Analysis of Automobile Scattering Center Locations by SAR Measurements

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***Abstract*—Synthetic aperture radar (SAR) is known to have the capability for a range independent high-resolution cross range processing. In this paper the SAR processing is used to localize the scattering centers of an automotive target at 24 GHz and 77 GHz at different bandwidths. Furthermore, the combination of digital beam forming (DBF) with SAR initiates the opportunity to determine the exact location of the scattering center in azimuth, height, and range.**

Keywords-scattering center; automotive radar; 24 GHz; 79 GHz; SAR processing

I. Introduction

In the automotive environment safety and advanced driver assistance systems are essential to avoid or mitigate accidents. Radar sensors are commonly used to recognize dangerous situations at an early stage. Due to diverse urban scenarios, radar sensors have to cope with different target types. A target, observed by a radar sensor, has several distributed scattering centers. If the radar sensor is receiving its originally transmitted and reflected signal, a superposition of different backscattered waves will occur. A preliminary knowledge of the main locations of the scattering centers can improve to determine the orientation of the vehicle and hence to provide further target information. Furthermore, by knowing the spacing of two neighboring main scattering centers, the required bandwidth and angular resolution of the radar sensor setup can be adapted.

II. Influence of the Scattering Center

A. Interrelation between scattering center and resolution

The scattering centers of extended targets, like vehicles, are often well distributed and exhibit an angular dependency of its backscattering characteristics [1]. Considering a backscattered radar signal, fluctuations of the power density depending on the direction of arrival occur. In the case of several scattering centers in one range and angular cell, symbolized by the asterisks in Fig. 1, constructive and destructive superposition of signals received from the different scattering centers arise. Small movements of the vehicle or even the vibration of the running engine have influence on the target signature or on the impulse response of the radar channel. Hence, each scattering center causes at a specific incident angle amplitude and phase fluctuations over time and space, symbolically depicted at the output of the radar sensor in Fig. 1, above. If the main scattering center is surrounded only by small or no additional scattering centers there will be less fluctuations compared with two closely located main scattering centers placed in the same range and angular cell. To reduce the time and space dependent fluctuations of the received signal, the bandwidth and the angular resolution can be adjusted to the spacing of two neighboring main scattering centers of the target. Hence, the output of the radar sensor will have less fluctuations over time and space, as illustrated in Fig. 1, bottom.

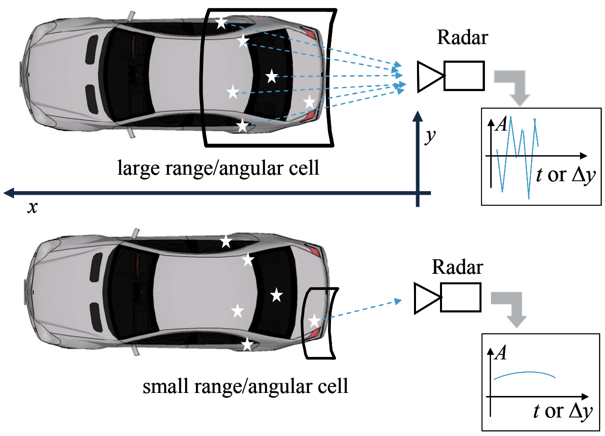

Fig. 1. Influence on amplitude fluctuations of the received signal by different range and angular cell size.

For example, automotive long range radar sensors (LRR) are confronted with this effect if they have a large range cell of 1 m (approx. 150 MHz bandwidth). If an extended target is mainly within the range cell (defined by the range resolution), amplitude fluctuations can be caused by longitudinal as well as lateral movements of the target, due to the interfering scattering centers. By increasing the bandwidth to 2 GHz, the range cell size will be reduced to around 7.5 cm. Reducing the range cell size increases the complexity of the signal processing if the maximum range of the radar sensor does not change. However, a smaller range gate can contain less scattering centers in the same range cell, and hence the parasitic amplitude fluctuations can be reduced. Fewer fluctuations in target signature will improve the reliability of the electronic control unit (ECU) for safety applications.

