# Next Generation, Low-THz Automotive Radar - the potential for frequencies above 100 GHz

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***Abstract:*** *Current automotive radars operate under 100 GHz. The natural progression to higher frequencies beyond 100 GHz offers significant benefits in the form of increased bandwidth and exploitation of phenomena associated with shorter wavelength. Higher operating frequencies offer the possibility of significant improvement in range resolution to cm level, improving target classification, reduction in sensor size, mass cost and easier packaging of multiple sensors per vehicle. A comprehensive research program is being undertaken at the Microwave Integrated Systems Laboratory (MISL) at the University of Birmingham to quantify the advantages and limitations of operating at frequencies beyond 100 GHz for automotive applications. This paper summarizes the findings of these studies.*

## 1. Introduction

Automotive radar research and development has evolved since the 1960's from academic curio to present day safety feature requirement. Developments in the 1960s began at around 10 GHz [1], increasing the potential operating frequency to 24 GHz [2], 47 GHz [3], and 95 GHz [4], finally settling at 76-77 GHz by international agreement around 1994 [5]. Current radar sensors are constrained by international regulation to operate within frequency and power constraints defined in documents such as EN 301- 088, (24 GHz) [6], EN 301-091, (76 GHz), EN 301-264, (79 GHz) [7].

The worldwide push to produce autonomous vehicles will mean that tens of millions of radar sensors will be fielded annually and the question of mutual interference and co-existence will have to be addressed. Increased available bandwidth will be one of the parameters of use to mitigate some of the effects. The advantages of increased operating frequency are wider available bandwidth, providing increased range resolution, smaller antennas which result in reducing cost, mass and packaging issues, and also, increased sensitivity to surface texture. Set against this is the perceived drawback of increased atmospheric loss. Propagation losses are often cited as being prohibitive for automotive radar operation at frequencies above 100 GHz. However, at the ranges of interest for automotive applications, around 150 m, there is a requirement for accurate measurement of these losses to provide quantitative data. To provide this data simultaneous free space propagation measurements at 77 GHz and 300 GHz, over a 2 way path of 160 m, have been made over a time period over 6 month to encompass a wide range of weather, atmospheric and propagation conditions. Radar performance in the case of installation behind automotive surfaces and accumulation of contamination on the radome is also required to be investigated. Finally, reflectivity of typical road objects at Low-THz frequencies needs to be studied to compare Low-THz automotive radar performance with current automotive radar performance.

## 2. Low-THz wave attenuation

The areas of potential attenuation in automotive radars are as follows: (2.1) radar installation behind the car's surface components, (2.2) accumulation of contaminants on the radome, (2.3) wave propagation through atmospheric conditions. Understanding these areas is critical before applying Low-THz technologies into automotive applications. This section summarizes the research results obtained by the MISL group that covers all three areas. It is worth mentioning that similar comprehensive research publications are missing for current automotive radars.

*2.1 Transmissivity through bumpers*

Automotive sensors for various safety application are installed behind different parts of the vehicle. For instance, sensors for autonomous cruise control (ACC) and rear collision warning are often installed behind the front and rear bumpers and sensors for blind spot detection and parking aid are installed on both sides at the rear of the car. Therefore, bumpers and/or light covers may be used as a radome. Comprehensive measurements of attenuation through bumpers with various paints type were conducted at 77 GHz and Low-THz frequencies. The attenuation was measured by changing the incident angle between the bumper samples and radar beam to simulate the real case scenarios of a radar scanning behind the bumper. Comparison between the measured results at 0º incident angle at all the frequencies show that the loss through the bumpers increases when frequency increases, however this increase stays below 5 dB for polypropylene (PP) automotive bumpers. However, polyurethane (PUR) bumpers introduce higher loss and the difference between 670 GHz and 77 GHz is approximately 15 dB. In addition, comparing the results of nine PP plastic bumpers with various type of paints shows that metallic paint introduces 1 dB~2 dB higher loss than samples with solid and pearlescent paint. The measured attenuation through a plastic headlight cover shows that increasing frequency up to 670 GHz will result in about 7 dB increase compared with 77 GHz.

