Radar range in multi-target mode

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Abstract. The paper presents the theoretical simulation results of mmWave frequency
modulated continuous wave (FMCW) radars in multi-target mode. The speed of objects is
determined by a segment of constant frequency, and the ranges are determined twice - by the
first and second chirps of long duration, but with different deviations and frequency rise
steepness. The method consists in the fact that the proposed functional with the correct speed-
range pair has a minimum, which allows you to select the correct speed-range pair from the sets
of speeds and ranges of all targets. The dependence of probability of multiple targets speed and
range correct determination in the multi-target mode on the range of the FMCW radar has been
investigated. The results can be used by developers to design optimized radars.

1. Introduction
Remote sensing of parameters of ground unmanned vehicles (UV) and unmanned aerial vehicles
(UAVs) is the basis of vehicle management in "smart city" technologies. To solve the problems of traffic
control of vehicles, two types of systems are used - with autonomous vehicle control and systems with
external control.

Autonomous systems imply the installation of sensors on an individual vehicle that can determine
the speed, range and angle of direction to the nearest objects. These sensors can be made in the form of
radars, video cameras, lidars or ultrasonic systems [1]. Millimeter-wave radars have an advantage over
other sensors because of its ability to work in the dark, all-weather, and relatively inexpensive cost.
Frequently, autonomous automotive sensors of various types are used, for example, radar and video
cameras at the same time, which allows the use of joint processing of data of different types in order to
improve the technical characteristics of the control system of an unmanned vehicle [2, 3].

The second type of control systems for unmanned vehicles in the "smart city" - systems with external
control. In this case, a transmitter is installed on an autonomous vehicle, and base stations are located
on the territory of a "smart city" that receive signals from the transmitters of autonomous vehicles to
local positioning systems [4]. Base stations process the received data from the transmitters of
autonomous vehicles. Data processing, as in autonomous systems, includes determining the speed, range
of targets, trajectory tracking, and the formation of vehicle control commands [5,6].

All vehicle control systems are characterized by a multi-target mode [7,8,9,10,11]. In the first place
in terms of importance among the technical characteristics of vehicle management systems is the ability
to work in multi-target mode. A vehicle in an urban environment is surrounded by moving objects,
which include other vehicles, as well as objects of wildlife - pedestrians, cyclists, animals, etc. Missing
at least one of these objects can lead to disastrous consequences.
FMCW radars traditionally use the classical form of the radio signal, which is a sequence of numerous chirps with a linearly increasing frequency [12]. Fast Fourier Transform is performed on samples from the chirp (fast time) and on samples from all chirps at times of the same frequency on each chirp (slow time). The maximum of the spectrum of samples of the same frequency makes it possible to determine the speed of the vehicle, and after the speed of the object is known, the distance to the object can be determined from the FFT of the chirps. The classical form of the radio signal has the disadvantage that it takes a considerable amount of time in the duration of each chirp to reach the linear section of the frequency change of the radio signal. There is also some limitation in the implementation of a wide range of speeds and distances to objects. In [13,14,15], signal forms that differ from the classical one are proposed. More accurate models of FMCW radars for high speeds [16] and tangential components of the speed of objects [17] have been proposed. Recently, deep machine learning methods have been widely studied for radars [18,19,20].

In the multi-target mode, many maxima from each object in terms of speed and range appear in the spectra, as a result of which it becomes necessary to apply the algorithm for correct pairing of the speed and range of each object. That is, it is necessary to establish the correct correspondence of the speed from the set of speeds of all objects to the range from the set of distances of all objects for each object.

