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Overview

This report develops introductory information on millimeter wave (MMW) radar for automotive longitudinal control. It addresses the fundamental capabilities and limitations of millimeter waves for ranging and contrasts their operation with that of conventional microwave radar. The report can serve as a primer or tutorial for researchers who are working in the field of automotive control and who may apply radar for headway and lane control studies during platooning operations. The report analyzes pulsed and FMCW radar configurations, and provides detailed treatment of FMCW radar operating at MMW frequency, its advantages and pitfalls as they relate to range and velocity measurements.

Some of the material of this report can be found in texts and periodical publications, while some of the material is not dealt with in much detail in the general literature. The report has seven sections in addition to the introductory section. Section 2 discusses the effects of the atmosphere on MMW. Section 3 discusses MMIC technology and its effect on MMW radar development for the control of cars. Section 4 discusses the characteristics of millimeter waves. Section 5 discusses the transmitting power requirements for automotive radar. Section 6 discusses radar waveforms . Section 7 discusses the key performance factors for the sawtooth waveform and the effects of motion on range accuracy. Section 8 discusses signal processing requirements for FMCW MMW radar. References are provided for further study.

1. Introduction

There is a surprisingly wide interest in the application of MMW technology to automotive use. TRW, Hughes, and Alpha in the U.S., and Thompson CSF, Siemens, Telefunken, Daimler Benz, Philips, and Marconi in the European community have active programs in automotive millimeter waves. The Japanese led by Toyota also have an active, aggressive millimeter wave program.

The automotive MMW possibilities have been greatly aided by recent large-scale government and industry investments in microwave integrated circuit producibility programs. Recent advances in Microwave Monolithic Integrated Circuit (MMIC) technology and flat or active MMW antennas stimulated the development of many different applications. They range from semiautomatic headway monitoring and control to collision warning and avoidance, to traffic management. The most promising short-term application in this area is to provide contactless measurement of range and closing velocity to a vehicle in front for maintaining a safe following distance.and use this information as input to semiautomatic and automatic longitudinal control, collision warning and avoidance, and automotive telecommunications systems, with the goal of maintaining a minimum safe following distance and improving safety of travel. Figure 1 is a block diagram of a MMW automotive radar. The radar operates by transmitting a signal with a center frequency f_0 linearly swept over a bandwidth B during a time T. The received signal is used as an input to an intelligent adaptive speed control ysstem which would adapt the speed of the car, whenever traffic induced changes in speed require to keep the vehicle at a saft distance from the vehicle in front of it.

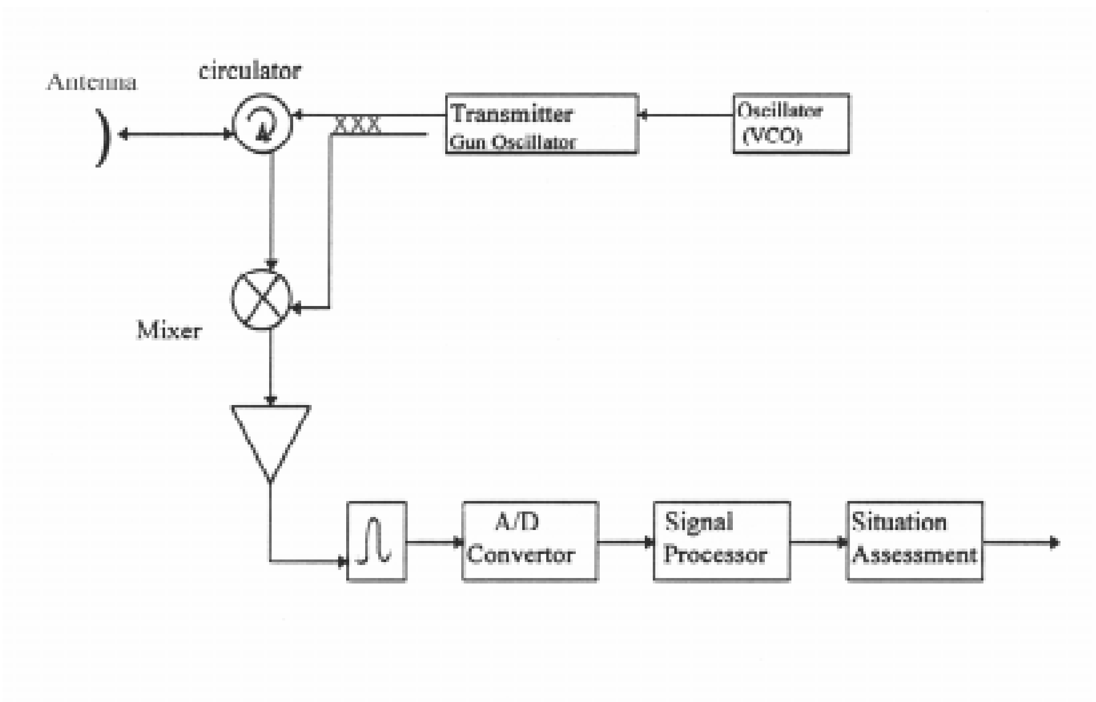

Figure 1 Millimeter Wave Automotive Radar

Table 1 is a sample listing by automotive application category and current active developers. The list is by no means exhaustive or inclusive.