*2.2 Signal attenuation through contaminated radome*

A substantial proportion of signal power of an automotive radar may be lost due to contamination on the radome. Contaminants interact with the signal, resulting in attenuation and generating a detrimental effect on radar performance, up to complete signal blockage and sensor failure. Published information on the impact of radome contaminants on wave propagation is rather limited even at 77 GHz and practically absent for Low-THz bands. The authors have run comprehensive theoretical and experimental studies on the loss effect of many common contaminants that occur in automotive practice, namely: water, ice, sand, diesel, gasoline and fallen leaves at Low-THz frequencies. The measured two way transmission loss through these contaminants are summarized in Table 1 [8]-[12]. A more detailed explanation of the measurement methodology and theoretical modelling can be found in the referenced literature. The highest measured signal reductions are shown in bold. The experimental results are in a good agreement with the theoretical modelling results. To give a flavour of the loss dependence on the radar carrier frequency and the nature of contaminations, transmission through a thin film of water at 77 GHz is taken from [13]-[14] and the effect of other contaminants on the radome at 77 GHz, as missing in the literature, are calculated based on the theoretical modelling [11]. Comparison between the results presented in Table 1 shows that the presence of water on the radome surface or contaminant containing water has the greatest effect in degradation of performance at all the frequencies. Water can be present on the radome as a thin layer or as isolated and closely spaced droplets distributed over the radome [11]. The second formation is the common case and has less detrimental effect on the wave propagation in comparison with a uniform layer of water on the radome.

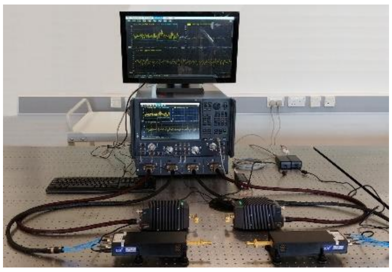
The results for sand in [9] indicate that coarser sand particles produce greater attenuation than finer particles. However, in practice sand with smaller particle sizes is more likely to attach to the radome, possibly forming a uniform layer. Moreover, transmissivity dramatically reduces when the moisture content of sand increases, at all frequencies and for all the sand particle sizes. Other common automotive contaminants which include ice, diesel and gasoline are almost transparent at 77 GHz and rise slightly at Low-THz frequencies.

Transmissions through the leaves was measured constantly from the stage when they were fresh until they had lost almost all of their water content through evaporation. This identified the contribution of the water content of leaves on signal reduction. The measured signal reduction through fresh leaves is shown to be equivalent to the transmissivity through ~0.5 mm of uniform layer of water and results in about 40 dB at 300 GHz. Hence, we can expect signal reduction of about 30 dB and 34 dB at 77 GHz and 150 GHz, respectively, when the leaves are fresh. Transmissivity close to zero is expected when the leaves have lost almost all of their water content if we omit attenuation caused by solid plant material of leaves. The values shown underlined in Table 1 are just from the calculation.

Table 1. Two way signal reduction (in dB) on a contaminated radome

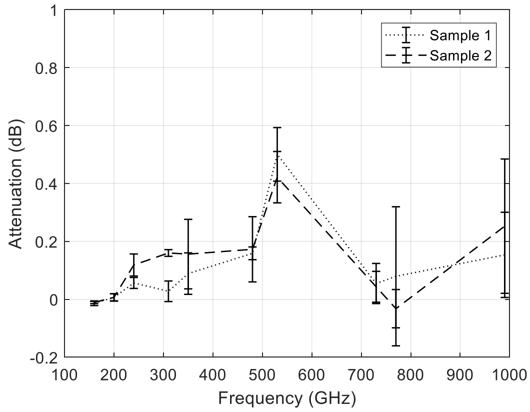
| **Contaminant** | | **Frequency in GHz** | | |
|---|---|---|---|---|
| | | **77** | **150** | **300** |
| *Water (0.45 mm) [6]* | *PW* | ***30**[9] (0.425 mm)* | ***29*** | ***38*** |
| | *SW (3.5%)* | ***23.2*** | ***22*** | ***31*** |
| | *DW* | *NA* | ***34.6*** | ***40*** |
| *Sand (Particle size:0.3-0.15 mm) (thickness:1 mm)[4]* | *Dry* | *NA* | *~0* | ***10*** |
| | *Moist (10 Vol. %)* | *NA* | ***12.6*** | ***26*** |
| *Ice (1 mm) [3]* | | *0.4* | *1.4* | *3.2* |
| *Diesel (1 mm) [5]* | | *0.6* | *0.8* | *1.1* |
| *Gasoline (1mm) [5]* | | *1* | *1.4* | *1.5* |
| *Leaf (0.37 mm) [7]* | *Fresh* | ***30*** | ***34*** | ***40*** |
| | *Dry* | *~0* | *~0* | *4* |
| *Water droplet with coverage area in % [6]* | *10* | *NA* | *2* | *2* |
| | *20* | *NA* | *4* | *1.6* |
| *Abbreviations: PW-Pure water, DW-Contaminated water with road dirt, SW-Salty water* | | | | |