Various methods are proposed to solve the multi-target problem. In [21], it is proposed to use different initial frequencies of chirps (using different starting frequencies), which allows using a change in the superposition behavior of all reflected signals to separate different targets. In [22], an algorithm is proposed that combines FFT and an algorithm based on chirp z-transform (CZT) for high precision ranging in multi-target scenarios with FMCW radar. In [13] to solve the problem of targets pairing between up-chirp and down-chirp in triangular frequency modulation continuous wave radar for multi-targets, a new method combined with interferometer direction finding is proposed. In [23] is proposed a novel ghost-target removal algorithm using the inter-relationship between the upbeat and downbeat frequency after the Fast Fourier Transform (FFT). [10] proposes a novel signal power based multi-target detection in which authors attempt to pair the beat frequencies from the same target by reference to the corresponding signal powers. In [24], a traffic pattern with the installation of passive reflectors was investigated, which allows the vehicle radar to detect approaching vehicles at the intersection of streets outside the line of sight.

The aim of this work is to study the dependence of probability of multiple targets speed and range correct determination in the multi-target mode on the range of the FMCW radar and to model this dependence in computational experiments under the influence of noise.

2. Multi-target detection method for FMCW radar

On the basis of the form of the radio signal presented in figure 1, which is sufficiently effective for implementation in the radar, we have proposed a method for eliminating incorrect correspondences between the ranges and velocities of targets in the multi-target mode [7].

![Figure 1. Waveform of the proposed signal.](image)
Obviously, the distances to the object, determined by two different segments (long chirps) at a certain speed, must coincide. The method consists in the fact that functional (1) with a correct speed-range pair has a minimum, which makes it possible to select the correct speed-range pair from the sets of speeds and ranges of all targets.

$$\Xi(f_{r1}, f_{r2}) = f_{r1} \frac{T_1}{\Delta f_1} - f_{r2} \frac{T_2}{\Delta f_2} - f_D \left( \frac{T_1}{\Delta f_1} - \frac{T_2}{\Delta f_2} \right) \rightarrow \min$$  \hspace{1cm} (1)

The beat frequencies are $f_{r1}$ and $f_{r2}$, i.e. the signal frequencies at the mixer output in the I and Q quadrature channels of the intermediate frequency of the radar receiver for chirps respectively with numbers $k = 0$ and $k = 1$, based on the refined model [16], are determined by the expressions

$$f_{r1} = \frac{\Delta f_1}{T_1} r_0 - \frac{2V_R}{c} f_0;$$  \hspace{1cm} (2)

$$f_{r2} = \frac{\Delta f_2}{T_2} r_0 - \frac{2V_R}{c} \left( f_0 - \frac{3\Delta f_2}{2} \right);$$  \hspace{1cm} (3)

3. Radar view range of FMCW radar in free space

The principle of operation of the continuous wave radar is based on the simultaneous operation of the transmitter and receiver of the FMCW radar. The radiation from the transmitter is a radio frequency signal with linear frequency modulation. The power density of radio emission at the object is determined by the expression

$$I_{\text{target}} = \alpha \frac{P_{\text{TX}} G_{\text{TX}}}{4\pi d^2}$$  \hspace{1cm} (4)

where $P_{\text{TX}}$ is radar transmitter power; $G_{\text{TX}}$ is TX antenna gain, $d$ is distance to object, $\alpha$ is attenuation coefficient of radio waves during propagation from the transmitter to the receiver and vice versa. The value of $\alpha$ depends on weather conditions and the wavelength of radio emission [25]. Reflected power is

$$P_{\text{target}} = \alpha \frac{P_{\text{TX}} G_{\text{TX}}}{4\pi d^2} \cdot \sigma_{\text{target}}$$  \hspace{1cm} (5)

where $\sigma_{\text{target}}$ is radar cross section of the target. The reflected wave is received by the radar’s receiving antenna. Power density of electromagnetic radiation at the receiving antenna aperture is

$$I_{\text{RX}} = \alpha^2 \frac{P_{\text{TX}} G_{\text{TX}} \sigma_{\text{target}}}{4\pi d^2} \cdot \frac{1}{4\pi d^2}$$  \hspace{1cm} (6)

