantages of short pulses and high resolution [1].

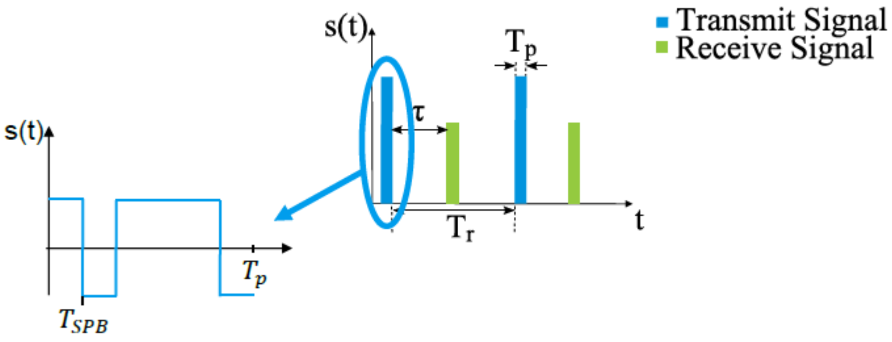

Fig. 3-3: Pulse compression in a single pulse.

Therefore a signal with the desired transmit duration is generated by modulation in frequency or phase (high time bandwidth product), Figure 3-3. An automatic compression of the radar echo signal is performed by a Matched Filter (MF). In case of e.g. a linear frequency modulated chirp this MF is designed to let low frequencies pass more slowly compared to high frequencies. This causes positive interference at the filter output and an increased Signal to Noise Ratio (SNR). Using pulse compression maximum range can be extended by increasing transmit duration and keeping range resolution. Additionally pulse compression radar offers better immunity against noise jamming, because SNR is increased by the MF.

Comparison of Pulse Radar and Pulse Compression Radar		
	Pulse	Pulse Compression
Range Resolution	$\Delta R = \frac{c}{2} T_p$	$\Delta R = \frac{c}{2} T_{SPB}$
Unambiguous Range	$R_{max} = \frac{c}{2} T_r$	

Table 3-1: Pulse and pulse compression radar.

Adverse effects are larger blind range due to long pulses, since the radar receiver is switched off during transmission and radar echoes from close range targets cannot be detected. Also range/Doppler sildelobes accompanying the compressed signal at the MF output can mask echoes with low power or cause ambiguities. The distortion of the radar echo pulse in time delay and Doppler frequency is described by the ambiguity function, which depends on the properties of the pulse and the matched filter.

4 Radial Velocity Measurement

Radial velocity of an object detected is measured using Doppler frequency[3]. This section describes Continuous Wave radar and Pulse Doppler radar in more detail and notes resolution and possible ambiguity of the measurement.

4.1 Continuous Wave Radar (CW)

By using Continuous Wave radar (CW-Radar) Doppler frequency shift can be measured instantly by down conversion and Fourier transform [6]. As a monofrequent CW is transmitted to a moving object, the receive signal is shifted by the Doppler frequency f_D proportional to the relative radial velocity of the object, Figure 4-1.

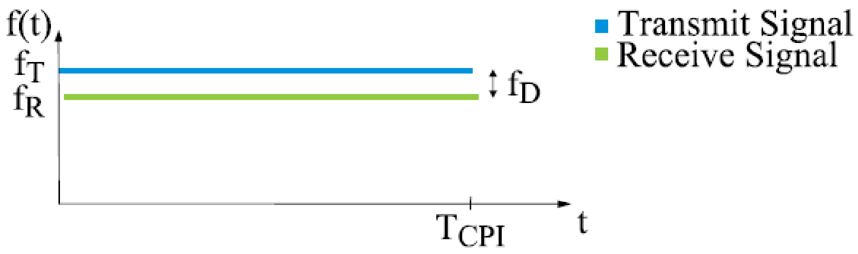

Figure 4-1: Monofrequent Continuous Wave radar.