B. Measurement setup to determine the main scattering center localizations

There are different techniques used to determine the reflectivity of targets, like measuring the radar cross section (RCS) of a target placed at a turntable [2]. Typically, only the superimposed contribution of all scattering centers at one specific angle can be measured and hence, the actual position of each scattering center is not resolved. By using synthetic aperture radar (SAR) instead, together with a large bandwidth, both range and cross range resolution is much better, and the contributing scattering centers can be exactly located. With the strip map SAR principle as used here, the cross range resolution amounts to approximately half of the dimension of the SAR antenna.

The SAR measurement setup for the analysis of the scattering centers consists of a height adjustable linear unit which drives a monostatic FMCW radar sensor, as depicted in Fig. 2. The lateral movement of the sensor is driven by the stepper motor of the linear unit and can be controlled by the RS-232 interface of the laptop computer. The necessary driveway of the entire measurement movement has to be selected such that at both sides the target is just at the slope of the antenna beam. For signal processing the control unit of the radar sensor supplies the AD converted time signal via the USB 2.0 interface to the laptop computer. This laptop computer communicates as well via the RS-232 interface with the control unit for initializing and polling the data of the radar sensor [3].

The used FMCW radar sensors includes a phased-locked-loop stabilized signal source and has a range compensating intermediate frequency filter in the receiving path to exploit efficiently the dynamic range of the analog to digital converter. The specifications of the used high performance FMCW radar sensors can be seen in Table I. The start frequency, sweep time, and bandwidth of each FMCW radar sensor can be adapted to the needs of the measurement setup. For the two dimensional measurements of the vehicle signature the FMCW radar sensor 1 and 2 were arranged with a reflect array antenna. Extending the analysis of the scattering centers of the target to the third dimension (elevation), radar sensor 3 was applied with a lens antenna, fed by a patch array with 32 switchable transmitting and 2 simultaneous receiving antenna elements [4]. With this concept an equivalent aperture of 64 antennas spaced by half a wavelength is formed [5] and the delay&sum beam forming algorithm could be used to process the scattering centers of the target in elevation.

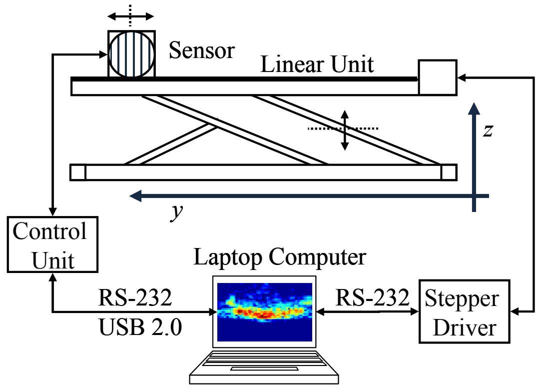

Fig. 2. SAR measurement setup for the scattering center determination.

TABLE I. TECHNICAL DATA OF THE FMCW RADAR SENSORS

Parameter	**FMCW Radar Sensor Variants**		
	Sensor 1	***Sensor 2***	***DBF- Sensor 3***
Start frequency	24 GHz	73.5 GHz	74 GHz
Bandwidth	2 GHz	(0.5..7) GHz	4.8 GHz
Theor. min. range cell size	7.5 cm	2.1 cm	3.1 cm
Antenna HPBW (azimuth)	4.9°	2.6°	6°
Antenna HPBW (elevation)	4.9°	2.6°	2.5° [a]
Stepping size	33.9 mm	18.6 mm	9 mm

a. DBF: delay&sum (32 TX, 2 RX antenna elements)

III. MEASUREMENT OF THE SCATTERING CENTERS

In the following results of SAR measurements the scattering centers of a Mercedes Benz S-class will be shown and analyzed at different views of the vehicle, center frequencies, and bandwidths. The radar sensors were placed at the SAR measurement unit, moving lateral in front of the car. The measurements took place on an asphalted lane. The radar antenna was adjusted at the height of 60 cm with horizontal polarization.