Signal power at the output of the radar receiving antenna is

$$P_{\text{RX}} = \alpha^2 \frac{P_{\text{TX}} G_{\text{TX}} \sigma_{\text{target}}}{(4\pi)^2 d^4} \cdot A_{\text{RX}}$$  \hspace{1cm} (7)

where $A_{\text{RX}}$ is effective aperture area of the receiver antenna, which is equal to

$$A_{\text{RX}} = \frac{G_{\text{RX}} \lambda^2}{4\pi}$$  \hspace{1cm} (8)

where $\lambda$ is the wavelength of the radio emission. After substitution

$$P_{\text{RX}} = \alpha^2 \frac{P_{\text{TX}} G_{\text{TX}} G_{\text{RX}} \sigma_{\text{target}} \lambda^2}{(4\pi)^2 d^4}$$  \hspace{1cm} (9)
If the noise at the input can be considered white, the noise power at the output of the linear part of the receiving device is

$$P_{\text{noise}} = k \cdot T \cdot \Delta f \cdot NF_{\text{RX}}$$

where $T_{\text{meas}}$ is measurement time (duration of one segment - chirp), $k$ is Boltzmann constant, $T$ is antenna temperature, $NF_{\text{RX}}$ is radar receiver noise ratio. Signal-to-noise ratio by power at the output of the linear part of the receiving device is

$$SNR_{\text{RX}} = \frac{P_{\text{RX}}}{P_{\text{noise}}} = \alpha^2 \frac{P_{\text{RX}} G_{\text{TX}} G_{\text{RX}} \sigma_{\text{tag}}^2}{(4\pi)^3 d^4} \frac{T_{\text{meas}}}{kT \cdot NF_{\text{RX}}}$$

The received signal is fed to an RF signal mixer, which can be either passive or active. A passive mixer has a Conversion Loss (CL), moreover, the noise figure of passive mixers is numerically equal to the conversion loss $CL_{\text{mix}} = NF_{\text{mix}}$. Since noise figure is the ratio of the signal-to-noise ratio at the mixer input to the signal-to-noise ratio at the mixer output, the signal-to-noise ratio at the mixer output is given by:

$$SNR_{\text{mix}} = \frac{\alpha^2 \frac{P_{\text{TX}} G_{\text{TX}} G_{\text{RX}} \sigma_{\text{tag}}^2}{(4\pi)^3 d^4} \frac{T_{\text{meas}}}{kT \cdot NF_{\text{RX}}}}{CL_{\text{mix}}}$$

In the range of millimeter waves, the values of the noise factors of the radio receiving part and the mixer are located in the range of approximately 6÷8 dB, thus the product $NF_{\text{RX}} \cdot CL_{\text{mix}}$ is equal to 10÷12 dB.

The sensitivity of the radar is determined by the minimum value $SNR_{\text{mix}}^{\min}$, that determines the maximum range of the radar view

$$d_{\text{max}} = \sqrt{\frac{\alpha^2 \frac{P_{\text{TX}} G_{\text{TX}} G_{\text{RX}} \sigma_{\text{tag}}^2}{(4\pi)^3 d^4} \frac{T_{\text{meas}}}{kT \cdot NF_{\text{RX}} \cdot CL_{\text{mix}}}}{SNR_{\text{mix}}^{\min}}}$$

For radars that only detect targets, the choice of $SNR_{\text{mix}}^{\min}$ is determined by the trade-off between the probability of missed detections and the probability of false alarms. For control radars for unmanned vehicles (UVs) and unmanned aerial vehicles (UAVs), the probability of a false alarm does not fully characterize the technical capabilities of the radar. More fully, the technical capabilities of the UVs radar in a "smart city" will be represented by the probability of correctly determining the speed and range in the multi-target mode, determined by the value of $SNR_{\text{mix}}^{\min}$ for a different number of simultaneously evaluated targets.