The Doppler frequency f_d is measured and determines the relative radial velocity v_r as a function of wavelength λ described in Equation 4-1.

$$f_D = -\frac{2}{\lambda} v_r$$

Equation 4-1: Doppler frequency determines relative radial velocity.

The velocity resolution describes the smallest difference between two distinguishable measurement values and depends on the measurement duration T_{CPI}. In CW radar measurement duration can be unlimited, which results in a limitless resolution in principle. In case of limited measurement duration T_{CPI} the velocity resolution is determined by Equation 4-2.

$$\Delta v_r = \frac{\lambda}{2} \frac{1}{T_{CPI}}$$

Equation 4-2: Velocity resolution.

[3] Refer to white paper 1MA207 "Introduction to Radar System and Component Tests" to learn more.

As CW radar transmits and receives all the time there is no information about range. The main advantage of CW however is to measure Doppler frequency without ambiguities or blind speeds (see Pulse Doppler radar), because the maximum representable Doppler frequency is unlimited in CW radar in principle.

In military applications CW radar is often used for target illumination. Due to constant transmission with low power, CW radar is harder to detect as compared to Pulse radar and hence often classified as Low Probability of Intercept (LPI) radar.

4.2 Pulse-Doppler Radar

Radial velocity can also be measured by transmitting consecutive pulses [Lud08]. Therefore a coherent transmitter and receiver are used where phase variation from pulse-to-pulse measurements holds the Doppler frequency. Range is still measured by signal propagation time. To measure both range and radial velocity pulse the repetition frequency f_{PRF} is an important parameter. Pulse-Doppler radar are thus mainly characterized by its pulse repetition frequency f_{PRF}. It is distinguished between Low PRF (LPRF), Medium PRF (MPRF) and High PRF (HPRF) Radars.

As shown in Equation 3-3, unambiguous range depends on the pulse repetition interval and thus pulse repetition frequency. LPRF radars are used for long range due to their great unambiguous range and HPRF radars for short range surveillance due to ambiguities.

The unambiguous radial velocity is also determined by the pulse repetition interval T_r. Doppler frequency is reconstructed from consecutive pulses, therefore sampling frequency has to be at least twice the maximum Doppler frequency $f_{D,max}$. Hence $f_{PRF} > 2f_{D,max}$ which leads to Equation 4-3.

$$v_r \epsilon \left[-\frac{\lambda}{4}\frac{1}{T_r}, \dots, \frac{\lambda}{4}\frac{1}{T_r}\right]$$

Equation 4-3: Unambiguous radial velocity.

While LPRF radar has a small unambiguous radial velocity interval and great unambiguous range interval, HPRF radars on the other hand have great unambiguous radial velocity interval and small range unambiguity. This contradiction between range and radial velocity ambiguities is called the Doppler Dilemma. To solve this dilemma, pulse-Doppler radars usually vary their pulse repetition interval during operation depending on the situation addressed.

Pulse-Doppler Radar is used to measure range and radial velocity. However, depending on the pulse width both values can be measured either simultaneously or not. In case Doppler can be measured, Doppler frequency has to be so high that it can be reconstructed from a single echo pulse; hence pulse width has to be long. In case of very short pulses and low Doppler frequency, consecutive radar echo signals have to be received. Depending on the application a simultaneous measurement of both object values is desired which is one of many reasons for the development of more advanced waveforms.

5 Simultaneous Range and Radial Velocity Measurement

A specific task of radar is to measure range and radial velocity of a single object simultaneously and within a single measurement cycle. Range is measured by transmitting and receiving a single pulse. Radial velocity is measured either by continuous wave or Pulse-Doppler radar. However, Pulse-Doppler radar performs several transmit and receive cycles to measure Doppler frequency by phase variation of the radar echo signals.