An additional form of contamination is accumulation of dust and dirt on the radome over period of time, when especially no cleaning has been performed on the radome. To address the effect of this form of contamination, cling film was placed behind the grill of two individual cars and various dirt and dust accumulated on the cling film. These films were mounted on 05 of August 2017 until 15 November 2018, identified as sample 1 and sample 2. The vehicles were driven for about 1400 miles each. The samples had an optically visible layer of dirt accumulated on them. The attenuation through two samples was measured by the THz Vector Network Analyser available in EESE department of the University of Birmingham. The Keysight PNA with frequency converters units covers from 5 MHz to 1.1 THz. The measured results of sample attenuation with accumulated dirt versus frequency are shown in Fig. 1. (c). The measured attenuation across the frequency range was below 1 dB.



(a)

(b)




(c)

Figure 1. (a) THz VNA measurement facility in EESE department (b) attenuation measurement through samples (c) measured attenuation of sample with accumulated dirt through frequency

*2.3 Atmospheric attenuation*

Analysing the effect of different weather conditions on Low-THz wave propagation is a fundamental factor of this study. Attenuation due to different atmospheric condition is expected at Low-THz radar in spite of the relatively short range of automotive radar operation, about 150 m one way. This attenuation must be taken into account in the radar design. Atmospheric attenuation (a) through clear air with relative humidity (RH) of 50% and 100% [15], (b) through two rainfall rates, heavy and very heavy rain [16], (c) through fog of 100 m and 50 m visibility [15] (d) through dry and wet snow, versus two way signal path (up to 300 m) is plotted at the current mm-wave automotive radar frequency and Low-THz frequencies.

Attenuation in clear air with maximum RH shows a loss of 3 dB over 300 m range at 300 GHz, this range corresponds to a long range automotive radar. Nevertheless more complex weather conditions, such as rain, fog and snow introduce greater attenuation as particles such as water droplet, snowflakes, etc. which interact with EMW and result in processes such as absorption, scattering and extinction. The higher attenuation in adverse weather condition results in decreasing the maximum range operation. The maximum difference between attenuation at 300 GHz and 77 GHz corresponds to extremely dense fog which reaches about 10 dB at 300 m range. For other atmospheric perturbations, the loss difference is within 3 dB between two frequency bands. More details about atmospheric losses in adverse weather condition may be found in the citied literature [16]-[18].

## 3. Target reflectivity

Very little research has been done so far on the evaluation of the reflectivity of road objects and actors at Low-THz frequencies. A detailed investigation on human Radar Cross Section (RCS) at 24 GHz and 77 GHz is presented in [19] and [20]. Analysis of vehicle reflectivity and other related automotive objects can be found in [21]-[23]. A proper and detailed analysis of pedestrian RCS in the Low-THz band has been presented in [24] and [25] and vehicle reflectivity results reported in [26]. Table 2 presents a summary of the average RCS for different road objects at Low-THz frequencies, obtained through measurements. Results show that RCS have similar values and are in good agreements with the results reported in literature.

