Human RCS Measurements and Dummy Requirements for the Assessment of Radar Based Active Pedestrian Safety Systems

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Abstract: *Based on EuroNCAP regulations the number of autonomous emergency braking systems for pedestrians (AEB-P) will increase over the next years. According to accident research a considerable amount of severe pedestrian accidents happen at artificial lighting, twilight or total darkness conditions. Because radar sensors are very robust in these situations, they will play an important role for future AEB-P systems. To assess and evaluate systems a pedestrian dummy with reflection characteristics as close as possible to real humans is indispensable. As an extension to existing measurements in literature this paper addresses open issues like the influence of different positions of the limbs or different clothing for both relevant automotive frequency bands. Additionally suggestions and requirements for specification of pedestrian dummies based on results of RCS measurements of humans and first experimental developed dummies are given.*

1. Introduction

Autonomous emergency braking systems for pedestrians (AEB-P) are already on the market, and their number will increase over the next years. According to the EuroNCAP Roadmap AEB-P systems will be evaluated as from 2016 onwards [1]. From a closer look at the accident analysis it becomes obvious that a considerable percentage of severe pedestrian accidents happen in artificial lighted urban areas, during twilight or even in totally dark inter-urban areas [2]. The aggravation of the visibility conditions and the related deficiency of hazard estimation seem to be possible reasons for this. Such scenarios could additionally be tightened through rainy weather and related reflections or glaring on the road surface. Future AEB-P systems will help to reduce the number of accidents even in these situations. Especially radar sensors are not affected by adverse lighting or weather conditions like rain or fog. Most of today's active pedestrian safety systems are based on the fusion of video and radar sensors. Both facts indicate that radar sensors will be among the environmental sensing systems being used in future AEB-P systems. For the correct assessment of the systems a pedestrian dummy suitable for both sensor technologies will be essential. To ensure real life performance during the assessment of radar based systems, human reflection characteristics must be induced by the dummy as realistic as possible. During specification of a suitable pedestrian dummy many questions regarding the human reflection characteristics arise. An important key parameter especially for radar is the definition of the dummy's Radar Cross Section (RCS). It describes the amount of energy which the target object is able to reflect back in the direction of the radar sensor. The value depends on material, size and the incident and reflected angle, etc.

2.Human Reflection Characteristics

The challenge to determine the RCS of a human being is treated in literature only a few times. Ritter [3] states that the human body could be divided in two parts, the HAT (Head, Arms, Trunk) and the locomotor system. Thereby the HAT forms the significant part of the total RCS. In [4] the variations in the RCS of the human body parts are assumed to be the most significant influence to the RCS of a human being. Absolute RCS values which can be found in literature are in range of -3 to +4.8 dBsm [5], [6]. First human RCS measurements in the 76 GHz band were published by Yamada [7]. It was found that the mean value of the human RCS is -8 dBsm with a variance of ±10 dB. Yamada further stated that the value of the RCS of a person illuminated from the side is 5 dB lower compared to that of the front or back view. During walking the posture, relative orientation, irradiated aspect and distance to the sensor are constantly changing. Therefore the pedestrian RCS underlies a higher fluctuation than that of a car. Measurements of clothing indicate that a human with wool clothing has a low RCS, and with cotton nearly the same RCS as without clothes [7]. Regarding the fluctuation model, Dogaru found that the human RCS follows the Swerling Model type three for frequencies less than 2 GHz and a Swerling Model type one for frequencies above 2 GHz [8].

Albeit these few results the knowledge published in the field of human reflection characteristics is not sufficient enough to specify a pedestrian dummy in detail. Partly the found values are contradictory, and the number of different investigated persons is still quite low. Open issues are especially the influence of different positions of the limbs or the effect of different clothing to the RCS of a human. Furthermore the human RCS was never measured in parallel in the two relevant automotive frequency bands (24 & 76 GHz) with exactly the same measurement setup. Also a big issue is how human reflection characteristics could be best represented by a pedestrian dummy.