4. Result and discussion

Modeling of the dependence of the probability of correct determination of the speed and range of objects in the multi-target mode was carried out in the LabVIEW software environment with the parameters of the objects and the FMCW radar: the number of objects 10, 4, 2; objects were located at the same distance from the radar, but had different speeds -100, -80, -60, -40, -20, 0, 20, 40, 60 and 80 km / h for 10 objects, -60, -20, 20 and 60 km / h for 4 objects and -60 and 60 km / h for 2 objects; the duration of each segment is the same and equal to 8.192 msec, the sampling frequency of each segment is 1 MHz, the initial radiation frequency of the radar is 76.5 GHz, the effective reflection surface of objects is 0.1 m², the power of the radar transmitter is 100 mW, the directivity of the transmitting and receiving antennas is 1, the ambient temperature is 297º K, receiver noise figure and mixer loss of 5 dB. With the correct determination of the speed and range of all objects, the experiment was counted as positive, if the parameters of at least one object were determined incorrectly, the result was counted as negative. The criterion for distinguishing between positive and negative results of the experiment was the
condition that the standard deviation of the speed value for one thousand computational experiments did not exceed 1 km / h and the standard deviation of the range did not exceed 1 m. The probability of correctly determining the speed and range of multiple targets, defined as the proportion of experiments with a positive result to the total number of experiments equal to 1000, is shown in figure 2.

With an increase in the number of simultaneously evaluated targets, the distance at which the speed and range of all targets are determined with a probability of 98% drops sharply. So, with the above parameters of objects and the FMCW radar, the maximum range of radar coverage for 10 targets is 1.3 times less than for 4 targets, and 1.6 times less than for 2 targets. The slope of the falloff of the probability is ~ 3% per meter of increase in the range of the radar coverage. The range of the radar view increases with the sampling rate of the analog-to-digital converter and the durations of the waveform segments.

![Figure 2. Dependence of the probability of correctly determining the multiple targets speed and range in the multi-target mode on the range of the FMCW radar.](image)

5. Conclusion
A distinctive feature of the real traffic situation of a UV and UAV in a "smart city" is the presence at the same time of a significant number of vehicles in the traffic situation analysis zone, the parameters of which must be determined. This article investigates the dependence of the probability of correct determination of the targets speed and range in the multi-target mode on the range of the radar coverage. A sharp drop in the maximum range of the FMCW radar survey from the number of targets, the parameters of which are simultaneously determined using the proposed method, is revealed. Recommendations for the selection of technical parameters of vehicle radars are developed on the basis of simulating a radar in multi-target mode in the LabVIEW programming environment and can be used by developers to create radars designed for a given maximum range of FMCW radar in multi-target mode.

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References
[1] Kamimura T, Kurashige K, Yasooka K, Suzuki T and Tsubota Y 2019 Compact 76 GHz automotive long-range radar with high linearity chirp generator based on low phase noise open-loop VCO 16th European Radar Conference (EuRAD)
[2] Kang D and Kum D 2020 Camera and radar sensor fusion for robust vehicle localization via vehicle part localization IEEE Access 8 75223-36
[3] Zhao X, Sun P, Xu Z, Min H and Yu H 2020 Fusion of 3D LIDAR and camera data for object detection in autonomous vehicle applications IEEE Sensors Journal 20(9) 4901-13
[4] Kuptsov V D, Badenko V L, Ivanov S I and Fedotov A A 2020 Method for remote determination of object coordinates in space based on exact analytical solution of hyperbolic equations Sensors (Switzerland) 20(19) 5472

[5] Yu Y, Wang H, Liu S, Guo L, Yeoh P L, Vucetic B and Li Y 2021 Distributed multi-agent target tracking a nash-combined adaptive differential evolution method for UAV systems IEEE transactions on vehicular technology 70(8) 8122-33

[6] Kumar M and Mondal S 2021 Recent developments on target tracking problems A review Ocean Engineering 236 109558