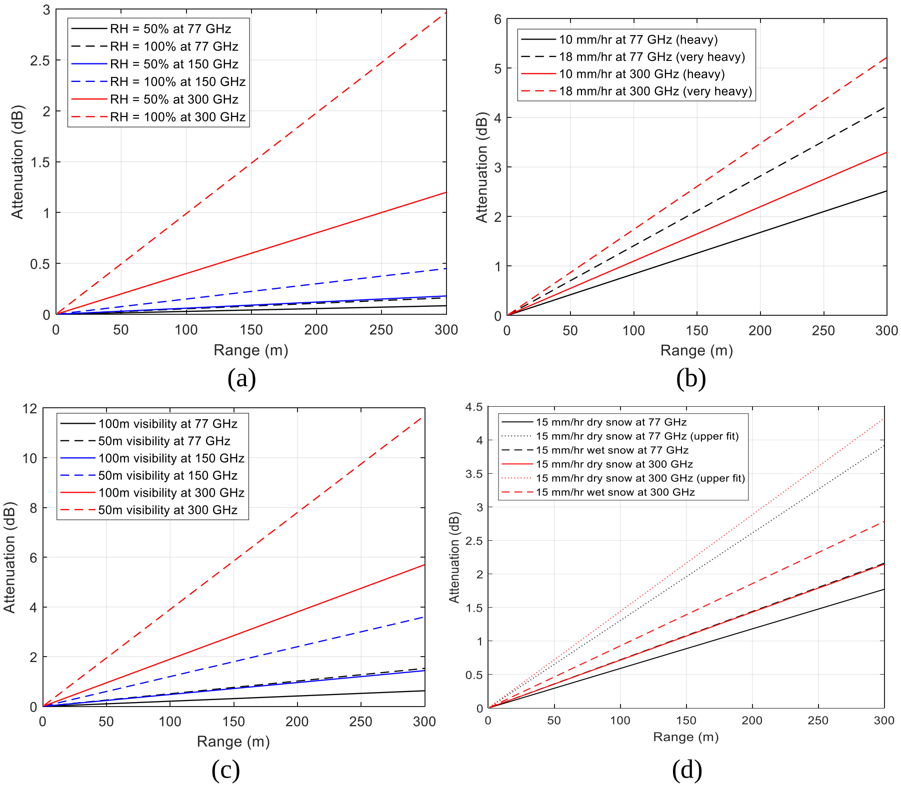



*Figure 2. Atmospheric losses in (a) clear air, (b) rain, (c) fog and (d) snow*

Table 2. Average RCS for different road objects

| **Target** | **Average RCS (dBsm)** | | | |
|---|---|---|---|---|
| | **24 GHz** | **77 GHz** | **150 GHz** | **300 GHz** |
| Pedestrian | -11.5±3.5 | -9.9±5 [13] | -10.5±4.5 | -9±2.4 |
| Bicycle | -4.1±16.2 | NA | -3.4±9.2 | -2.3±14.4 |
| Wheelchair | 2.1±15.3 | NA | 1.5±16.4 | 3.1±21.2 |
| Pushchair | -2.5±12.5 | NA | NA | -1.8±10.5 |
| Passenger car | NA | 2.6±10.1 | NA | 5.1±9.2 |

## 4. Conclusion

Recent study on feasibility and limitation of Low-THz frequencies for automotive applications is summarized in this paper. Measured results through automotive bumpers with PP substrate show only 5 dB difference by increasing operating frequency from 77 GHz to 670 GHz, and larger difference, about 15 dB, through PUR substrate bumpers. The results of signal attenuation due to radome contamination presented in Table 1 are useful to understand the requirements for radome design and packaging in a vehicle as well as the loss dependence on the radar carrier frequency. For all the considered bands, the largest attenuation occurs when water or other contaminant containing water cover entire radome surface. Other considered contaminants introduce smaller attenuation. Shifting the automotive frequency from the current automotive frequency to Low-THz frequency region does not introduce dramatic increase in attenuation through atmosphere over the range of operation on automotive radars. The measured RCS results suggest that sensors operating at Low-THz frequencies will have similar or even slightly better detection performances compared with traditional automotive sensors operating at lower frequencies.

## 5. Acknowledgement

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