3. Measurement Setup

Fig. 1 shows a picture of the measurement setup in the anechoic chamber of the European Microwave Signature Laboratory (ESML) of the European Commission's Joint Research Centre (JRC) in Ispra, Italy. Test objects were placed on a turntable with a distance of 3.4 m to the two standard horn antennas with a half power beam width of 20° in elevation.

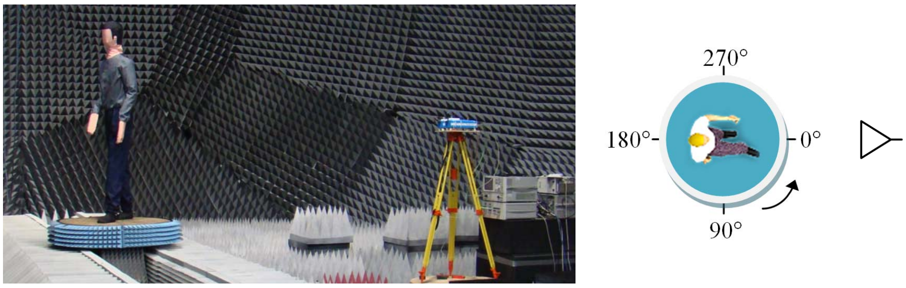
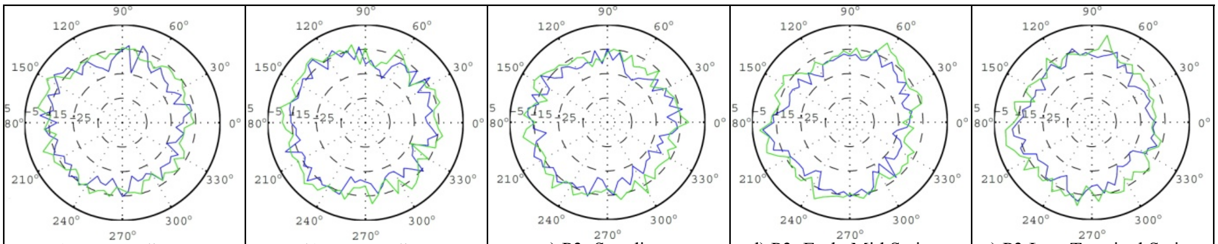


Fig. 1: Measurement setup in the anechoic chamber

In vertical direction the antennas were positioned 0.8 m higher than the turn table. This ensured an illumination of almost the entire pedestrian. Measurements were performed simultaneously in the two relevant automotive bands, 23-28 GHz and 76-81 GHz, by using two Vector Network Analyzers triggered by a common input signal. A very large bandwidth of 5 GHz has been chosen to achieve a high range resolution in the time domain. Hence time gating could be applied to isolate the backscatter from the target and to remove unwanted contributions like Tx/Rx coupling or background clutter. As a consequence the measured average power of the empty room was at least 35 dB lower as the power reflected by the investigated targets. Therefore background subtraction was not needed. To determine the RCS characteristics of humans and dummies three different types of analyses of the measured data are given in the next section. For evaluation of the angular dependency the RCS integrated over the respective frequency band is given in 360° polar plots. RCS signatures were measured over the entire azimuth angle using 1° steps for dummies and 5° steps for pedestrian to keep the error caused by possible unwanted position changes during the measurement time as low as possible. Furthermore, range profiles were computed to provide the possibility for deeper analysis of the scattering centers. In these plots the range of the different scattering centers and their corresponding RCS, expressed in dBsm vs. azimuth angle in degrees, are displayed. Additional to those high level analyses an easy comparable overall frequency and azimuth averaged RCS was computed.

4. Human RCS Measurement Results

To gain measurement data with a high level of reliability the RCS of three persons with differences in body structures have been measured. From Fig. 2a-c it can be seen that the mean value of the human RCS follows a nearly uniform distribution over the aspect angle. Because the reflected power corresponds to the size of the illuminated area the RCS of the front and back side is slightly higher than the RCS of the side of a human body. As a result of the plain shape of the back and the oval shaped front side of a human, the RCS of the back is slightly higher than the RCS of the front side. Comparing the measurements of the three different investigated pedestrians the frequency and azimuth averaged RCS of a standing human can be defined to be in range of [-4 -5.2] dBsm for the 23-28 GHz band and to be in range of [-6.1 -6.9] dBsm for the 76-81 GHz band with a variation up to 1.2 dB between the three mean values of the different persons of Fig. 2a-c.