Table 1. Emerging Automotive MMW Applications

Category	Frequency Band	Partial List of Developers
Semiautomatic Headway Control	MMW	GM, Toyota, Daimler Benz, Telefunken, Siemens, Thompson CST, Philips, Delco Electronics, Hughes, Toyota, Alpha
Traffic Management	MMW	FHWA, GM, TRW, EMS
IVHS	Light	Fiat, US DOT, Siemens, Daimler Benz
Collision Warning and Avoidance	MMW	Hughes, TRW, Alpha, Philips, Marconi
Automotive Telecommunications	MMW	

Like microwave radar, millimeter wave radar is an all weather radar. It can measure simultaneously the range, velocity, reflectivity, azimuth, and elevation and has several advantages over the microwave radar, namely: the system is relatively simple, of small size, offers high resolution, is easier to operate at short ranges, provides data over wide bandwidths, and is relatively inexpensive.

The millimeter wave region generally is considered to cover the frequency range of 30 to 300 GHz corresponding to wavelengths 10 mm to 1 mm respectively.

In 1979 the World Administrative Radio Conference [1] (WARC-1) established ten radar bands above 40 GHz, making frequencies above the 35GHz band available for radar for the first time.

The IEEE established letter bands [2] for radar and designated the 33-36 GHz band as the Ka band, the 46 to 56 GHz region as V band and 56 to 110 GHz as the W band. The remaining submillimeter regions have not been given special letter designations. Table 2 shows specific frequency band designation in common usage by various elements of the technical community.

Table 2. Microwave and Radar Usage

GHz: 100, 70, 50, 40, 30, 20

United States Usage	United Kingdom Usage	Official Joint Chiefs of Staff Band Designation
W-Band 56-100 GHz	V-Band 50-75GHz	M 60-100GHz
V-Band 46-56	O-Band 40-70	L 40-60GHz
Q-Band 36-46	Q-Band 27-40	K 20-40GHz
K_a 33-36		

For allocation purposes the spectrum was divided into regions of high attenuation (absorption) and lower attenuation (windows), as shown in Table 3.

Table 3. Atmospheric Window and Absorption Band Limits [3]

Window	Absorption Band	Limits GHz
Window 1		39.5–51.4
	Attenuation 1	51.4–66
Window 2		66–105
	Attenuation 2	105–134
Window 3		134–170
	Attenuation 3	170–190
Window 4		190–275

The use of MMW radar for detection and ranging at MMW frequencies is determined largely by the presence of so-called windows (minimal absorption regions). The regions of minimal absorption are located at 35GHz, 70GHz, 95GHz, 140GHz, and 220 GHz. Atmospheric attenuation, even for MMW operating in the atmospheric windows, is so high that long ranges are impractical. The reduced operating range of MMW radar has its advantages. The terrestrial atmospheric attenuation, which reduces the MMW radiation, also reduces the possibility of interference and increases immunity to unwanted detection of transmissions from neighboring radars. The frequencies in the absorption bands are not suitable for long range radar. However, they are ideally suited for special applications; for example, short range automotive radar and short range communication.

2. Propagation Effects

Propagation effects are of major concern to radar designers in the MMW region. Propagation characteristics can affect the detection, ranging and tracking functions of MMW radar. Principal propagation effects include atmospheric absorption; attenuation due to rainfall/snow/fog, etc.; atmospheric backscatter; phase variations; polarization effects; angle of arrival variations; ducting; and surface phenomena. These must be considered in the design of MMW radars. [3] The use of MMW radar is determined largely by the presence of the atmospheric windows in the atmosphere defined as a minimum in the clear air attenuation coefficient. A characteristic of the windows is the fact that the window minima increase with frequency. Therefore clear air attenuation needs to be considered in choosing the operating frequency of the radar. Table 4 gives the attenuation coefficients for clear air in radar windows at sea level. Table 4 shows that these windows are not clear.

Table 4. Attenuation Coefficients for Clear Air in Radar Windows at Sea Level

Radar Band	**Nominal Frequency (GHz)**	**Attenuation Coefficient k_a (dB/km)**
L	1.3	0.012
S	3.	0.015
C	5.5	0.017
X	10	0.024
Ku	15	0.055
K	22	0.3
Ka	35	0.14
V	60	35.0
W	95	0.8
No designation	140	1.0
No designation	240	15.0

As a rule of thumb if a radar encounters 6dB or more of two-way atmospheric attenuation, then that radar would be more economically designed in the next lower window. Rain and wet snow produce the most serious attenuation effects on MMW, while dry snow, clouds and fog have a much lesser effect. Table 5A lists MMW frequency attenuation values as a function of selected rainfall rates.

Higher frequencies are much more affected by rain than by the clear air. Using the criterion of 6 dB allowable attenuation, the economical ranges with 3mm/hr rain are as shown in the last column in Table 5B. It is of course possible to overcome attenuations greater than 6dB with more power and sensitivity, but unless the application already requires the smallest possible antenna it will prove more economical to use the next lower frequency band.

Table 5A. MMW Frequency Attenuation Values as a Function of Selected Rainfall Rates [25]

$\alpha = AR^B$				
	f = 10GHz λ = 3.2cm A = 0.00919 B = 1.16	f = 35Ghz λ = 0.86 A = 0.273 B = 0.985	f = 70Ghz λ = 0.43cm A = 0.634 B = 0.868	f = 95Ghz λ = 0.32cm A = 1.6 B = 0.64
R mm/hr	α(dB/km)			
5	0.0509	1.33	2.56	4.48
10	0.133	2.64	4.68	5.984
15	0.213	3.93	6.65	9.05
20	0.297	5.22	8.54	10.88
25	0.385	6.50	10.36	12.55
30	0.475	7.78	12.14	14.11
35	0.568	9.06	13.88	15.57
40	0.663	10.33	15.18	16.96
45	0.760	11.60	17.27	18.29
50	0.859	12.87	18.91	19.56
60	1.062	15.40	22.16	21.99
70	1.270	17.93	25.32	24.17
75	1.375	19.19	26.89	25.36
100	1.972	25.48	34.52	30.49

α= attenuation in dB/km, R = rainfall rate in mm/hr. A&B are parameters.

