1. INTRODUCTION

Road traffic characteristics imply the traffic volume expressed as the number of vehicles passing through a specified road segment in a given direction along a given traffic lane per unit of time as well as the speed, the traffic route, the distance, and the linear dimensions (most often the length) of the vehicle used for its classification and traffic route prediction.

There are two types of continuous wave radars used for measuring either all these characteristics or some of them. They are continuous wave radars without the carrier modulation known as CW radars (Continuous Wave Radars) and continuous wave radars with frequency modulation or FMCW radars (Frequency Modulation Continuous Wave Radars) [1]. Each radar has its own advantages and disadvantages. As a rule, direct frequency conversion to the zero intermediate frequency is used in both cases. CW radars can be used for measuring the traffic route and the radial speed (as well as the ground one determined with the help of recalculations), and FMCW radars, for measuring the traffic route, the radial (and ground) speed, and the distance to the target [1].

In principle, it is not a problem to measure the characteristics of the vehicle motion using both types of radars at a sufficiently large signal-to-noise ratio provided the radar beam is narrow in the horizontal plane and broad in the vertical one and if only one vehicle with small angular and linear dimensions (conditionally close to the point target) is illuminated by the beam during the measurements. However, the generation of such a beam requires antenna arrays with relatively large horizontal dimensions. Thus, in the frequency ranges allowable for these aims (10.525 GHz – X band [11]; 24–24.25 GHz – ISM or K band [12]; and 76, 77–81 GHz – Technical Standards EN301091, EN302288-1 V1.1.1, and ETSI [1, 2, 3, 4]), the beam’s width is usually (12...30° in the horizontal plane and (40...50° in the vertical plane at the acceptable dimensions of the radar and its antenna arrays [5, 6, 11].

The problems of measuring the parameters of targets, their number, and the distance to each of them are faced in the following cases:
—when there are several targets from one traffic route in the beam’s illumination zone and they partially or completely overlap;

—when the dimensions of one target are comparable with the beam size at the point of its location and this target creates several divisible points of reflection (several “bright” points) toward the radar, which (at the mentioned beam width and ranges of 3–50 m (short-medium range) to the target) is often met in practice.

In addition, very often a near lane vehicle is on one line of sight with a far lane vehicle moving in the opposing direction, and they are simultaneously illuminated by the radar beam. In this case, the near target can screen the far target. It is also important to study the effect of the lateral lobes of the directivity diagram (DD) of the radar antenna array and to fight this effect since the near target (depending on the range and dimensions) can generate a signal with a higher level and, thus, jam the signals from the opposing traffic route through the lateral lobes since its Doppler shift is of another sign than that in the main lobe.

It should be also noted that, as distinct from the police radars intended for measuring the distance to the specified car and its speed [1, 3, 5], the principles of designing recorder radars for real-time measurement of the current number of transport means are poorly described in the technical literature though, judging by the advertising material and published installation manuals [7, 8, 9, 10, 11, 12], such devices have been already developed and have been manufactured for a long time.

Thus, the description of the research work on the analysis and synthesis of such devices carried out by the authors and the discussion of the results of testing the developed radar prototype in real city conditions will be useful for a wide circle of specialists busy with the development of the equipment for analyzing the volume of city road traffic.

In the process of the research work, the possibilities of measuring the key characteristics of the road traffic (the current number of traffic means, the speed and the traffic routes of vehicles) with continuous wave radars of both types (FMCW and CW) in the case of solitary and multiple targets simultaneously moving in similar and opposing traffic directions illuminated by a beam were compared. The characteristics of the traffic routes of transport means were measured based on a newly synthesized method for digital signal processing that was not published before. This method was tested in situ with the help of the working experimental prototype of the 24 GHz radar with two (transmitting and receiving) integrated patch microstrip antennas. During the in situ measurement, the directivity diagram of the FMCW radar was positioned at the angles of \((45\ldots60)°\) with respect to the roadbed to measure the speed in addition to the distance. In the majority of the experimental scenarios, this angle for the CW radar was selected to be close to \((37\ldots45)°\). Due to the necessity of measuring the two parameters mutually affecting the accuracy and the resolution, namely, the range and the speed, the FMCW radar turned out to be more complicated from the standpoint of the digital processing algorithm and proved to be less noise-immune and less accurate when measuring the number of vehicles in the city road traffic conditions as compared to the CW radar. Thus, below we give the results of the performed experiments and the experimental verification for the CW radar only.

