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Research Article

Development of Verification Device for Multitarget Radar Velocimeter Based on Echo Signal Simulation Technology

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Speeding is one of the leading causes of traffic crashes worldwide. Radar velocimeter is widely used in the capture monitoring of road overspeed violations, which can effectively reduce the probability of traffic accidents and protect people's life and property safety to the greatest extent. As a new type of radar velocimeter, multitarget radar velocimeter (MTRV) can monitor the speed of more than two vehicles at the same time. However, the verification method and device of MTRV's performance need to be studied. In order to solve the problem of performance verification for MTRV, a verification device based on echo signal simulation technology is developed in this paper. The measurement mechanism of MTRV with different performance including velocity, distance, and angle is first introduced. Then, a verification method based on the echo signal simulation technology is proposed. The verification device can receive the emission signal of MTRV and process the signal by echo simulation technology, including target generation, Doppler frequency shift, time delay, and angel control, and targets are simulated with nominal velocity, distance, and angle value. The processed echo signal with simulated nominal parameter values is reflected to the MTRV. After the echo signal is received and processed by MTRV, the measurement values of simulated velocity, distance, and angle for targets are obtained. Comparing the measured values of the MTRV with the simulated nominal values of the verification device, the measurement error of MTRV is obtained. The verification device of MTRV is realized to verify the accuracy and reliability of the MTRV measurement results. The simulated velocity range of the verification device is up to (-300~300) km/h, and the simulated distance range of the verification device is up to (10~45) m when the simulated incident angle range was within the range of (-60~60)°. The simulation target generation for the two targets of the device is also verified. And the maximum permissible error (MPE) of the simulated velocity was ±0.05 km/h, the MPE of simulated distance is ±0.3 m, and the MPE of simulated angle is ±0.2°. Finally, the verification and uncertainty evaluation results of the MTRV sample validated the effectiveness and feasibility of the proposed verification method and the developed verification device of MTRV.

1. Introduction

Road traffic crash caused by driver speeding is one of the main causes of death worldwide, and the speeding violation is strictly monitored by the public security traffic management department. The motor vehicle velocimeter can measure the real-time speed of motor vehicles on the road. Various types of motor vehicle velocimeters [1] were widely used by the local traffic management departments to deal with the speeding violations.

According to different speed measurement principles, the motor vehicle velocimeters used in China can be divided into motor vehicle radar velocimeter [2, 3], motor vehicle laser velocimeter [4, 5], motor vehicle ground sensing coil velocimeter [6], etc. Among the above three velocimeters, the motor vehicle radar velocimeter based on the radar Doppler effect has the advantages of mature technology, low price, high all-weather adaptability, and clear traceability and has become the preferred speed measuring equipment of the Chinese public security traffic management department.

The radar velocimeter for law enforcement in China is single-target radar velocimeter (STRV) currently. In the process of specific road traffic management work, the STRV is worked in conjunction with the capture camera. When vehicles appeared within the measurement range of STRV at the same time, one of the speeding vehicles is detected by STRV and the camera is triggered to capture the picture about vehicles. However, there are unrelated vehicles in the captured image, so it is difficult to identify accurate speeding vehicles. This is apt to result in multicapture, and the traffic police cannot accurately identify speeding vehicles when they use STRV for collecting evidence. The legitimacy and measurement accuracy of STRV is doubted by motor vehicle drivers. That will reduce the management efficiency of the traffic law enforcement and lead to traffic law enforcement disputes easily.

Since the motor vehicle radar velocimeter is an important legal measuring instrument involving the safety of drivers on the road and the safety of people's lives and property, it is mandatory in various countries to compulsorily stipulate that motor vehicle radar velocimeter used for law enforcement must be verified by the metrology department in advance. And it is also a national compulsory verification measuring instrument in China. Thence, the motor vehicle radar velocimeter needs to be calibrated annually in the laboratory to ensure the accuracy and reliability. For this reason, metrology institutions in various countries have carried out a lot of research on the measurement and test methods of radar speedometers and the key measurement technologies involved.

The Organisation Internationale de Métrologie Légale (OIML) promulgated the Radar Speedometer International Recommendation R91 [7] as early as 1990, which limited important measurement performance parameters such as the speed measurement range, speed measurement error, and antenna measurement performance indicators of the radar speedometer. The Physikalisch-Technische Bundesanstalt (PTB) in Germany has developed the national standard for motor vehicle speedometer testing devices, and is responsible for the type identification of various speedometers, the OIML certificate test work, and international cooperative research and exchanges, etc. The Federal Institute of Metrology (METAS) also uses the self-developed motor measure equipment for pattern evaluation and routine testing of vehicle speedometers.