To measure radial velocity within a single measurement cycle, waveforms such as Linear Frequency Modulated Continuous Wave (LFMCW), Frequency Shift Keying (FSK), Multiple Frequency Shift Keying (MFSK) or Chirp Sequence (CS) are used in radar. Future trends where CS waveforms are combined with other waveforms are addressed shortly. Each waveform has specific features and shows the development and importance of radar waveform within the past years.

5.1 Linear Frequency Modulated Continuous Wave Radar (LFMCW)

Using Linear Frequency Modulated Continuous Wave (LFMCW) Radar [6] a frequency modulated signal (Chirp) with a specific bandwidth f_{sweep} is transmitted within T_{CPI}, Figure 5-1.

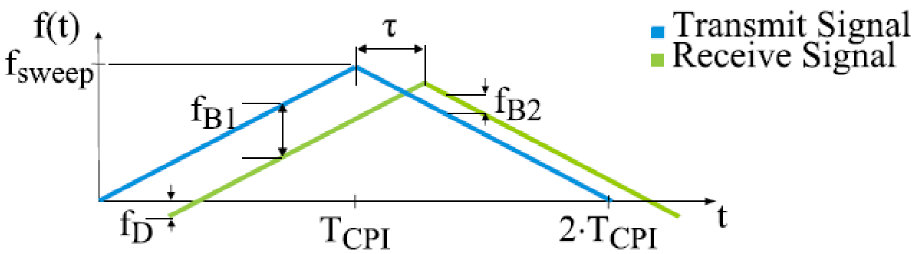

Figure 5-1: LFMCW radar with upchirp and downchirp.

Both parameters, range R and radial velocity v_r, contribute to the measured frequency shift, called beat frequency f_B. Thus, the beat frequency consists of a Doppler frequency f_D and a frequency shift due to signal propagation time f_τ, Equation 5-1.

$$f_B = f_D - f_\tau$$

Equation 5-1: Beat frequency.

In Figure 5-1 two chirps with different slopes are depicted. A reflected radar echo is received and holds propagation time and Doppler frequency shift. For a static target, signal propagation time f_τ is determined by applying the intercept theorem (see Figure 5-2) to the first transmit signal with $f_B = f_{B1}$depicted in Figure 5-1.

Where $\frac{\tau}{T_{CPI}} = \frac{f_{B1}}{f_{sweep}}$ and inserting $\tau = \frac{2R}{c}$ determines frequency shift due signal propagation $f_\tau = f_{B1} \ = \frac{2}{c}\frac{f_{sweep}}{T_{CPI}} R$ in case of a static target.

In case of a moving target Doppler frequency f_B also contributes to beat frequency f_B. Inserting f_τ and f_D to Equation 5-1 solves to Equation 5-2.

$$f_B = -\frac{2}{\lambda} v_r \ -\frac{2}{c}\frac{f_{sweep}}{T_{CPI}} R$$

Equation 5-2: Beat frequency determined by radial velocity and range.

In order to solve Equation 5-2 unambiguously v_r to and R two beat frequency measurements are necessary as shown in Figure 5-1 where beat frequencies are denoted as f_{B1}, f_{B2}. Two equations with two unknowns can be solved unambiguously for $v_r$and R in case of a single target, see Figure 5-2.

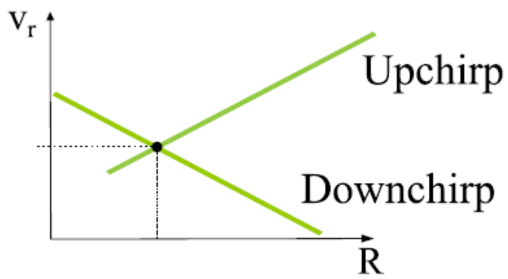

Figure 5-2: Interception between Up- and Downchirp Radar Echo Signals.

For multi target situations range and radial velocity cannot be resolved unambiguously by two consecutive chirps measuring different beat frequencies. This causes ghost targets which can be resolved by additional Chirps with different slopes transmitted in LFMCW radar.