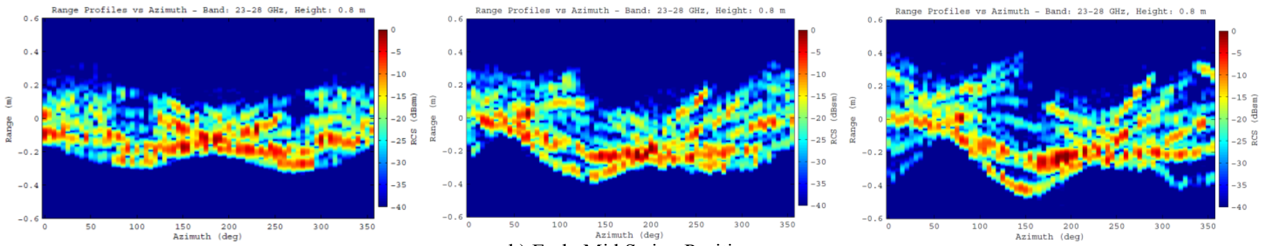


a) P1: Standing			b) P2: Standing			c) P3: Standing			d) P3: Early Mid Swing			e) P3:Late Terminal Swing		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
-11	**-5.2**	**0**	**-15**	**-4.0**	**0**	**-11**	**-4.7**	**0**	**-14**	**-4.3**	**+2**	**-10**	**-4.6**	**+2**
-15	**-6.9**	**0**	**-15**	**-6.1**	**0**	**-15**	**6.7**	**-1**	**-16**	**-7.0**	**+1**	**-15**	**-7.4**	**-2**

Fig. 2: Polar plots of freq. avg. RCS in the 23-28 GHz band (green) and 76-81 GHz band (blue) and corresponding frequency and azimuth averaged RCS. All values in dBsm.

To determine the influence of different limb positions RCS measurements during two different phases of the human gait cycle have been recorded. Additional information relating the eight phases of the human gait cycle are available in [9] and [10]. According to the symmetric geometry of the locomotor system and the challenge of holding exactly the same position until the entire 360° measurements have been completed, it was considered as sufficient to measure the RCS in positions of the early Mid Swing phase and the late Terminal Swing phase of the gait cycle. Thereby test persons kept their positions static until measurements over the whole aspect angle were completed. RCS polar plots of pedestrian number three in both bands and both mentioned positions are shown in Fig. 2d-e. The angular distribution of the RCS of gait cycle positions is slightly unsymmetrical compared to the polar plots of the standing position. This is caused by the unsymmetrical shape of the pedestrian in moving position. Further the frequency and azimuth averaged RCS values in the 76-81 GHz band are slightly lower compared to the value in standing position. In moving position the shape of a human becomes more complex e.g. caused by the slant position of the arms and legs. It is assumed that the amount of power backscattered in other directions than in the direction of the receiver antenna is higher compared to the standing position. Further, in moving position, a higher RCS of the side view of the pedestrian can be observed. This is caused by the extension of the reflective surface in moving position whereas in standing position the legs shadow each other when illuminated from angles near 90° or 180°. Typically the observed variations caused by the different positions are less than 1 dB.

In Fig. 3 the 24 GHz range profiles of the tall person in standing, early Mid Swing and late Terminal Swing positions are given. For a standing person illuminated from the front (0°), side (90°/270°), or back view (180°) the scattering centers lie in a narrower radial range than when illuminated from other aspect angles. This implies that the human's surface is mainly responsible for the reflection. For aspect angles in between the above mentioned the range becomes wider, caused by the slant position of the human in which the radar waves are reflected by several body parts after traveling different distances, e.g. when reflected from the left and right side of the back. The significant range profile between the angles 125° and 250° in which the two reflection ranges cross each other is caused by the symmetry of the standing human body and the turntable related contrary position changes of left and right body parts.