In the 1980s, the metrology departments of China have begun to study the verification methods and technologies of radar velocimeters. However, with the continuous progress of radar velocimeter technology and emergence of new products of radar velocimeter, the original verification measurement methods and technologies for radar velocimeter can no longer meet the needs of the current situation.

The GB/T 21255-2019 "Motor Vehicle Speed Detector" [1] of China is implemented on July 1, 2020. It stipulates that the microwave transmission frequency of the radar velocimeter can be used in X-band (8 to 12 GHz), K-band (18 to 26.5 GHz), and Ka-band (26.5 to 40 GHz). The multitarget velocimeter (MTV) is first defined as a velocimeter that measures the running speed of two or more motor vehicles at the same time. In addition, the specific requirements of the measurement performance specification are defined, such as the maximum permissible error of microwave emission frequency, speed detection range, and simulating speed measurement error.

The multitarget radar velocimeter (MTRV) is one of them; the speed value of the motor vehicle should be marked on the corresponding measured target by MTRV in the measurement area in the image. Different from STRV, MTRV can judge more vehicle targets, where the accuracy and efficiency of traffic police evidence collection have been effectively improved. However, due to the difference in working principle and application, the verification device of STRV is no longer applicable to MTRV. The GB/T 21255-2019 has provided specific specifications for the measurement performance of MTRV. In the next step, it is urgent to provide detection methods and schemes and develop measurement devices.

2. Related Work

At present, the verification method of radar velocimeter in China has formed a scheme combining laboratory simulation verification technology with actual road verification technology. The laboratory simulation verification technology is to simulate a velocity value for motor vehicle through the verification device of motor vehicle radar velocimeter in the laboratory and to verify the measurement performance of radar velocimeter under ideal conditions, such as the velocity measurement range, the measurement error of simulated velocity, the microwave emission frequency, and the characteristic index. However, the actual road verification technology is more complicated. Firstly, it is necessary to close the monitoring road which is equipped with the radar velocimeter. Secondly, we use the test vehicle equipped with an accurate speedometer to drive into the velocity measurement area of the radar velocimeter. The test vehicle is captured by the radar velocimeter to obtain the velocity. Finally, the velocity measurement error of the radar velocimeter in the actual road can be obtained by comparing the velocity measurement value of the radar velocimeter with the velocity value of the test vehicle.

Compared with the laboratory verification method, the actual road verification method is greatly affected by the weather and road conditions. There are some new achievements in the field of the verification method for MTRV measurement performance specification.

Felguera-Martin et al. [3] proposed a Ka-band interferometric linear frequency-modulated continuous wave (LFMCW) radar method, which can measure the speed and distance of multiple vehicles simultaneously. However, the radar monitoring system needs to be verified on multilane actual roads, which is greatly affected by environmental factors. Lim et al. [8] proposed a 24.1 GHz radar road monitoring system based on probabilistic data association filters (PDAF), which can estimate the distance and angle of vehicle within 300 meters in four lanes in real time. This system also needs to be verified in actual roads. Du et al. [9] developed a fixed standard instrument for field tests of vehicle speed measuring devices based on actual traffic, which can provide the standard speed value at five different positions in three lanes simultaneously. The speed value measured by the radar velocimeter is compared with the standard speed value to obtain the speed measurement error. However, these velocimeter verification devices need to be tested in the field road, which are greatly affected by the traffic conditions, environment, installation conditions, etc., and the detection time is also difficult to guarantee. Furthermore, since the traditional verification devices of radar velocimeter (e.g., sound forks [10] and single-target simulation verification device [11]) can only simulate a single target, these are not applicable to the verification of multitarget radar velocimeter.

Thus far, the radar target simulator has been widely used to verify radar sensors in the laboratory environment, but the research on verification device of multitarget radar velocimeter is still rare. Du et al. [12] proposed a train speed calibration method based on Doppler frequency shift signal simulation and designed a 24 GHz LFMCW radar target simulation system to achieve speed calibration of dual-channel Doppler sensor on trains. Xu et al. [13] built a kinematic parameter calibration device for automotive millimeter wave radars based on virtual instrument technology to evaluate the speed and distance performance of 24 GHz and 77 GHz millimeter wave radar sensors. Dou et al. [14] set up a 76~81 GHz multitarget radar simulator, which can realize the parameter test of the target speed, distance, and angle of the vehicle-borne radar. Unfortunately, it is not suitable for testing the 24 GHz traffic speed radar. Wang [15] developed a verification device for radar velocimeter, which can meet the needs of simulation and field verification simultaneously, but it is not suitable for multitarget radar velocimeter verification. The SAPSAN-4 radar velocimeter verification device developed by OLIVA Company of Russia can simulate the direction, speed, and distance of multitarget, but it costs a lot.