[7] Kuptsov V D, Ivanov S I, Fedotov A A and Badenko V L 2019 Features of multi-target detection algorithm for automotive FMCW radar Lecture Notes in Computer Science 11660 355-64

[8] Kutsov V D, Badenko V L, Ivanov S I and Fedotov A A 2020 Millimeter wave radar for intelligent transportation systems: A case study of multi-target problem solution E3S Web of Conferences 157 05011

[9] Kuptsov V D, Ivanov S I, Fedotov A A and Badenko V L 2020 Multi-target method for small unmanned vehicles parameters remote determination by microwave radars J. of Physics: Conf. Series 1515(3) 032045

[10] Tachibana Y and Han C 2021 A novel signal power based multi-targets detection for FMCW radar IEEE Radar Conference (RadarConf21)

[11] Ivanov S I, Kuptsov V D, Fedotov A A and Badenko V L 2020 CFAR multi-target detection based on non-central Chi-square distribution for FMCW J. of Physics: Conf. Series 1515(3) 032059

[12] Stove A G 1992 Linear FMCW radar techniques IEE Proceedings on Radar and Signal Processing 139(5) 343-50

[13] Huang L, Zhang R and Sheng W 2019 Multi-target detection for FMCW radar based on interferometer direction finding 2019 International Applied Computational Electromagnetics Society Symposium - China (ACES)

[14] Fan Y, Yang Z, Bu X and An J 2015 Radar waveform design and multi-target detection in vehicular applications 2015 International Conference on Estimation, Detection and Information Fusion (ICEDIF 2015) 286-9

[15] Kronauge M and Rohling H 2014 New chirp sequence radar waveform IEEE Trans. Aerosp. Electron. Syst 50 2870-7

[16] Ivanov S I, Kuptsov V D and Fedotov A A 2019 The signal processing algorithm of automotive FMCW radars with an extended range of speed estimation J. of Physics: Conf. Series 1236(1) 012081

[17] Ivanov S I, Kuptsov V D, Badenko V L and Fedotov A A 2020 An elaborated signal model for simultaneous range and vector velocity estimation in FMCW radar Sensors (Switzerland) 20(20) 5860

[18] Altmann M, Ott P, Stache N C, Kozlov D and Waldschmidt C 2020 A cognitive FMCW radar to minimize a sequence of range-doppler measurements Proceedings of the 17th European Radar Conference 226-9

[19] Pérez R, Schubert F, Raschofer R and Biebl E 2019 A machine learning joint lidar and radar classification system in urban automotive scenarios Adv. Radio Sci. 17 129-36

[20] Cenkeramaddi L R, Rai P K, Dayal A, Bhatia J, Pandya A, Soumya J, Kumar A and Jha A 2021 A novel angle estimation for mmWave FMCW radars using machine learning IEEE Sensors Journal 21(8) 9833-43

[21] Olbrich S and Waldschmidt C 2018 Optimization of target separation capability for FMCW radar systems 2018 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM)

[22] Babaeian K, Modarres-Hashemi M, Zahabi S J and Naghsh M M 2019 A CZT-based algorithm for improving multi-target ranging in FMCW radar 27th Iranian Conference on Electrical Engineering (ICEE2019) 1465-9
[23] Son Y and Heo S W 2018 A novel multi-target detection algorithm for automotive FMCW radar 2018 International Conference on Electronics, Information, and Communication (ICEIC)

[24] Solomitckii D, Barneto C B, Turunen M, Allén M, Zhabko G P, Zavjalov S V, Volvenko S V and Valkama M 2021 Millimeter-wave radar scheme with passive reflector for uncontrolled blind urban intersection IEEE transactions on vehicular technology 70(8) 7335-46

[25] Kuptsov V D, Ivanov S I, Fedotov A A and Badenko V L 2021 Rain attenuation in millimeter wave, centimeter wave and visible light ranges IOP Conf. Ser.: Mater. Sci. Eng. 1047 012197