2. REAL-TIME RECORDING OF THE NUMBER AND SPEED OF THE TRANSPORT MEANS WITH THE HELP OF CW RADAR

A CW radar uses a transmitter with unmodulated radiation. Thus, it cannot be used for measuring the distance to the target at such high frequencies as 24GHz. Using the Doppler effect, it is possible to measure both the speed and the traffic route of the targets; moreover, it will be shown below that it can be done even when two or more targets are simultaneously illuminated by the beam provided they do not screen one another in the beam’s direction. In this case, it is possible to simultaneously count the number of targets on each opposing traffic route in the real-time mode. As far as the ground speed is concerned, it is estimated by recalculating the radial speed at the known angle between the speed vector (considered to be parallel to the road axis) and the direction toward the radar. In this case, it is assumed that the radar DD is sufficiently narrow for the error of the speed measurement due to the DD’s finite width to be negligible.

The key problem to be solved by the radar when measuring the road traffic volume is to determine the number of vehicles passing by the radar in opposing routes (to serve as a Remote Traffic Counter). Several solutions to this problem can be proposed.

The first method is the separate recording of the targets based on the envelope amplitude maxima of two complex analytical signals (each corresponding to its own traffic route) obtained from the signal received after the quadrature mixer with the help of the fast Fourier transform (FFT), the separation of
the complex spectrum into positive and negative frequencies, the inverse FFT for each spectrum half, and the calculation of the Gilbert envelope for each of them.

In the second method, it is proposed to use the speed (Doppler) trajectories of the targets obtained during the time period when they were illuminated by the radar beam with the main DD beam being at the angle of (−45°) with respect to the road axis. The use of the speed trajectories for the vehicle classification with the help of a CW radar in the longitudinal beam was considered, e.g., in [6].

The first method has been implemented and tested. It has a number of disadvantages. The first and the most principle one is related to the substantial spread in the amplitudes of the envelope maxima formed due to reflections at the transport means that are at different distances away from the radar in the presence of the receiver noises and Doppler interferences. False detection is possible if the recorder operating threshold is set close to the noise level; if the threshold is set to be high, far targets can be missed. Moreover, there is another drawback associated with the amplitude and phase unbalance of the IQ mixer. In addition to the maxima in the envelope of its own route, the unbalance from the high-level targets running along one route yields the formation of pronounced maxima in the envelope of the opposing route at the same time positions; they lead to false detection of the vehicle on this route. The check of the first method for target recording in real conditions demonstrated its poor efficiency.

From the standpoint of the vehicle number recording, the second method based on using the speed trajectories of the moving transport means illuminated by the CW radar beam proved to be the most effective.

The idea of the trajectory method can be explained with the help of Fig. 1 showing the schematic of the CW radar and the estimation of the current number of the maxima and their magnitude (i.e., the radial speed) for the trajectories of the variations (simultaneously in both directions) in the speed of the vehicle illuminated by the radar beam.

The continuous signal of the transmitter generated by a small-size patch microchip antenna is reflected at the moving vehicle illuminated by the beam and received by a similar antenna of the receiver; then it is amplified by a low-noise amplifier (microwave device (MWD)) and fed to the IQ-mixer output. After amplification and LF prefiltering ("for anti-aliasing") the quadrature beat-frequency signal from the outputs of the I and Q mixer is fed to the ADC inputs and is digitized. After the decimation of the counts and the addition of zeros (applied for more accurate fixation of the maxima positions and their magnitudes in the frequency range (zero-padding procedure)), it is supplied to the FFT input either directly (without amplitude and phase correction) to the I₁ and Q₁ inputs or to the I₂ and Q₂ inputs through the IQ-mixer circuit for automated amplitude and phase correction.

After the FFT, the amplitude—frequency spectrum (AFS) is calculated separately for the positive (“+”) and negative (“−”) Doppler frequencies. The reflections from stationary and low Doppler targets are picked off by the speed threshold by nulling the Doppler positions from the zero speed to the specified hump speed value.

Using the AFS, with the help of the moving averaging within the limits of the Doppler frequency band selected based on the minimum of false alarms of the counter, the “floating” threshold is calculated and a selected constant component (pedestal) is also added to it. The floating amplitude threshold is used for suppressing noise-like interferences.

Then, the following operations are performed for the positive and negative AFS frequencies: (1) isolation of two (the largest and the largest but one) maxima (the first and the second peaks) and their Doppler positions (they being integers) in the spectrum; (2) the median time filtering of the Doppler position trajectories (medial smoothing) separately for the first and the second peaks; and (3) the linear LF filtering of the same trajectories aimed at their temporal smoothing. The median and the linear filtering are performed in real time (floating filters) as the data are received. It is necessary to isolate two maximum peaks to use them for the simultaneous detection of several targets illuminated by the beam. In many cases, the joint use of the speed trajectories of both maxima allows solving such problems.

