On the Use of a 77 GHz Automotive Radar as a Microwave Rain Gauge

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Abstract—**The European Telecommunications Standards Institute (ETSI) defines the frequency band of 77 GHz (W-band) as the one dedicated to automatic cruise control long-range radars. A car can be thought as a moving integrated weather sensor since it can provide meteorological information exploiting the sensors installed on board. This work presents the preliminary analysis of how a 77 GHz mini radar can be used as a short range microwave rain gauge. After the discussion of the Mie scattering formulation applied to a microwave rain gauge working in the W-band, the proposal of a new Z-R equation to be used for correct rain estimation is given. Atmospheric attenuation and absorption are estimated taking into account the ITU-T recommendations. Functional requirements in adapting automatic cruise control long-range radar to a microwave rain gauge are analyzed. The technical specifications are determined in order to meet the functional requirements.**

Keywords-radar; microwave rain gauge; 77 GHz; W-band; Mie scattering; Z-R relation; weather radar; car as sensor

I.   INTRODUCTION

The advances of the automotive industry are highly dependent on the number of sensors installed on cars. In 2001 the number of sensors installed on a car was more than 100 [1] and this number keeps increasing. These sensors are considered essential components of any vehicle regardless of its luxury. Car sensors are provided with a large set of systems and technologies that are commonly used to improve safety and comfort: Antilock Braking System (ABS), Electronic Stability (ESP), tire pressure control, accelerometers, thermometers, rain sensors that on newer cars are able to automatically turn on the windscreen wipers [2] etc. Of course, as the demand for more automotive advances is increasing, the number of sensors in a vehicle is also increasing. For this reason, cars are also referred to with the innovative conception of "car as sensor". Cars as sensors can be used not only for purposes related to safety, monitoring and maintenance, but for a huge number of other applications that could be performed implicitly.

Some cars are equipped with radars. In particular, according ETSI and its 20 published standards about automotive radars, two frequency bands are dedicated to specific automotive radar applications: the anti-collision short-range radar operating at 24 GHz and 79 GHz and the automatic cruise control long-range radar operating at 77 GHz. A single car can also be thought as an integrated meteorological sensor providing real time weather monitoring. This work aims to show that, it is possible to use a 77 GHz radar as a microwave rain gauge for meteorological purposes and real time monitoring operations. This work is focused on this application and it also includes a theoretical analysis of Mie scattering mechanism for raindrops at 77 GHz. The research group of remote sensing of the Department of Electronics and Telecommunications (DET) of Politecnico di Torino, has a strong background in environmental monitoring [3-5], active remote sensing [6, 7], and atmospheric studies. Since 2010 it has also developed an X-band mini weather radar for rain measurements with high spatial and temporal resolution. It is capable of detecting rapid and extremely localized intense phenomena with very good accuracy [8] and it is particularly suited to be employed in complex orography environment and for local analysis of extreme events [9]. The idea presented in this work is the application of the acquired knowledge on radar meteorology in order to use a 77 GHz radar as a short-range microwave rain gauge, since many 77 GHz components are already on the market with relative low cost.

II.   RADAR METEOROLOGY AT 77 GHZ

In order to use a 77 GHz radar as a microwave rain gauge, the first step is to evaluate the atmospheric absorption and attenuation, since they can put some constraints on the operative range. According to [10, 11] the atmospheric absorption at the operative frequency of 77 GHz is about 1 dB/km and it is sufficient low for a W-band microwave rain gauge. Looking at the atmospheric absorption curve, the W-band is located in correspondence of one of its relative minimums. The attenuation path can be evaluated according to [12]. For a distance equal to 1 km the free space attenuation is about 130 dB. At the frequency of 77 GHz there is an atmospheric attenuation of 0.07 dB/km caused by dry air and of 0.36 dB/km caused by water vapor component. These values are computed considering the International Standard Atmosphere (ISA) conditions, defined by the International Civil Aviation Organization (ICAO) at the latitude of 45°. In

calculations, the value of relative humidity was increased up to 100% since the radar is operative during a rain event. According to the ITU recommendations, it is possible to evaluate the adjunctive attenuation due to the rain for different rain rates, both in horizontal and in vertical polarization. Attenuation varies from 0.4 dB/km for both polarizations and rain rate R=0.25 mm/h to 41.5 dB/km for horizontal polarization and R=150 mm/h (an extremely high value). Because of the raindrops' shape (flattened on the bottom and with a curved dome on top) the attenuation on horizontal polarization is higher than the one on vertical polarization. Summarizing all the partial values given by the recommendation, the adjunctive free space attenuation is less than 0.5 dB/km and considering a standard rain rate of 20 mm/h, a realistic value of rain attenuation is 10–15 dB/km. By combining all the values of absorption and attenuation, it is possible to conclude that a commercial 77 GHz automotive anti-collision radar can be used also for meteorological purposes since these values do not affect too much its propagation performance. However, since for a distance equal to 1 km the free space attenuation is about 130 dB the operative range is quite short (maximum 100 m). This is why it can be used as a "short range" microwave rain gauge.