A. Influence of the scattering centers at 24 GHz and 77 GHz

To analyze the effect of different carrier frequencies on the distribution of the scattering centers, radar sensor 1 and 2 were placed in front of the car's rear end at a distance of approximately 10 m for measurement. In Fig. 3 the contour of the vehicle's rear end can be seen clearly at the center frequency of 24 GHz as well as at 77 GHz, both adjusted to a bandwidth of 2 GHz. The main scattering centers were found at the region of the license plate and the rear light unit at a distance of 10.5 m. At 11 m, the tire tread and the wheel rim of the left and right side of the vehicle's rear end were identified. The exterior rear view mirror reflected at the distance of 13.6 m. At 24 GHz the effect of the tire tread, the wheel rim, and the mirror on the right hand side of the vehicle front end could not be seen due to the short driveway of the linear unit of 2.3 m and the lateral misalignment of the vehicle.

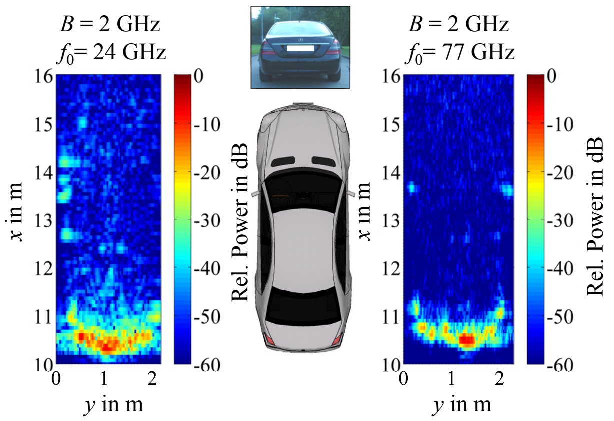

Fig. 3. Comparision of the location of the scattering centers at 24 GHz and 77 GHz of the vehicle rear end with a bandwidth of 2 GHz.

B. Comparision of different bandwidths at 77 GHz

The comparison of different bandwidths supports to analyze if there are certain physical limits considering the spacing of two neighboring main scattering centers. Hence, radar sensor 2 was attached to the SAR measurement unit. The rear end of the car was analyzed by varying the range resolution, adjusting the bandwidth from 0.5 GHz to 7 GHz at the center frequency of 77 GHz. The reduction of the range resolution was done by reducing the sweep time duration of the transmitted linear FMCW sweep, maintaining a constant slope of 3.571 GHz/ms. However, reducing the time duration of one linear FMCW sweep reduces the signal level, and hence the signal to noise ratio (SNR) from 7 GHz to 0.5 GHz declines. The relative power of each measurement result, shown in Fig. 4, is normalized to the highest occurring signal peak of the measurement at the bandwidth of 7 GHz.

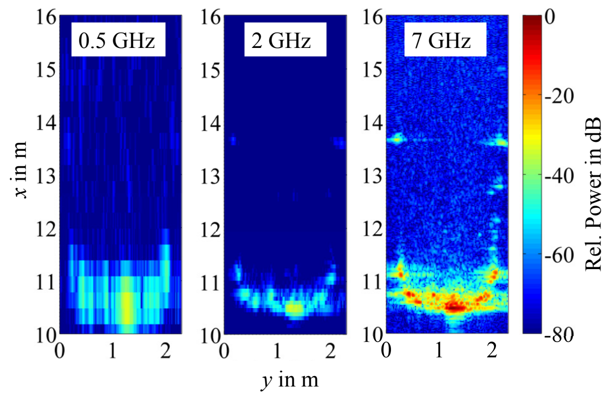

Fig. 4. Influence of the bandwidth from 0.5 GHz to 7 GHz on the vehicle rear end at 77 GHz.

Reducing the bandwidth increases the range cell size. Hence, the amount of scattering centers within one range cell augments, and therefore the superposition of all scattering centers within one range cell increases as well. This influence was seen at the location of the license number (*x*: 10.5 m, *y*: 1.25 m), the tire tread (*x*: 11.1 m, *y*: 0.26 m/2.01 m), and the exterior rear view mirror (*x*: 13.7 m, *y*: 0.19 m/2.18 m). It can be noticed, that the actual location of these scattering centers shifted and the size of the scattering center seemed to be expanded by reducing the bandwidth from 7 GHz to 0.5 GHz. However, the size of the scattering center does not really change, moreover the spatial sampling in range coarsens the range information and hence the superposition of several scattering centers within one range excites. However, increasing the range cell size worsens the uncertainty of the exact location and size of the scattering center. Due to the range independent lateral resolution in SAR processing the width of the vehicle still could be recognized even by reducing the bandwidth.