Table 5B. Attenuation Coefficients in 3mm/hr Rain

Radar Band	**Nominal Frequency GHz**	**Two-Way Attenuation Coefficient (dB/km)**		**Range (km) for 6dB Attenuation**
		Rain	**Total**	
L	1.3	0.001	0.013	
S	3	0.004	0.019	
C	5.5	0.023	0.04	250
X	10	0.11	0.13	45
K_u	15	0.25	0.3	20
K	22	0.7	1.0	6
K_a	35	1.7	1.8	3
V	60	4.0	39	0.15
W	95	6.0	6.8	0.9
	140	7.0	8.0	0.7

Clouds and Fog

In practice, signal attenuation due to fog is usually modest compared with the attenuation rates for rain. The smaller particles suspended as clouds or fog have a relatively small effect on MMW radar propagation. For a density of condensed water of $0.3 g/m^2$, the attenuation coefficients will be about half those for rain at 3mm/hr. Dry snow has even less attenuation, except at the highest precipitation rates. However, that attenuation by wet snow at shorter wavelengths of the MMW region could produce attenuation comparable to that produced by rainfall of equivalent precipitation rate. Thus, at least for frequencies below about 100 GHz, the attenuation caused by fog, snow, and hail can generally be expected to be significantly less than the rainfall attenuation for most regions of the earth. Under these circumstances design considerations can be based on rainfall statistics alone.

Dust and Smoke

Because of the small size of the suspended particles that make up dust and smoke this type of obscurant will have a negligible effect on MMW radar operation.

Total Attenuation on Paths Through the Atmosphere

In addition to the propagation factors already discussed, one must account for the attenuation due to free space or spreading loss as well as the attenuation due to other processes along the path such as reflection, refraction, cross polarization, and antenna misalignment. The total attenuation on paths through the atmosphere is then found by adding the attenuation due to these factors to the attenuation due to precipitation and/or fog and the attenuation due to oxygen and water vapor absorption.

3. Millimeter Wave Technology

Millimeter wave technology strongly drives millimeter wave radar system development. This technology has been reported extensively in many publications [3,4,5,6], journal articles, conference papers, and reports. The automotive millimeter wave possibilities have been greatly aided by recent large scale government and industry investment in microwave integrated circuit producibility in such programs as MMIC, USAF MANTECH, MILSTAR, and others.

The MMIC program has developed monolithic chips, such as voltage controlled oscillators (VCOs), driver amplifiers, power amplifiers, doublers, mixers, switches, P-HEMT amplifiers and P-HEMT monolithic transceivers.

The new devices and subsystems are low voltage, of high resolution, reproducible, lightweight, small sized, low in cost, and provide sufficient output power to drive the output of a transmitter/receiver module at 94GHz with impressive performance characteristics in noise figure, power gain, and power output up to 100 GHz. For example, improvements in processing technology have resulted in noise figures as low as 1.4 dB and power output in excess of 50 mW both at 94GHz (W band). The new technology also made possible the fabrication of coherent radars up to 95GHz capable of generating the kinds of sophisticated waveforms (such as FMCW coherent moving target indicator (MTI) for radar) previously available only at microwave frequencies.

A complete W band transceiver [11] implemented on a single MMIC chip was produced by TRW and a complete radar system has been tested on the W band single chip front end. The 6.9x3.6 mm^2 monolithic chip was fabricated using 0.1 micron pseudomorphic InGaAs/AlGaAs/GaAs HEMT process technology. The transmitter output power is more than 10mW for frequencies between 90-94GHz and maximum tuning bandwidth is 500 MHz for the VCO. The receiver channel has 6dB conversion gain when the output transmitting power is 10mW.

The MMIC chip was integrated with two DC voltage regulators and a pair of transmit receive lens antennas for detecting both stationary and moving targets. A PC based signal processor was used to control the FMCW waveform and to do real time range and range rate measurements from the target return signal.

The success of the MMIC programs enabled other manufacturers to develop transmitter/receiver chip sets at 77GHz [12] and other product lines of MMW devices and monolithic integrated circuits centered at about 35, 60, 76, 77, 80, 94, and 95 GHz.

The MMW technologies already developed can find a unique opportunity in longitudinal control, range measurements, and collision avoidance production programs with projected costs fully compliant with automotive program requirements.

The most promising short-term application of this technology in this area is the headway monitoring radar, which can be used for longitudinal control during freeway platooning operations, to keep the car at a safe distance away from the vehicle in front of it. It is now possible to build such systems at very low costs, compatible with automotive requirements, and their power levels will enable them to succeed where previous simpler systems for automotive radar were unsuccessful.

The use of radar systems in cars is not new. [26, 27, 28, 29] Much of the pioneering work was done in the 1970s. However, previous attempts to introduce affordable radar into motor vehicles failed to reach realization and remains to be reduced to affordable and practical realization. The challenge is to develop a practical low cost, small size radar sensor, at high bandwidths for efficient and robust execution of automotive headway and lane control during normal highway operation, that can satisfy the requirements of automatic and semiautomatic navigation and provide emergency alerting mechanisms.