The standard bands used for meteorological purposes are the S-band (frequencies equal to 2700-2900 MHz, with corresponding wavelength λ≈10-11 cm), the C-band (f=5600-5650 MHz, λ≈5 cm), the X-band (f=9300-9500 MHz, λ≈3 cm) and the Ka-band (f=35 GHz, λ<1 cm). The Rayleigh scattering model used in radar meteorology is valid for all of them. The model assumes that the physical size of the drops is much smaller than the used wavelengths. According to different studies about Drop Size Distributions (DSD) (e.g. [13, 14]) raindrops have a diameter between 0.5 mm and 5 mm (Figure 1). In the W-band (f=77 GHz, λ<4 mm), it is necessary to use the Mie theory which gives a complete and mathematically rigorous solution to the scattering problem of an electromagnetic wave hitting a sphere, because raindrop size is comparable with the used wavelength. Of course, the application of the Mie theory implies the considering of raindrops as perfect spheres. Although this is a rough approximation, it provides a first good estimate of raindrops shape that does not affect the results very much.

Assuming Rayleigh scattering at a specific wavelength λ, the reflectivity η is given in (1):

$$\eta = \frac{\pi^5}{\lambda^4}|K|^2 \int_o^{D_{max}} D^6 N(D)dD = \frac{\pi^5}{\lambda^4}|K|^2 Z \qquad (1)$$

where K is the absorption coefficient of water, D is the spherical particle diameter, and N(D) is the DSD. The Radar Reflectivity Factor Z is proportional to the sixth moment of the DSD. Assuming the Mie scattering, the radar reflectivity factor Z can be rewritten as in (2):

$$Z = \frac{\lambda^4}{\pi^5|K|^2} \int_o^{D_{max}} \sigma_{Mie} N(D)dD \qquad (2)$$

where σ_{Mie} is the backscattering cross section of a raindrop evaluated according to the Mie theory.
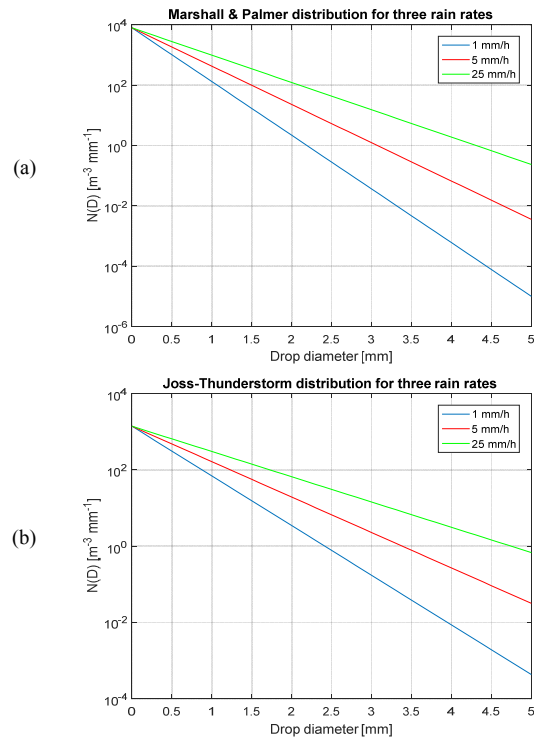

Fig. 1.   DSD according to Marshal and Palmer distribution [13] (a) and Joss distribution for thunderstorm (b) for three different rain rates. It can be shown that according to both DSDs, most of raindrops have a diameter lower than 5 mm.

It is worth noticing that, according to the Mie formulation, Z is a function of the wavelength unlike the Rayleigh scattering model in which it is frequency independent. Therefore when using Mie theory, for a microwave rain gauge operating at 77 GHz, a proper Z-R relation must be specifically derived. Most of Z-R relationships determined in the scientific literature are obtained after the Rayleigh hypothesis. The result of a relation obtained with Mie scattering theory can be very different from the standard, analytically derived and empirical ones (e.g. [15]) and, since it is frequency dependent, it must be carefully evaluated. Some examples of Z-R relations obtained with Mie Theory can be found in [16, 17]. The DSD is related to the rain rate R defined as in (3):

$$R = 6\pi \cdot 10^{-4} \int_o^{D_{max}} D^3 N(D)v(D)dD \qquad (3)$$

where v(D) is the raindrop terminal velocity.