5.2 Frequency Shift Keying Radar (FSK)

Frequency Shift Keying (FSK) radar [3] systems are based on CW radar but transmit two or even more in time alternating unmodulated signals at different carrier frequencies with a frequency difference f_{Shift}, Figure 5-3.

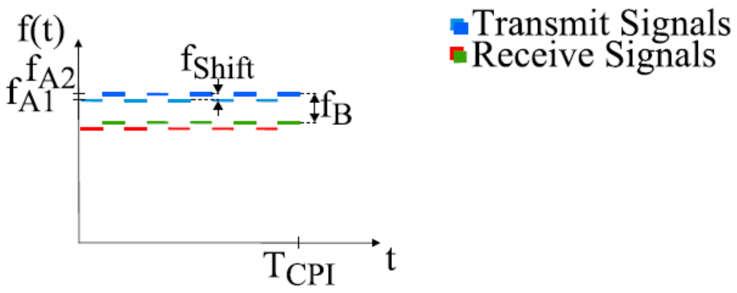

Figure 5-3: Frequency Shift Keying.

Two transmit signals cause two radar echo signals each shifted by a certain Doppler frequency f_{D1}, f_{D2}. As the carrier frequencies f_{A1} and $f_{A2}$are high compared to the Doppler frequencies both frequencies are nearly equal and represent the beat frequency f_B by which radial velocity is determined, Equation 5-3.

$$f_B = f_{D1} \approx f_{D2} = -\frac{2}{\lambda} v_r$$

Equation 5-3.

This beat frequency does not have any propagation time influence thus no range information. Nevertheless range can be determined using phase information between the two received radar echo signals carrying $\Delta\varphi = \varphi_{A1} - \varphi_{A2}$, Equation 5-4.

$$R = \frac{C}{4\pi f_{Shift}} \Delta\varphi$$

Equation 5-4.

Phase measurement is unambiguous within $[0; \dots; 2\pi]$. This results in an unambiguous range, which depends only on f_{Shift}, Equation 5-5.

$$R_{max} = \frac{C}{2\, f_{Shift}}$$

Equation 5-5: Unambiguous range.

FSK radar is able to resolve in Doppler frequency and measure range. There is no range resolution, which targets with the same radial velocity but in different ranges (e.g. static targets) to appear at the same Doppler frequency and cannot be resolved. Depending on the shift frequency between the transmit signals an extremely long unambiguous range is possible.

5.3 Multiple Frequency Shift Keying Radar (MFSK)

In many radar applications simultaneous range and radial velocity is of importance. So far LFMCW and FSK are mentioned to fulfill these requirements. However, LFMCW needs multiple measurement cycles and mathematical solution algorithms to solve ambiguities while FSK lacks from range resolution. Therefore LFMCW and FSK were combined to a single waveform called Multiple Frequency Shift Keying (MFSK) introduced by Meinecke [1]. MFSK was specifically developed to serve radar development for automotive applications and consists out of two or more transmit frequencies $f_{A1}$and $f_{A2}$with a frequency shift f_{Shift}in an intertwined way and with a certain bandwidth f_{sweep} and duration T_{CPI}, Figure 5-4.

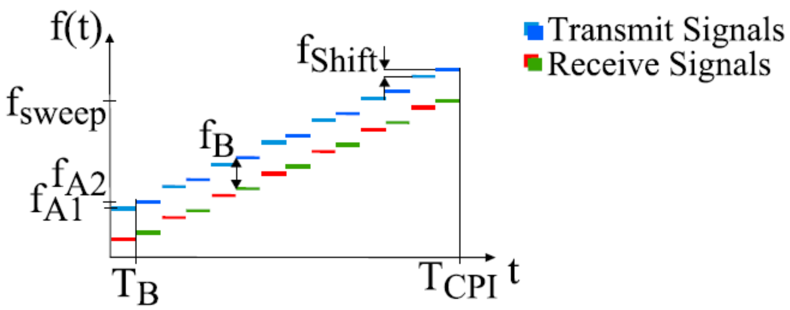

Fig. 5-4: Multiple Frequency Shift Keying.