For the time reality of the entire processing procedure to be ensured, the input data blocks at the neighboring FFT determination ranges are formed with half overlapping (real-time FFT). In this case, as one range is being processed by the FFT-processor, the other range is being filled with the data and then, vice versa, the last block is being processed by the FFT-processor while the first one is being filled with the data; this process going on periodically.

The AFS maxima are isolated using the technique of moving triads of the neighboring counts exceeding the floating threshold. To avoid the errors during this isolation (since the targets are not point-like), such a procedure is performed in two stages: the first passage over the triads; the second one, over the previous results. To avoid the blanks due to the limited digit capacity of the number representation, a moving
The triad can be supplemented with one more count, which can be taken beforehand to check the mutual equality of the two previous counts.

A moving vehicle is recorded by the counter when fixing the maximum current speed trajectory (Doppler position trajectories). The maximum of the speed trajectory approximately corresponds to the instant

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**Fig. 1.** Functional diagram of the radar intended for recording the number of vehicles and measuring their speed simultaneously for two opposing traffic routes using the second method with the help of speed trajectories.
when the recurrent target leaves the main lobe of the radar antenna DD (beam) during its left-to-right motion or when it enters the beam in case of its right-to-left motion (see Fig. 2). The position of the AFS maximum in this case corresponds to the radial speed, which is the closest to the ground speed when the vehicle intersects the beam Right-to-Left or, vice versa, Left-to-Right.

In the process of the measurements, the lateral lobes of the radar antenna DD can lead to jamming (see Fig. 2). The left lateral lobe of the DD in the case the vehicles pass close by the radar can yield formation of interference speed trajectories in the opposing direction, while the right lobe, in the same direction. These interferences can be effectively suppressed if the radar is turned so that the left lateral lobe is in the range of zero radial speeds while the left one is turned from the road and its influence becomes weaker. Then, the speed trajectories formed by the left lateral lobe can be picked off as trajectories of the low Doppler targets, and the signals received by the right lateral lobe can turn out to be below the threshold level in case of such an additional amplitude turn and do not affect the counter response. In Fig. 2, $\Delta \theta$ is the angle of the additional turn.

Note that the considered method for the indication of mobile targets with a CW radar based on the maximum of the speed (position) trajectories has two significant advantages over the method of their detection based on the maxima of the direction signal envelopes. The first advantage is related to the fact that the maximum speed trajectories for the majority of the recording places (which can be determined beforehand) have a narrower dynamic range as compared to the maxima amplitudes in the envelopes. For example, the majority of the transport means in the road segments between the street lights in town or on highways out of town have speed limitations from above and from below. The speed depends on the position of the Doppler peak in the spectrum determination range rather than on the amplitude of this maximum, and variations in the maximum from range to range affect the detection (the fact of the counter response) of the mobile object to a lesser degree. The second advantage is associated with the fact that the radial speed of the target at the trajectory maximum is close to the ground speed (at least, it can be easily recalculated to the ground speed of a mobile object), i.e., the fixation of the maximum along the time axis and the speed of the object are combined in one event that does not require separate processing procedures during recording. The maximal value of the peak (its position in the spectrum) is, in fact, the radial speed of the corresponding vehicle, which can be easily recalculated to the ground speed. If the transport means are detected based on the maxima in the envelopes of the traffic route signals, the speed should be calculated using a separate procedure. In the last case, the fact of recording will substantially depend on the distance to the target, its position, interferences, and the target itself (namely, its effective reflecting area).

Figure 3 exemplifies the processing of a CW radar signal using the method for vehicle detection with the help of speed trajectories. The radar was positioned on a 1.6 m-high holder ~12 m away from the middle of the roadbed (with the viewing angle of the radar beam in the horizontal plane being $-45^\circ$) and it was focused on the dashed line separating the third and the fourth traffic lanes. Figures 3(a) and 3(b) show the radial speed (speed trajectories) as a time function for two traffic routes, namely, left-to-right and right-to-left, obtained as the result of processing one and the same 30 second-long record no. 64 in one of the
scenarios of the experiment for the beat-frequency signal from the I and Q outputs of the quadrature mixer.