Assuming the validity of the common exponential relationship between Z and R as in (4), and the definition of Z in (2), a numerical simulation procedure has been set up to obtain the numerical values of the coefficients a and b of (4). The simulation procedure has been implemented in Matlab exploiting the functions included in the Maetzler toolbox [18, 19] which implements the numerical procedures of [20, 21] to solve the Mie equations.

$$Z = aR^b \qquad (4)$$

The suitable Z-R equation to be used for a weather radar operative at 77 GHz is reported in (5) and represented in Figure 2 where it is also proposed a comparison with the most common equation based on Rayleigh model [13]. Equation (5) avoids the underestimation of the rainfall rate R caused by a wrong evaluation of the backscattering cross section, and hence the whole scattering raindrop mechanism [22].

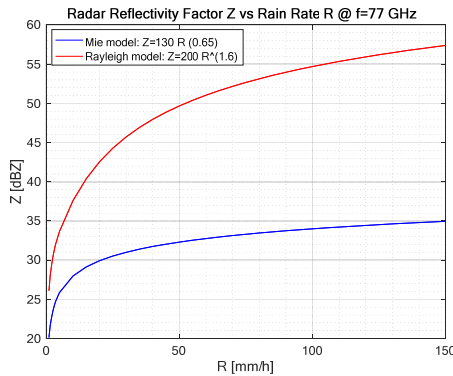$$Z(77GHz) = 130R^{0.65} \qquad (5)$$

Fig. 2.   Example of underestimation of rain using a common Z-R equation obtained with Rayleigh scattering theory with respect to the one obtained with Mie theory considering the Marshall and Palmer DSD The underestimation varies from 5 dB to more than 20 dB. In terms on rain rate it is an underestimation of some tenths of mm/h.

III.   FUNCTIONAL AND TECHCNICAL SPECIFICATIONS

A.   Functional Specifications

According to the theoretical results mentioned above, it is possible to define the functional specifications for an automotive anti-collision radar used as a short microwave rain gauge. Table I summarizes the functional specifications. The use of dual polarization is not strictly necessary for simple rain measurements. However, exploiting the polarimetry would improve the Quantitative Precipitation Estimation (QPE) and would allow a classification of the hydrometeors [23]. Moreover, the use of a Frequency Modulated Continuous Wave (FMCW) radar allows the transmitting of a very low power signal, with respect to the higher power values needed for alternative technologies.

TABLE I.   SUMMARY OF MAIN FUNCTIONAL SPECIFICATIONS

Specification	Value
Max operative range	100 m
Range resolution	5-10 m
Sensitivity	Rain rate R=0.5 mm/h at 100 m
Operative frequency	77 GHz (W-band)
Polarization	2 orthogonal polarization (V – H)
Radar technology	FMCW

B.   Techcnical Specifications

The definition of technical specifications starts from the identification of the sensitivity required by the system to give the rain estimation with the desired level of accuracy. In radar meteorology, the sensitivity value is defined as the minimum detectable rain rate R at the maximum operating range of the radar. Exploiting (5), the value of rainfall rate R [mm/h] is converted into the corresponding radar reflectivity factor Z. A sensitivity value of R=0.5 mm/h is considered as a good value for a microwave rain gauge operating at 77 GHz at a maximum operative range of 100 m. It corresponds to Z=20 dBZ which will be used to obtain the radar constant. A noise figure F_{dB}=15 dB is assumed as a worst performance case, a value certainly high for a standard 77 GHz radar receiver. A receiver bandwidth B=20 MHz is also considered since it is sufficient to guarantee a spatial resolution of 10 m. According to F_{dB} and B it is possible to obtain the equivalent noise power P_N=– 85 dBm. Considering that a minimum signal to noise ratio SNR=3 dB must be guaranteed for the proper working of the system, the transmitted power and the radar constant are determined. A good value of transmitted power is P_{TX}=6 dBm, which is commonly used in commercial hardware for automotive radar. This value leads to an evaluation of radar constant k_{FMCW}=66 dB. It can be obtained using horn antennas with a gain G=30 dBm and Half Power Beam Width (HPBW) equal to 20° (0.35 rad). Since 77 GHz commercial horn antennas usually have a maximum gain G=25 dB, in order to realize a meteorological radar with the desired characteristics it is necessary to compensate the loss of 5 dB with other techniques, such as amplification chains or even the use of different antenna types.