The most promising frequencies for MMW radar appear to lie in the 76-77GHz band and the 94-95GHz band (W band). In Europe the frequency band for private use has been allocated and firmly established in the 76-77GHz band. The band 76 to 81GHz, which is relatively new to the U.S. MMW community, provides a viable alternative to the potentially crowded 95GHz band. This may also become the standard in the U.S. and Japan, although some radar manufacturers (TRW and others) are also considering 60, 94, and even 140GHz.

The practical difference between operations at 94GHz and 77GHz is small and the exact frequency is easily changed. It involves only a scaling of the component sizes at any time prior to the final tooling for mass production. In the U.S. the 94GHz frequency is more mature because it was the preferred frequency for some military applications.

A reduction in frequency slightly reduces production costs at a marginal degradation in the tradeoff between size and resolution, particularly for the antenna. The short range operating distance of 100 to 300 meters envisioned for current MMW radar systems for automotive applications makes MMW radar with an average output of 10mW at W band (using solid state MMW RF sources) most acceptable for longitudinal control.

4. Characteristics of Millimeter Wave Radar

Millimeter waves offer several advantages over microwaves for radar applications.

1. A smaller antenna diameter is required for the same antenna gain/bandwidth. The antenna diameter required at MMW frequencies is smaller than the diameter required at lower microwave frequencies. This is probably the most important advantage of millimeter wave systems over microwave systems. For a given physical antenna size, the beamwidth is smaller and the gain is higher than at microwave frequencies used for microwave radar. This characteristic is important in applications where the size and weight of the hardware are constrained such as for automotive range finding sensors for longitudinal control. Comparison of X band (9GHz) and W band (95GHz) frequencies shows that the antenna diameter required at the latter millimeter wave frequency is less than the diameter required at the lower microwave frequency by a factor of 10.

2. Increased angular resolution for the same antenna diameter. This results from the smaller antenna beamwidth. A narrow beamwidth is of paramount importance since it directly provides the competing radar return from the "clutter patch" around the target. The beamwidth of the diffraction limited antenna is given by:

$$\theta = \frac{k\lambda}{D} \text{ (radians)} \qquad (1)$$

where θ is the half power beamwidth in the plane corresponding to dimension D, which for a circular aperture would be the diameter, and λ is the wavelength in the same units. The constant k may be in the range from 0.9 to 1.4 depending on the amplitude taper across the aperture, which frequently is chosen to reduce sidelobe levels to a desired value. A typical empirical rule of thumb equation is:

$$\theta = \frac{65\lambda}{D} \text{ (degrees)} \tag{2}$$

For example, a circular aperture antenna having a diameter of 5.9 inches has a half power beamwidth of 5.4° at a frequency of 24.125GHz but has a beamwidth of 1.4° at a frequency of 94GHz. Values calculated from equation (2) are shown in Table 6.

Table 6. Antenna Beamwidth, $\theta = \frac{65\lambda}{D}$ (degrees)

Antenna Diameter (Inches)	**Beamwidths (Degrees)**			
	10GHz	35GHz	94GHz	140GHz
4.0	19.2	5.5	2.00	1.37
20.0	3.84	1.1	0.4	0.27
24.0	3.2	0.9	0.34	0.23
30.0	2.56	0.73	0.27	0.18

Beamwidth Degrees	**Antenna Diameters (Inches)**			
	10GHz	35GHz	94GHz	140GHz
0.25	--	87.7	32.67	21.9
0.5	153.5	43.86	16.34	10.96
1.5	51.2	14.6	5.44	3.67
6.0	12.8	3.66	1.36	0.9

3. Increased bandwidth availability for radar target signature processing.

4. Increased range resolution. The range resolution of any radar is proportional to the bandwidth over which it transmits. On a percentage basis a given quantity of frequency coverage corresponds to a much greater bandwidth at MMW than at microwaves.

One percent bandwidth at 100GHz is 1GHz. This exceptionally wide bandwidth permits increased range resolution of MMW radars. A typical advantage is a factor of 10 or more compared to microwave radar. One of the constraints suffered by earlier automotive radar systems was that narrow frequency allocations within which they had to work inevitably limited their range resolution.

5. Increased Doppler sensitivity at millimeter wavelengths. The amount of frequency shift is given by:

$$f_d = \frac{2V_r \cos\gamma}{\lambda} = \frac{2V_r f \cos\gamma}{c} \qquad (3)$$

where f is the operating frequency, V is the target velocity, γ is the angle between the target heading and the line of sight of the radar, and c is the velocity of propagation.

Doppler frequency shift is a function of the carrier center frequency, which is beneficial in some MMW radar applications. There is a rule of thumb that 1 mile per hour produces approximately 300Hz Doppler at 100GHz; this is easy to scale in speed or carrier frequency (e.g., 100 miles per hour race car would produce about 100 x 300 = 30kHz). The ability of a radar to measure Doppler frequencies is determined in part by the noise sidebands and the coherency of the transmitter and local oscillator. At millimeter wavelengths such sources are visually more noisy than at microwave frequencies and therefore phase-locking, injection locking, and/or frequency stabilization are often necessary. Some examples of Doppler frequency for commonly posted highway speeds are given in Table 7.

6. Increased immunity to interference. This results usually from the very small antenna beamwidths of MMW radars and their accompanying high antenna gains. Increased atmospheric attenuation of MMW even in the windows of Table 3 contributes to interference immunity and can be used to good advantage in automotive radar applications.

7. Increased immunity to unwanted detection is another benefit from the usual high antenna gains and increased atmospheric attenuation of MMW radars.

8. Smaller and lighter components is an advantage that accrues from the shorter operating range envisioned for the MMW radar applications over microwave systems, which is another benefit of MMW system. Other advantages include reduced sensitivity to smoke, clouds, and haze. It will be noted that all of these advantages favor the MMW radar for automotive applications.