Figure 3(c) shows the time dependences of the average DDF module for positive and negative frequencies of the Doppler spectrum (from range to range). Figure 3(d) demonstrates the analogous time depen-
DEVELOPMENT AND EXPERIMENTAL VALIDATION OF AUTOMATED RADAR

Method for determining the number of vehicles (“Doppler position trajectories”). The positions of the maxima (position), the total number of intervals (interval number), the frame number (FRAME), the speed (Gr. speed), and the number of the video filming frame (Video FRAME), km/h

<table>
<thead>
<tr>
<th>Number of vehicles “Left-to-Right”</th>
<th>Position (km/h)</th>
<th>Interval number</th>
<th>FRAME</th>
<th>Gr.speed</th>
<th>Video FRAME (Real moment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>134.8358</td>
<td>248</td>
<td>156</td>
<td>51.5986</td>
<td>113 1st vehicle, cabin</td>
</tr>
<tr>
<td>2.</td>
<td>135.0409</td>
<td>304</td>
<td>191</td>
<td>51.6771</td>
<td>169</td>
</tr>
<tr>
<td>3.</td>
<td>127.1527</td>
<td>424</td>
<td>266</td>
<td>48.6585</td>
<td>243</td>
</tr>
<tr>
<td>4.</td>
<td>142.2993</td>
<td>520</td>
<td>327</td>
<td>54.4548</td>
<td>303</td>
</tr>
<tr>
<td>5.</td>
<td>137.6203</td>
<td>576</td>
<td>362</td>
<td>52.6642</td>
<td>343</td>
</tr>
<tr>
<td>6.</td>
<td>133.0544</td>
<td>632</td>
<td>397</td>
<td>50.9169</td>
<td>368 passenger car with trailer</td>
</tr>
<tr>
<td>7.</td>
<td>133.9032</td>
<td>736</td>
<td>463</td>
<td>51.2417</td>
<td>441 jeep</td>
</tr>
<tr>
<td>8.</td>
<td>134.5199</td>
<td>808</td>
<td>508</td>
<td>51.4777</td>
<td>490</td>
</tr>
<tr>
<td>9.</td>
<td>137.5654</td>
<td>912</td>
<td>573</td>
<td>52.6432</td>
<td>553 minivan with metal table on the roof</td>
</tr>
<tr>
<td>10.</td>
<td>134.5708</td>
<td>1000</td>
<td>629</td>
<td>51.4972</td>
<td>608 white car of Audi-4 type</td>
</tr>
<tr>
<td>11.</td>
<td>135.8292</td>
<td>1368</td>
<td>860</td>
<td>51.9788</td>
<td>846 end of 2nd wagon of the 2nd bus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of vehicles “Right-to-Left”</th>
<th>Position (km/h)</th>
<th>Interval number</th>
<th>FRAME</th>
<th>Gr.speed</th>
<th>Video FRAME (Real moment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>-176.6885</td>
<td>1080</td>
<td>679</td>
<td>67.6147</td>
<td>663 wagon with platform trailer</td>
</tr>
<tr>
<td>2.</td>
<td>-162.9649</td>
<td>1112</td>
<td>699</td>
<td>62.3630</td>
<td>679 car whose roof is seen above the wagon platform</td>
</tr>
</tbody>
</table>

The Doppler spectrograms (the time-and-frequency analysis was performed) shown in Fig. 4 were obtained for the same record of the beat-frequency signal at the outputs of the IQ-mixer. They are given for both traffic routes at the zero threshold level for the amplitude maxima values and a low speed threshold for the target radial speeds (a white band at the bottom of the spectrograms).

The normalized Doppler frequency (Doppler position) is plotted on the ordinate, while the number of the frame of the video filming performed simultaneously with the recording, on the abscissa. The upper value (500) of the Doppler position scale corresponds to the radial speed of 134.1 km/h.

Figure 4 clearly shows the marks of the signals reflected at the moving transport means corresponding to the speed trajectories and the time dependences of the DDF given in Fig. 3. One can also see interference marks created by the most intense reflections at the targets received through the DD lateral lobes (above and below the darkest marks from the main lobe) and also due to the IQ-mixer’s unbalance. For example, Fig. 4(a) clearly shows the IQ-interference replicating the shape of the mark of the main and the lateral lobes from the van in Fig. 4(b). The analogous interference from a bus with two vans that has a mark on the “Left-to-Right” route at the end of the spectrogram in Fig. 4(a) is seen at the same place in Fig. 4(b).