Since the system is probably an FMCW radar, it is necessary to evaluate its working parameters related to the maximum operative range (the sweep time T) and the spatial resolution (the chirp bandwidth B_W). According to the functional specifications reported in Table I, the spatial resolution must be at least 10 m. It means that the chirp bandwidth must be at least B_W=15 MHz. This value can be easily obtained with commercial systems available in the automotive market and it is compatible with the previously considered noise bandwidth B. Sweep time values in the range between 1 ms to 20 ms allow the reaching of a maximum range equal to 100 m. Integrated chips already developed for the automotive field reduce greatly both costs and complexity, but the signal coherence cannot be usually guaranteed. Therefore, in order to design a polarimetric system, while it is always possible to work with the magnitude of the polarimetric quantities of the scattering matrix to study the precipitations, the use of phases of polarimetric quantities depends on the type of the receiver and the used electronic components. A polarimetric microwave rain gauge must have two different hardware receiver chains, one for each orthogonal polarization. The processing unit follows the chains and computes all the required polarimetric quantities considering a single chain or both of them, if necessary. According to the specifications summarized in Table II, derived with the discussion about technical specifications, a brief sensitivity analysis has been carried out. Figure 3 shows the variation of the radar reflectivity factor Z and the received power P_{RX} as functions of the rainfall rate R. The system has a variation of about 15 dB in terms of Z and P_{RX} that corresponds to variation of R between 0 and 100 mm/h. It does not seem to be a large dynamic

variation but it must be considered that most common values of rain rate are between 1 mm/h and 30 mm/h, corresponding to a variation of 12 dB. A good acquisition software together with a good hardware system can be useful to measure the rain rate with the desired accuracy, confirming that a 77 GHz automotive anti collision radar can be used as a short range microwave rain gauge.

TABLE II.   SUMMARY OF TECHNICAL SPECIFICATIONS

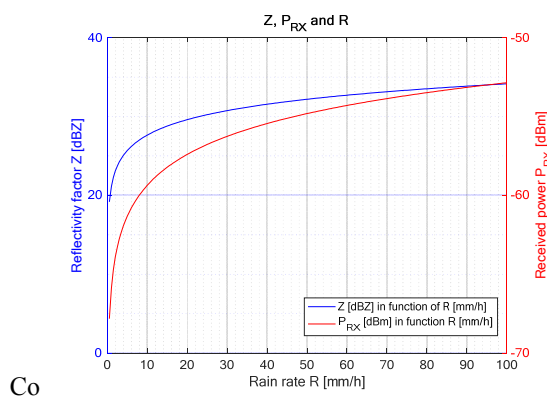| Specification	Value
Sensitivity	0.5 mm/h at 100 m (20 dBZ at 100 m)
Noise figure	15 dB
Receiver bandwidth	< 20 MHz
SNR	3 dB
Transmitted power	6 dBm
Radar constant	66 dB
Antennas (Gain and HPBW)	30 dB – 20°
Chirp bandwidth	< 15 MHz
Sweep Time	< 20 ms

Fig. 3.   Variation of radar reflectivity factor and received power with respect to rain rate.

IV. CONCLUSIONS

This work presents how common automotive anti-collision radar operating at 77 GHz can be used as a microwave rain gauge. Particular attention has been paid to numerically determine the proper Z-R relationship for a radar operating in W-band using the Mie scattering theory. At such frequencies, the Z-R equations commonly determined with the Rayleigh scattering model are not valid. The Z-R relation obtained with Mie scattering theory can be implemented on cars already equipped with the automatic cruise control "long-range radar" operating at 77 GHz. Analyzing the functional and technical specification it has been shown that commercial anti-collision radar could, in principle, work well as a standalone microwave rain gauge providing a good QPE. In future, acquired and measured data can be elaborated with different parallel processing chains in order to allow cars to become "moving rain gauges" and build a network for precipitation monitoring and measurement, enhancing their conception of "car as sensor". Note that this kind of microwave rain gauges could be used on cars or standalone, and could be an integration of the common rain monitoring networks made by standard rain gauges and weather radars operating in different bands. A

short-range microwave rain gauge could be very useful in complex orography environment where narrow valley and high mountains do not allow standard instrumentations to get detailed and localized information about precipitations.

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