Millimeter wave systems are limited by several factors. Atmospheric attenuation due to oxygen and water vapor can provide some limitations on range even in clear weather. Absorption and backscatter, in rain and to a lesser extent in heavy fog, reduce range capability. Table 8 summarizes the advantages and limitations of MMW radars.

Table 7. Doppler Shift Frequencies for Commonly Posted Highway Speeds

Miles/hr	**km/hour**	**Doppler Frequency f_d at f = 24.125GHz**
1		71.899
10		718.99
	30	1340.28
25		1797.47
30		2156.97
	60	2680.55
45		3235.45
	80	3574.07
55		3954.45
65		4673.44
	120	5361.11

Table 8. Characteristics of MMW Radar Systems

Advantages	**Disadvantages**
Physically small equipment High resolution • angular • Doppler • Small beamwidths • high accuracy • reduced interference • low multipath/clutter • high antenna gain Large bandwidth • high range resolution • Doppler processing Atmosphere penetration • fog, smoke, and dust • much better than for IR/EO	Reduced range in adverse weather

5. Transmitter Power Requirements

Automobile radar systems will require detection of objects of $1m^2$ radar cross-section (RCS) [13,14] at approximately 150-200 meter range in bad weather. The RCS is a measure of the effectiveness of the target as a radar reflector. The RCS depends on the size and nature of the target surface exposed to the radar beam and enables describing the reflected signal in terms of target size, shape, and orientation. The radar cross-section is estimated by measuring the amplitude of the received signal. Table 9 lists the radar cross-section of a number of automotive targets at a range of about 200 meters.

Table 9. Typical Radar Cross-Sections at ≅ 94GHz

Target	RCS
Man	$1m^2$
Car	$10m^2$
Van	$30m^2$
Debris on road	$0.1–10m^2$
Road surface	$10–4m^2/m^2$

The smallest target that the system must detect reliably is that of a human. To detect a man at 200 meter range, a transmitter power of about 10 mW should be used, the aim being to obtain a detection probability of 99.99%.

For the short operating distance of 200 meters envisioned for the current MMW radar systems, the average output power required for longitudinal vehicle control is about 10mW at W band. The average mean power from a target received by the radar receiver may be accurately predicted from the radar range equation.

$$\overline{P}_r = \frac{P_t G^2 \lambda^2 \overline{\sigma}}{(4\pi)^3 L_s L_{ATM} R^4} \tag{4}$$

where

P_r = received power
P_t = transmitted power
G = antenna gain
λ = wavelength
σ = target cross-section
L_s = system loss (> 1.0)
L_{ATM} = atmospheric loss (> 1.0)
R = range to target

This figure (10mW) compares well with the power available from simple solid state oscillators at MMW frequencies. At this stage of technology the achievable power output of most RF sources is an inverse function of the operating frequency. The higher the frequency, the lower the output power. Operating efficiency also usually decreases with frequency. Unlike vacuum tubes, solid state devices, because of their small physical size, are inherently unable to raise their peak power handling much above their continuous ratings. The cheapest way of generating power at MMW frequency is to use a solid state Gunn diode oscillator. Such devices can easily generate many tens of milliwatts of power at 94GHz, which gives a comfortable margin above the power of about 10mW, which will be required for vehicle longitudinal control operations. The output power is much more than would be needed for a production system to detect a car at maximum range; and if the signal processing would be more efficient, an output power of less than 10 milliwatts would be satisfactory.

6. Radar Waveforms

One of the important capabilities that has become synonymous with MMW radar technology is measuring distance to a moving object or ranging. The basic waveforms that are most commonly employed by the MMW radar system designer to achieve a desired level of system performance are pulse and frequency modulated continuous wave (FMCW). The simpler of the two pulse delay ranging is used for larger target distances. In this case, a burst of Rf energy is transmitted, and it propagates to the target, reflects from the target, and propagates back to be received as a much attenuated burst of energy, the strength of which is related to the target radar cross-section (RCS) and range. The time delay, t_d (relative to the time the pulse was transmitted), is directly related to the range to the target, as given by:

$$t_d = \frac{2R}{C} \tag{5}$$

where R is the range and C is the propagation constant (velocity of light).

The range resolution ΔR of a pulsed radar is inversely proportional to the bandwidth of the transmitted pulse

$$\Delta R = \frac{C}{2B} = \frac{C\tau}{2} \tag{6}$$

where τ is the transmitted pulse length . A convenient rule of thumb for the relationship between range and pulse width is that 100 ns pulse has a bandwidth of 10MHz and provides 15 meters range resolution; 1.5 meters resolution requires a 100MHz bandwidth. For applications requiring detection of small changes in target position we must employ higher bandwidth pulses if the conventional pulse technique is used. For example, a range resolution of 0.3 meters (30 cm) would require a transmitted bandwidth of at least 500MHz. Achieving such a high resolution (high bandwidth) would require a very narrow pulse of approximately 2 ns. Aside from the fact that it is difficult to obtain a pulse this narrow, the resulting transmitted average power, on which detection depends, may be too low. Further, to compensate for a small pulse width, the pulse repetition frequency (PRF) (or the peak power) must be increased to produce the highest average power available from the transmitter. There is, however, a natural maximum PRF that can be employed. Generally, it is desired to avoid transmitting a pulse until after the signal resulting from the previous pulse has sufficient time to reflect from the target and return to the radar system. If sufficient time is not provided, then it is not known whether a given returned signal is a result of reflection of the most recent pulse from a nearby target or the reflection of an earlier pulse from a more distant target. If this condition cannot be met, the radar will exhibit range ambiguities. It follows that in pulsed systems the peak power is limited by the maximum unambiguous range. Another problem with the narrow pulse approach involves the data acquisition sampling bandwidths. The received radar signal must be digitized for the digital processors used in today's MMW radar systems. When the range swath from which the backscattered signal is being received is equal to the maximum unambiguous range, then the A/D sampling rate is equal to the radar bandwidth (e.g., 500MHz for 0.3 meters resolution). These sampling rates are difficult to achieve for A/D converters with any appreciable dynamic range.