C. DBF combined with SAR processing

The DBF sensor 3 of Table I was applied to the SAR measurement unit for the three dimensional analysis of the scattering centers. As in previous measurements the scattering centers of the vehicle were obtained in azimuth by SAR processing and in elevation by DBF. The DBF sensor 3 using horizontal polarization was aligned vertically for elevation measurement. The measurement took place at a standard asphalted lane. The vehicle was placed in a distance of 5 m in front of the radar sensor. The radar sensor was started at the origin of the *x*, *y*, and *z*-axis and drove in y direction for measurement. The asphalted lane was located at *z*-axis of -60 cm. Corner reflector A was adjusted at the height of 0.9 m (z = +0.3 m) with a RCS of +20 dBsm (at 77 GHz) and the corner reflector B with a RCS of +30 dBsm (at 77 GHz) was placed a the road surface hidden behind the vehicle. The measurement result with normalization to the highest signal amplitude is depicted in Fig. 5. All measurement data, lower than the threshold of -10 dB, are suppressed. In Fig. 5 multilayered reflection regions are depicted, hence strong reflections are covered partly by reflection regions with lower reflectivity. This influences the coloring of the displayed relative power of Fig. 5.

The measurement result of the characteristic scattering centers of two corner reflectors A and B, and the scattering centers C to I of the vehicle are depicted in Fig. 5. The corner reflector A was standing in line of sight with the radar sensor. The corner reflector B instead was placed behind the vehicle, and the position could only be determined by multipath propagation. These two corner reflectors were used for reference purposes. Reflection regions C to I of Fig. 5 remain from signal reflections of the vehicle. The door outer skin C had a strong reflection region starting close to the front wheel and ending close to the back wheel. However, there were two remarkable disruptions of the continuous backscattering at the door gap D of the front door. This leads to the assumption that at small door gaps in between of the body cavities the backscattering behavior of the gap is low. Furthermore, there were distributed reflection regions at the side sill beneath the door outer skin, represented by E of Fig. 5. Additionally, pseudo reflection regions F were measured below the road surface. These reflections were caused by multipath propagation between the road surface and the door outer skin. Finally, the front as well as the rear wheel had distinct backscattering characteristics. The wheel-arch panel itself had no significant influence to the front and rear signature of the vehicle. Mainly the wheel rim with the tire tread G as well as the wheel suspension H excited strong reflections. In Fig. 5 the reflection region I is depicted, which arises at the rear wheel. It results from backscattering behavior of the tire tread in combination with the road surface. This effect could also be seen if a dihedral would be sited instead at the same position of the wheel.

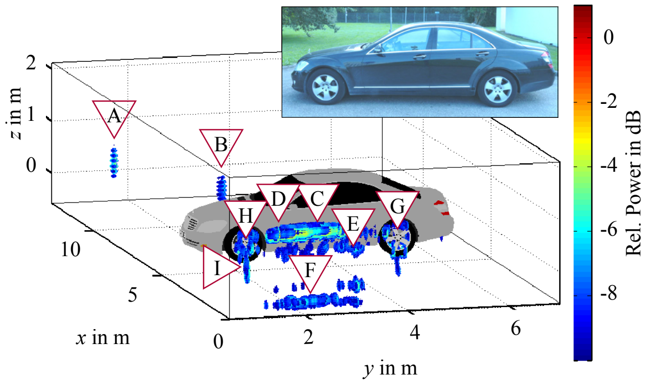

Fig. 5. DBF+SAR processed radar image of the vehicle side view at 77 GHz with a bandwidth of 4.8 GHz.

Conclusion

By using SAR processing the location of the scattering centers of vehicles can be measured precisely. The knowledge of the real location of the scattering centers can be used to improve the estimation of the orientation of vehicles in front of the radar sensor. The measurement results show that there is no remarkable difference of the scattering centers considering a carrier frequency of 24 GHz or 77 GHz. The bandwidth instead has a strong influence on the resolution capability of the scattering centers. The three-dimensional analysis of the vehicle side view shows that there are strong reflections at the tires and at the center body of the vehicle. These measurements will help to build up an improved model of the respective car.

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