Each of the two radar echo signals cause Doppler frequency shift and time delay in the receive signal. Both signals are down converted by its instantaneous carrier frequency and Fourier transformed. Like in LFMCW, beat frequency f_B holds range and radial velocity. As in FSK, phase difference between the intertwined signals at the position of the beat frequency can be measured and also holds range and radial velocity. Both values are used to solve Equation 5-6 and Equation 5-7 unambiguously in multiple target situations and in a single measurement cycle to R and v_r.

$$f_B = f_D - f_\tau$$

$$f_B = -\frac{2}{\lambda}v_r - \frac{2f_{sweep}}{cT_{CPI}}R$$

Equation 5-6: Beat Frequency.

$$\Delta\varphi = \frac{4\pi}{\lambda f_a}vr - \frac{4f_{Shift}}{c}R$$

Equation 5-7: Phase Difference between two receive signals.

As in pulse radar range resolution depends on the bandwidth f_{sweep}. Radial velocity resolution is determined by coherent processing interval T_{CPI} as in CW radar.

5.4 Chirp Sequence Radar (CS)

MFSK waveforms use frequency and phase measurements to determine range and radial velocity unambiguously. Estimation of range and radial velocity is less accurate of radar echoes with low SNR when using MFSK radar waveform compared to LFMCW, as phase measurements are involved. One solution is to transmit MFSK chirps with a positive slope and negative slope, solve ambiguities by phase and frequency measurements of the first chirp and correct these results by combining the first beat frequency measurement and a second beat frequency measurement using the radar echo signal of the downchirp alike LFMCW in multi target situations.

Another solution is a LFMCW waveform with very fast chirps [5]. This waveform is called Chirp Sequence (CS) and consists out of several very short LFMCW chirps each with a duration of T_{Chirp}transmitted in a block of length T_{CPI}, Figure 5-5. As a single chirp is very short the beat frequency f_B is mainly influenced by signal propagation time and Doppler frequency shift f_D can be neglected.

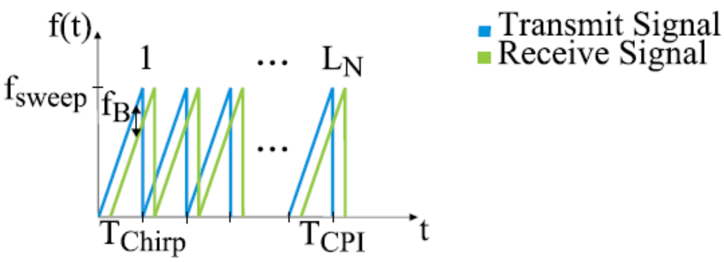

Figure 5-5: Chirp Sequence.

The signal processing follows the straight approach with an initial down conversion by instantaneous carrier frequency and Fourier transformation of each single chirp. The beat frequency is mainly determined by range. Thus under assumption of a radial velocity $v_r = 0\frac{m}{s}$ target range R is calculated as in LFMCW using $f_B = \frac{2}{c}\frac{f_{sweep}}{T_{Chirp}} R$.

The radial velocity is not measured during a single chirp but instead over the block on consecutive chirps with the duration of T_{CPI}. A second Fourier transformation is performed along the time axis, which holds Doppler frequency shift f_D. After obtaining Doppler frequency shift the true radial velocity is given whereby target range is corrected using Equation 5-2.

Radial velocity resolution depends on the coherent processing interval T_{CPI} as noted in Equation 4-2. The unambiguity of the radial velocity due to sampling is in the interval $v_r \in \left[-\frac{\lambda}{4}\frac{1}{T_{Chirp}}\right]$, see also Equation 4-3.

5.5 Future waveform trends

Until now the growing demand for radar to cover techniques such as simultaneous, high accuracy, multi target measurement as well as increased unambiguous range and radial velocity has been achieved with a combination of different waveforms.