Another factor influenced by the PRF is the maximum Doppler frequency that can be unambiguously measured. It appears the maximum PRF desired due to maximum range considerations is less than the minimum PRF desired due to Doppler considerations. In these cases either the Doppler measuring capability or the range measuring capability will be ambiguous for a given PRF. For some PRFs both of these parameters may be ambiguous.

For shorter distances FMCW ranging [16,17] is selected. The use of FMCW has several advantages for an automotive radar. The FMCW waveform offers easy modulation, high average power, large bandwidths, permitting very good range resolution and Doppler processing, good short range performance, yielding high accuracy. The FMCW waveform can operate even at extremely short ranges, is less likely to have range ambiguity problems, and uses narrow band IF processing. In addition an FMCW sensor is simple to mechanize, uses a single RF source for transmitter and local oscillator, and small size components. Because the transmissions are continuous, the radar can use simple solid state transmitters with much lower peak output power than would be the case if it were necessary to obtain the same sensitivity from a pulsed system in which the peak power is dependent on the average power, pulse length, and pulse repetition frequency. It is possible now to generate tens of milliwatts of CW power at 95GHz with state-of-the-art solid state devices but getting even 1 milliwatt of mean power from an equivalent solid state pulse system is still a difficult task. FMCW radar allows the use of low voltage power supply, a compact transmitter unit and the RF component of the transmitter can be integrated with the antenna feeder system to produce a true solid state FMCW radar.

For low power systems FMCW undoubtedly offers the simplest transceiver designs of any radar which can give range information, although this is somewhat offset by the need to perform some frequency analysis on the IF spectrum. However, the cost of the FFT processor for this application is not a major consideration.

In FMCW systems the range to the target and range resolution are obtained by sweeping the transmitter frequency rather than by trying to generate, transmit, and receive very narrow pulses; this means that it is much easier to obtain the very high range resolution with FMCW than with a pulse radar.

The fact that the frequency sweep is relatively slow (taking of the order of a millisecond) also means that the spectrum of the FMCW radar can be much better controlled than is the case with the pulse radar, which may be a significant consideration for a radar which is to be used in mass consumer application.

An automotive radar application typically requires a range resolution of 0.3 meters. The spectral width required to obtain 0.3 meter range resolution is 500MHz for 1 millisecond modulation, the resulting beat frequency (IF) is 1MHz requiring a digital sampling rate which is at least twice that frequency or 2MHz to satisfy the Nyquist criterion, which is low enough for direct A/D conversion and range bin filtering with FFT techniques. This permits convenient application of weighting functions to reduce range side lobes. (The A/D converter and digital processing would need a wide dynamic range because radar returns from near and far ranges are present simultaneously.) The availability of this degree of spectrum (bandwidth) to measure range resolution is another reason for selecting FMCW for shorter range measurements.

Leakage

The most significant practical factor which must be addressed in the design of FMCW radar, which does not occur with pulse radars, is leakage of the transmitter into the receiver and the undesirable multiple reflections (clutter) resulting from obstacles between the transmitter and the target. These problems must be treated with respect and demand careful design if an FMCW system is to be successful.

Standard techniques exist for improving the isolation between the transmitter and receiver [20] and these can be employed to reduce problems due to transmitter leakage or antenna leakage around the circulator.

To improve range measurements in the presence of clutter, some form of digital filtering [18,19] can be employed as a spatial filter to eliminate the unwanted reflections. The filtered response may be considered as a response obtained with only the primary target illuminated and single target radar techniques can then be applied to obtain a range measurement.

Another disadvantage of the FMCW system is that the frequency generating source of FMCW radar has to be highly linear with low FM noise and low amplitude modulation in order to produce the required range and velocity resolution. This type of error is usually relatively small if the source (sweep oscillator) is locked to a stable oscillator by means of an FM feedback loop. Using the FM feedback linearizer, linearities of better than 0.5% are achieved using production techniques.

Another potential source of uncertainty in an FMCW system results from the use of components such as transmission lines, oscillators, amplifiers, wave guides, and antennas, which exhibit a nonlinear frequency dependence. However, in a well designed system such effects are relatively minor and can usually be neglected.

7. The Frequency Modulation Continuous Wave (FMCW) Method

The measurement of range in CW radars can be accomplished by frequency modulation (FM) of the transmitted waveform. The FMCW technique operates by continuously changing the frequency of the transmitted energy in some predetermined fashion. Figure 2 depicts the operation of the FMCW waveform showing the transmitted signal and the received signal for a given set of targets.