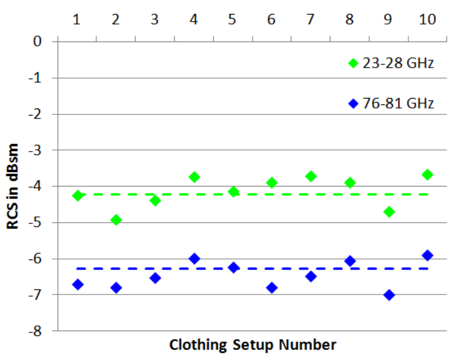


a) Standing Position b) Early Mid Swing Position c) Late Terminal Swing Position

Fig. 3: Range profile vs. azimuth in the 23-28 GHz Band

Fig. 3b and Fig. 3c show the range profiles of the two previously mentioned positions of the gait cycle with leg to leg distances of 0.3 m in the early Mid Swing position and 0.5 m in the late Terminal Swing position. In comparison to the standing position both range profiles are not symmetric related to the 180° axes because of the unsymmetrical pedestrian's shape in the two different gait cycle positions. Generally the range profile is stretched in the investigated gait cycle positions. Nevertheless minima in the range spread can still be recognized in azimuth ranges around 45° and 225°. At these angles both legs were in radial line with the antenna boresight such that the front leg shadowed the rear leg.

Further investigations were made to determine the influence of different clothes. Thereby measurements of test person three, dressed in several clothes of different fabrics and sizes, have been carried out. The frequency and azimuth averaged RCS of each setup measured in the two frequency bands are displayed in Fig. 4. Corresponding average values of -4.2 dBsm regarding the 23-24 GHz band and of -6.3 dBsm regarding the 76-81 GHz band are marked by dotted lines. Since the RCS of all the investigated clothing setups were measured in a narrow range of less than ±1 dB around their mean values, a significant RCS dependency on the investigated clothing setups cannot be deduced. The reason for this seems to be the thickness of the clothes which for all investigated materials is smaller than the wavelength. Therefore the cloths are almost transparent for the radar waves.



Clothing Setups:
01 - Polyester Sport Shirt
02 - Polyester Fleece
03 - Polyester Softshell Jacket
04 - Polyacrylnitril Sweater
05 - 50% Polyester / 50% Cotton Sweater
06 - Leather Jacket
07 - Wool Coat (finely woven)
08 - Wool Cardigan (large meshed)
09 - Cotton Shirt & Cotton Trousers
10 - Rain Jacket & Rain Trousers

Fig. 4: Frequency and azimuth averaged RCS of different clothing setups

5. Pedestrian Dummy RCS Measurement Results

In this section RCS measurements of experimental developed pedestrian dummies are compared to previously introduced measurement results of humans. Fig. 5a displays a picture and the measured range profile over azimuth of a synthetic foam based dummy developed by the vFSS group. To add radar reflectivity to the less reflecting foam body the dummy has been equipped with several scattering centers consisting of aluminum tape. Thereby frequency and azimuth averaged RCS values of -7.6 dBsm for both investigated frequency bands weree achieved. At least for the 76-81 GHz band this seems to be a reasonable value compared with human measurement results. Taking a look at the range profile of the dummy it can be seen that reflections are not equally distributed over the aspect angle and underlie a higher level of fluctuation. Further the strongest scattering centers are in different range domains, and the overall RCS is not only caused by the surface but also by some internal parts of the dummy.

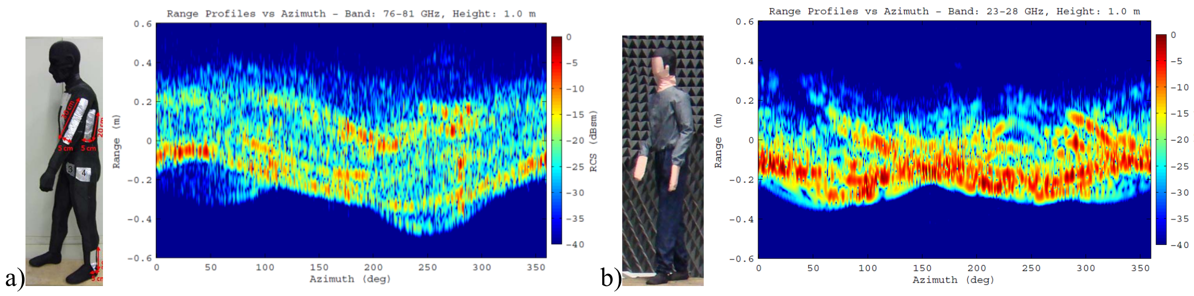


Fig. 5: Picture and range profile of a dummy with spotty (a) and distributed reflection capabilities (b)