As the conclusion, Table 1 lists the results of processing of the digital record of the reflected signal made at the outputs of the IQ-mixer accomplished with the help of the developed software. For the sake of comparison, the rightmost column no. 6 gives the numbers of the frames of the video filming that recorded the real appearance of the vehicle on the line of sighting of the principle radar beam with the visual evaluation of its type being mentioned. The fourth column FRAME gives the number of the frame where the same vehicle was detected by the CW radar itself. The time shift between the sixth and the fourth columns toward the time delay of the data in column no. 4 is explained by the error of the visual recording of the actual frame number. Another factor determining the delay is the position of the trajectory maxima at the edge (at the output from the DD main lobe) where the radial speed is the maximum, and the delay during...
the median and linear smoothing of the speed trajectories by the real time filters (due to the transient characteristics of the filters) that allow avoiding multiple recording of one and the same vehicle.

It follows from Table 1 that, when the transport means were detected by the CW radar in this specific experiment, no vehicle was missed (or falsely added), and even such complex targets as a bus and a wagon (the second bus consisting of two vans, and the wagon having a trailer) were recorded as one vehicle.

Note that counting errors can appear in the case of some mutual positions of the vehicles simultaneously illuminated by the radar beam. Such situations are not numerous; for example, as was noted above, they can be observed when one vehicle completely or partially screens the other during uni-directional or opposing motion. In the case of opposing motion, it is a situation when both vehicles are in the beam simultaneously and the near vehicle with larger angular (or linear) dimensions screens the far vehicle till it leaves the beam illumination zone. Such situations are sufficiently rare. To anticipate or partially neutralize them, the radar should be mounted 3–4 m away from the road at a height of not less than 3–3.5 m (higher than the majority of vehicles). It is also undesirable to mount the radars near signal-controlled junctions, parking lots, public transport stops, or pedestrian crossings, where transport means can move with low speeds or even stop (maneuver) remaining in the radar beam. In this case, some of them pass to the category of low-Doppler or even stationary targets and cannot be detected (picked off by the speed threshold). These recommendations were confirmed by the experience in operating the working radar prototype and are in agreement with the analogous recommendations for the existing radars intended for traffic recording [7, 8]. It is advisable to mount the radar in places where the traffic is free flowing. On average, the percentage of such blanks is not high, and the accuracy reached by us corresponds to the existing branch standards [12].

The developed CW radar model was tested as a production sample prototype on July 20, 2011; the tests confirmed its good quantitative and qualitative characteristics.

3. CONCLUSIONS

The method intended for recording the number of vehicles per unit of time and measuring their speed proposed by the authors has been analyzed and proved to be effective. It is based on using speed trajectories of transport means calculated with the help of the digital apparatus of the FFT-based CW radar when a vehicle, its speed, and the traffic route are independently recorded on each opposing route based on the maxima of the speed trajectories.

Such recording is possible even if several vehicles of different types moving along the same or opposing traffic routes are simultaneously in the illumination zone of the radar antenna beam provided they do not completely screen one another.

As compared to the devices intended for analogous applications, namely, recording of the current volume of a bidirectional traffic stream, the key advantage of the analyzed solution is the use of the CW radar instead of the FMCW radar (with the beam perpendicular to the traffic route), since the CW radar makes it possible not only to record the number of transport means, but also to measure their speed with a sufficient degree of accuracy.

Such a solution provides high-quality operation in close city traffic conditions, which was experimentally confirmed using a working CW radar prototype.

The advantage of this method is also associated with the possibility of using comparatively cheap components in addition to PLIC and not very high requirements for the PLIC resources, which, in the long run, substantially decreases the net cost of the device as a whole. Different radar units such as the processor controlling the radar radio, the unit for the digital processing of the received signal, and the users’ USB interface are mounted on one and the same PLIC matrix (chip), which is profitable both from the economic standpoint and from the point of view of the manufacturing. The application of PLIC in the radar prototype allowed making the process of the designing and adjustment maximally flexible for updating of the digital processing as early as at the stage of developing and makes it possible to introduce future improvements with minimal expenses, e.g., by using a digital AGC of the receiver and automated indication of the equality of the average signal level by traffic routes. At the initial stage of the experimental validation, the procedure of leveling was accomplished only roughly with the help of the spot line of the open sight, which was preadjusted with the help of the corner reflector by directing the spot line slightly higher than the axial line of the road. Prior to recording, it is recommended to calibrate the average level equality for 5–6 vehicles moving in both directions.
REFERENCES


SPELL: 1. radara, 2. microstrip, 3. unmodulated, 4. prefiltering