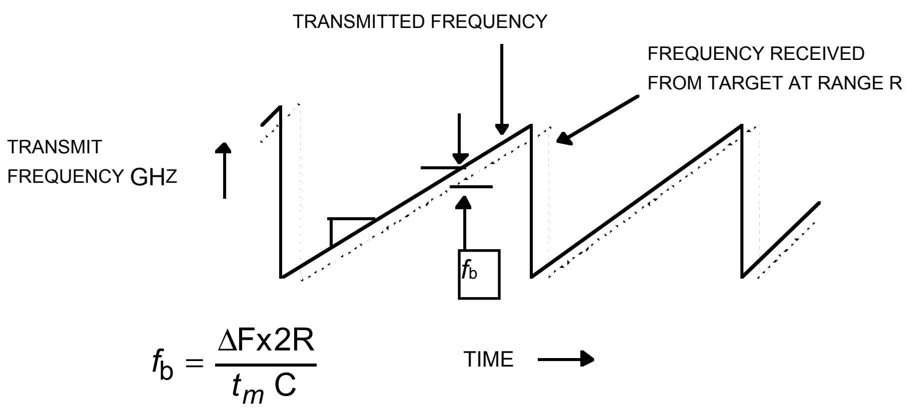

Figure 2. FMCW Sawtooth Waveform

In this arrangement the frequency of the transmitted wave is ramped by a linear waveform (sawtooth) between values f_1 and f_2 and transmitted toward a target. The transmitted waveform has a constant amplitude but a linear sawtooth variation with time. At any instant of time the received signal (from the target) is at a different frequency from the signal being transmitted by an amount related to the range to the target and frequency of deviation (ramp frequency). As can be seen, the signal received from the target represents a replica of the transmitted waveform delayed by the two-way propagation delay time and is at a different frequency from the transmitter frequency, because the transmitter has moved in frequency during the time the signal propagated from the transmitter to the target and back to the receiver. The propagation delay t is given by

$$t = \frac{2R}{C} \qquad (6)$$

where R is the range to the target and C is the propagation constant.

To obtain the range to the target we must determine the frequency difference between the transmitted and received signals. The frequency difference is detected by the homodyne technique [21] in which a sample of the transmitter frequency from the FM sweep oscillator is supplied as the local oscillator to the mixer and mixed with the reflected signal from the target. This process [22] gives rise to a constant difference frequency called the beat frequency f_b at the output of the mixer.

$$f_b = \frac{\Delta F 2R}{t_m C} \qquad (7)$$

where ΔF is the deviation frequency (or the swept bandwidth) and t_m is the modulation period. For a homodyne FMCW radar the frequency of deviation and the modulation period are ordinarily held constant, [21] and the beat frequency between the transmit and receive waveforms is linearly proportional to the range to the target. Rearranging terms from equation (7), the range is obtained as

$$R = \frac{t_m C}{2\Delta f} f_b \qquad (8)$$

For any radar waveform, the ideal range resolution ΔR_o is linearly proportional to time resolution Δt and inversely proportional to the bandwidth of the transmit waveform ΔF as given

$$\Delta R_o = \frac{C\Delta T}{2} = \frac{C}{2\Delta F} \qquad (9)$$

$$\Delta T = \frac{1}{\Delta F} \qquad (10)$$

where ΔR_o is the ideal range resolution, ΔT is the time resolution, and ΔF is the bandwidth of the transmit waveform. Note that the resolution depends only on the frequency deviation (sweep bandwidth). To obtain a high resolution, therefore, we need to use a large frequency deviation. For example, a 400MHz bandwidth corresponds to time resolution of 2.5 ns and range resolution 0.37 meters. For a homodyne FMCW radar, the radar's range resolution is given by

$$\Delta R = \frac{t_m C}{2\Delta f}\Delta f_b \qquad (11)$$

where Δf_b is the beat frequency resolution of the receiver. Δf_b is inversely proportional to the modulation period less the round trip propagation time t or

$$\Delta f_b = \frac{1}{t_m - t} \qquad (12)$$

Then the range resolution for a varactor tuned Gunn diode oscillator is given by

$$\Delta R = \frac{C t_m}{2\Delta f}\frac{1}{t_m - t} \qquad (13)$$

<u>Range Doppler Coupling in the Sawtooth Waveform</u>

For moving targets the beat frequency depends on both range and velocity. For an FMCW sawtooth waveform that sweeps up in frequency, the beat frequency of a moving target is given by

$$f_b = -\frac{\Delta F 2R}{t_m C} + \frac{2vf}{C} \qquad (14)$$

where $\frac{2vf}{C}$ is the Doppler frequency shift, v is the target velocity, and f is the nominal radar frequency.

During the upsweep time of the ranging cycle, the signal frequency is proportional to the algebraic sum of the target velocity and range. The target range is then obtained as

$$R = \frac{t_m C}{2\Delta f} f_{b_1} \qquad (15)$$

where f_{b_1} is the beat frequency during the upsweep part of the ranging cycle and $\frac{t_m C}{2\Delta f}$ is the rate of FM linear sweep in Hz/sec.

It can be seen that in the case of moving targets the accuracy of the target range indication will be affected by the superimposed Doppler shift in received frequency caused by moving targets. The Doppler frequency on the target return manifests itself as an error in determining range to the target.

In order the resolve the range Doppler coupling in the sawtooth waveform, the waveform must be modified to have two frequency slew rates or slopes in order to resolve this range-Doppler coupling. The triangle waveform with equal upslope and downslope linear sweeps is a common choice. Figure 3 shows the operation of the triangular waveform.