In Fig. 5b a picture of a dummy developed by 4a engineering GmbH and its corresponding range profile are presented. A different concept of adding reflectivity to the foam body was applied. Thereby the dummy was covered by a special jump suit consisting of a combination of fabric and aluminum. The RCS averaged over frequency and azimuth amounts to -2.1 dBsm (23-28 GHz band) and to -2.9 dBsm (76-81 GHz band). Both values are several dB higher than corresponding values of humans. Analyzing the range profile it can be observed that the main part of the power is reflected by the surface of the dummy. Furthermore, previously described human reflection characteristics, like characteristic reflections of arms, legs and the body, could be also observed in the dummy's range profile. In summary the range profile over azimuth of the dummy of Fig. 5b with distributed RCS shows a higher degree of similarity to the human range profile of Fig. 3a. Although only range profiles in the 76 GHz band are presented in Fig. 5, same effects have been observed in the 24 GHz band.

6. Conclusion and further activities

Extending the small amount of previously published information, detailed evaluations of human RCS measurements have been presented. Combining all achieved measurement results of section four it can be concluded that the RCS of pedestrians averaged over frequency and azimuth are in ranges of [-3.6 -5.2] dBsm for the 23-28 GHz band and [-5.9 -7.4] dBsm for the 76-81 GHz band. Applying further averaging of all presented measurements mean RCS values of -4.3 dBsm for the 23-28 GHz band and -6.6 dBsm for the 76-81 GHz band can be derived for humans. Evaluations of range profiles and polar plots show that variations in position or clothing cause only marginal impact to RCS.

After comparing measured data of humans and data of some experimental realized pedestrian dummies, it was recognized that simply adding a small amount of reflectors with appropriate RCS values to a dummy made of low reflecting material is not sufficient enough to represent realistic human reflection characteristics. Comparable to pedestrians, the entire surface of the dummy must be capable to reflect electromagnetic waves in both relevant frequency bands instead. Thereby a so called distributed RCS is achieved. Additionally mean values of the RCS similar to that of real humans should be achieved over the entire aspect angle by pedestrian dummies. Concerning this, the RCS averaged over frequency and azimuth of the dummy shown in Fig. 5b is several dB too high.

Another strong argument for the requirement of distributed RCS is the way automotive radar sensors are designed. To ensure high detection ranges with today's available emission power elevation angles of automotive radar sensors are kept rather small. Although only the lower part of the pedestrian body is illuminated by radar sensors at short distances, today's radar sensors do not have significant problems detecting pedestrians. By reproducing the distributed human reflection capability over the dummy's entire surface the problem of detection loss caused by elevation angle limitations is avoided. Pedestrian dummies with distributed reflection capabilities are also more suitable to be used in future possible enhanced AEB-P test scenarios addressing turning maneuvers or intersection accidents for example. In such scenarios the angles between sensor and pedestrian changes highly dynamically over a large range. Therefore the RCS should be defined in a specified range over the whole azimuth. This issue can be easily addressed by a distributed RCS of the dummy. Another point to be considered is the evaluation of the Micro-Doppler effect. This effect, caused by limb movement, could be used by future radar based AEB-P systems to classify detected objects as pedestrians. The effect could easily be added to the pedestrian dummy by simply implementing arms and legs articulations without touching the RCS specification again.

As a conclusion of all the facts stated above the requirement for distributed reflection characteristics leads to a higher level of usability of the specified pedestrian dummy. Additional investigations must be carried out in future to select more suitable materials and methods to reproduce human reflection characteristics distributed over the entire dummy surface while simultaneously achieving adequate RCS values over frequency and azimuth.

7. Acknowledgements

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