One example is the success of the MFSK waveform where FSK and LFMCW have been used to determine range and radial velocity within a single measurement cycle. MFSK makes use of additional phase differences to solve the shortcomings of LFMCW (which have been solved initially due to several consecutive chirps with different slopes) and to determine both object parameters simultaneously. Some radar sensors apply MFSK with an ascending and descending slope, solve the ambiguities due to phase and frequency measurements of the MFSK signal and increase the measurement accuracy by combining the frequency measurements of consecutive chirps like in a pure LFMCW signal.

Other radar sensors use a CS waveform to determine range and radial velocity with high accuracy and resolution in a single measurement cycle as only frequency measurements are involved. However, high resolution lacks from ambiguity. In order to increase the unambiguous range, CS can be combined with other signals. To increase the unambiguous radial velocity interval, different length of coherent processing intervals T_{CPI} can be used. Transmitting for example three different sequences with a different T_{CPI} each can extend the maximum radial velocity by multiples.

Also waveforms used in communication (e.g. OFDM used in LTE) could be used in radar. The advantage of these signals is that both communication and radar needs will be served with similar hardware. Just the signal processing is different. Applications in Aerospace and Defense as well as commercial applications would benefit from these kinds of waveforms due to cost / volume effects.

These examples give an idea of what has been developed and could be developed by combining different radar waveforms in some kind of "hybrid radar waveforms" or even use waveforms which are nowadays applied in communication systems.

6 The Agony of Choice

Frequency Modulated Continuous Wave radars and Pulse Doppler radars have to adhere to the same physical laws. But next to the opportunity to measure range and radial velocity simultaneously in a single measurement cycle continuous, these waveforms are of interest due to their low radiated power and potentially reduced hardware complexity. Additionally, the required bandwidth of Pulse Doppler radar is inversely proportional to its pulse width; whereby LFMCW radar needs much smaller analog bandwidth in comparison. These are some reasons why continuous wave radars are often used in portable or mobile/semi mobile military applications with maximum ranges of up to dozens of km or in automotive radar applications where fast, accurate simultaneous and unambiguous measurement in multiple target situations is of interest.

Pulse Doppler radars using moving target indicator (MTI) filter out slowly moving targets to reduce false alarm caused by background clutter like trees or bushes. These objects can appear with a certain Doppler frequency when moving in the wind. However, applying such a threshold (blind speed) objects moving tangentially or below the threshold are not detected and can move through the entire surveillance area without being detected. LFMCW does not suffer from blind range or blind speed measurement.

On the other hand Pulse Doppler radar can reach extremely long ranges due to its clutter suppression capabilities, switching between TX/RX and thus possibility of high power transmission using magnetrons. In LFMCW radar TX and RX have to be isolated very well while TX is transmitting a power of some watts using solid state amplifiers. This allows on the other hand more flexibility for power supply, mobility or mounting locations. Also humans close to the antenna are at less risk. However, for a fair comparison the energy transmitted should be taken into account.

To cover close ranges switching time from TX to RX and short pulses are of importance, while latter require large bandwidth. LFMCW radar does not have a minimum detection range as the receiver is always on. The bandwidth just determines the range resolution and affects the receiver noise energy. However, using less bandwidth, results in less receiver noise energy that a target needs to exceed for detection.

Depending on the application Frequency Modulated Continuous Wave radars have advantages over Pulse-Doppler radars. Most pulsed Doppler radars used for wide area surveillance are derivatives of legacy military radar. On the other hand a new generation of portable, mobile and semi mobile LFMCW radar technology evolves for wide area surveillance, site security and force protection. These radars are instant on, do not require a standby period, are able to detect, track and even classify a large variety of different target types by measuring their speed, angles, range and apply classification algorithms to determine their object type within the radar echo signal pattern. There are a lot of differences and commonalities of mature Pulse Doppler radar and LFMCW systems, but the potential of latter for future development only just begun.

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
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