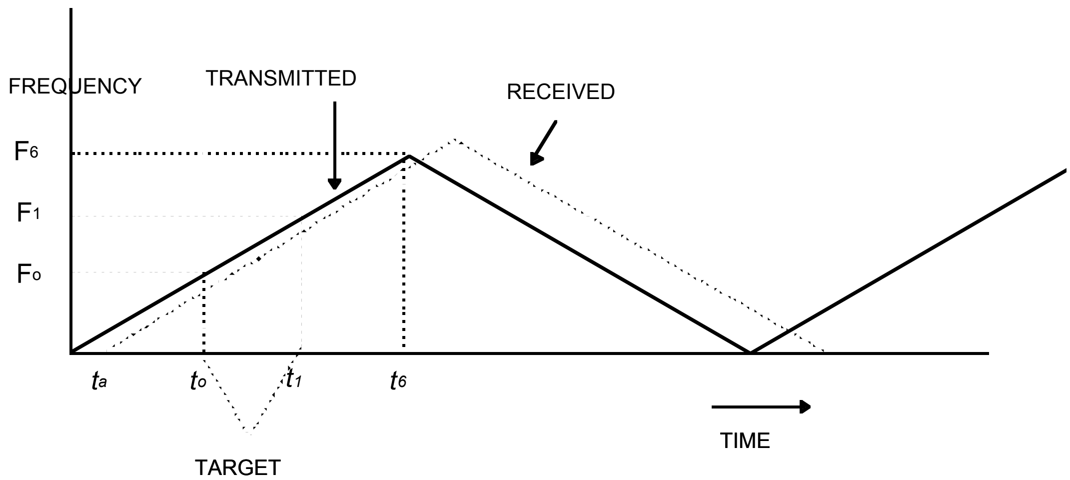

Figure 3. Triangular Waveform FMCW Operation

The beat frequency for the triangle wave is given by

$$f_{b\ \text{triangle}} = \frac{\Delta F 4\, f_m R}{C} = \frac{\Delta F 4 R}{t_m C} \tag{16}$$

where f_m is the modulation frequency, and the modulation period t_m is the inverse of the modulation frequency f_m. The magnitude of f_b for the triangle wave includes an additional factor of 2 in the numerator because the period of the triangle wave, including both upsweep and downsweep, is twice that of the sawtooth wave for the same frequency slew rate. [22] For moving targets the Doppler frequency shift is given by

$$f_d = \frac{2Vf}{C} \tag{17}$$

where f is the nominal radar frequency. For the triangle waveform, range is linearly proportional to the upsweep and downsweep beat frequencies, and velocity is proportional to the sum of the beat frequencies.

If the target is not stationary, the received signal will contain the Doppler shift in addition to frequency shift due to time delay t, , of the target as shown in Figure 2. In this case the shift due to range would subtract from the Doppler frequency shift during the positive slope if the target is closing and will add during the negative slope (the falling frequency segment). Designating the beat frequencies during positive (upsweep) and negative (downsweep) slope portions of the ranging cycle by f_{b+} and f_{b-} we get

$$f_{b+}(\text{triangle}, \text{upsweep}) = -\frac{\Delta F 4 R}{t_m C} + \frac{2Vf}{C} \tag{18}$$

$$f_{b-}(\text{triangle, downsweep}) = \frac{\Delta F 4R}{t_m C} + \frac{2Vf}{C} \quad (19)$$

Adding the above equations we get the expression for range so that the range is given by

$$R = \frac{t_m C}{8\Delta}(f_{b+(\text{downsweep})} - f_{b-(\text{upsweep})}) \quad (20)$$

Subtracting the same equation we get the expression for (range rate) velocity

$$V = \frac{-C}{4f}(f_{b-} + f_{b+}) \quad (21)$$

One complete ranging cycle should occur during the target illumination period to obtain R and V information.

8. Signal Processing

Modern radars utilize digital signal processors (DSP) to perform various functions within the radar. The signal processing techniques employed by MMW radars are very similar to conventional microwave radars. The signal processing difference between the two types of radar is in the radar signal processing philosophy adapted for MMW radars, which is to maximize target information that can be processed out of the MMW radar signal. Signal processing techniques that come to be associated with MMW radars in addition to target detection and ranging include: coherent and noncoherent Doppler processing techniques for achieving moving target identification, stationary target identification (STI) techniques, such as constant false alarm rate (CFAR) processing, clutter decorrelation processing, high range resolution processing, and polarimetric techniques to extract target geometrical features to achieve STI.

For longitudinal control the signal processor converts the beat frequency to independent range and range rate which are then used for headway control, for tracking the nearest vehicle, and for collision-mitigation braking. The processor does all the necessary filtering, averaging, and FFT in real time. The most time consuming activity of the processor is the calculation of the FFT. [23,25] All the other activities of the processor are performed using a small part of the capacity of the signal processor.

An automotive FMCW radar with a maximum indicated range of 200 meters would use a 1024 point FFT signal processor to give a range resolution of 0.3 m. The calculation of a 1024 point FFT every 2 milliseconds is within the capabilities of current DSP chips and constitutes the bulk of the processing that will be required for longitudinal control FMCW radar. To do this processing is far more cost effective than adding additional complexity to the microwave circuits to obtain a similar performance with pulse modulation.

9. Conclusion

This report has looked at the basic principles of FMCW radars and described a number of techniques that may be used with them that demonstrate their applicability for automotive applications. In the FMCW method, a large sweep bandwidth represents only a small fractional bandwidth, which lends itself to real time signal processing. In addition the FMCW method of operation enables high processing gains that allow low peak transmit power.

The FMCW radar lends itself to be used for ranging, hazards detection, feature or target recognition, or for automatic guidance. It should be evident that FMCW MMW radar techniques are well suited to applications calling for high range resolution for which the range interval to be observed is small.

The results which are now being obtained with automotive FMCW MMW radars show that modern technology has made it possible to fulfill the long-standing dream of making practicable radar systems for automobiles. It promises to be a significant commercial application that will reduce the driver's workload so that driving can become safer and less tiring.

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