Although the vehicle-borne radar target simulator can simulate multiple targets, the vehicle-borne radar and the traffic radar are in different frequency bands, and it is not suitable for the verification of MTRV in the laboratory environment. There is no applicable verification device to verify the measurement performance of MTRV including range of speed measurement and simulated speed measurement error. The problem of simulation verification for MTRV needs to be solved urgently.

It is necessary to generate targets for MTRV verification device equipment to simulate more realistic traffic scenes. By simulating the velocity, distance, and angle of multiple motor vehicles through MTRV verification device, the accuracy of vehicle identification, speed measurement, distance measurement, and other performances of the MTRV can be verified. It provides the metrological guarantee for speeding violation monitoring of traffic management department and provides the testing technology support for radar velocimeter industries.

3. Measurement Mechanism of Multitarget Radar Velocimeter

Frequency-modulated continuous wave (FMCW) is a widely used radar waveform that can measure distance and velocity, and its main advantage is low equipment cost [16]. The FMCW radar transmits the frequency-modulated continuous wave signal, and the distance and velocity information of the target can be extracted by fast Fourier transform (FFT) on the beat signal of the radar echo [17]. The GB/T 21255-2019 stipulates that the microwave transmission frequency of the radar velocimeter can be used in X-band (8 GHz to 12 GHz), K-band (18 GHz to 26.5 GHz), and Ka-band (26.5 GHz to 40 GHz). Among the various frequency bands, the 24 GHz band is one of the traffic, industrial, scientific, and medical (ISM) radio bands, which is a frequency band commonly used in automotive radar systems [8]. And it is mainly used for the short-range measurement, which includes the location information of vehicle, surrounding environment sensing of the vehicle, and blind spot detection [18]. Therefore, the frequency band most used by radar velocimeters is 24 GHz in China.

The velocity and distance measurement of the multitarget radar velocimeter are based on the Doppler effect principle and the principle of time of flight (TOF) [19]. The schematic diagram of working principle of MTRV velocity measurement is shown in Figure 1. MTRV is usually placed at the roadside at a fixed angle. Its radar antenna beam points to the road surface at a fixed and known angle φ, and φ is defined as the triggering angle, which denotes the included angle between the direction of measured vehicle movement and the direction from MTRV to the target vehicle at the triggering point. According to the chord theorem, the relationship between the radial velocity v_r of the target motor vehicle relative to the radar velocimeter and the actual running velocity v is as follows:

$$v_r = v \cdot \cos \varphi, \tag{1}$$

where v_r is the target vehicle's radial velocity, v is the target vehicle's actual running velocity, and φ denotes the included angle between the driving direction of the target motor vehicle and the normal direction of the transmitted signal of MTRV.

The target vehicle is radiated to the radar signal beam at a certain velocity by the MTRV's emitted antenna, and the echo signal after reflecting from the target vehicle is received by the MTRV's received antenna and then processes the received signals by mixing with the emitted signal to measure the velocity and position of the target vehicle. According to the Doppler effect [11, 20], the frequency difference between the emitted signal and the received one is called the Doppler shift and can be expressed as

$$f_d = f_r - f_0 = \frac{2}{C} \cdot f_0 \cdot v_r, \tag{2}$$

where f_d is the Doppler shift, C is the propagation velocity of electromagnetic wave in vacuum, f_0 is the nominal

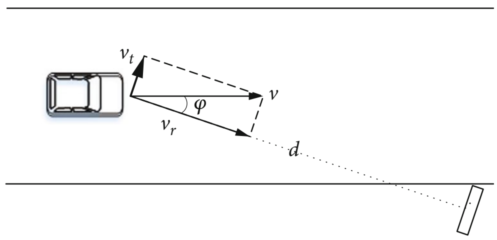

Figure 1: Schematic of MTRV velocity measurement.

emitted signal frequency of MTRV, and f_r is the received echo signal frequency of MTRV. According to Equations (1) and (2), the measured value velocity of target vehicle v_m is

$$v_m = \frac{C}{2\cos\phi} \cdot \frac{f_d}{f_0}. \quad (3)$$

The accuracy of measurement target vehicle velocity is determined by the computation of Doppler shift f_d, the stability of transmitted frequency f_0, and accuracy of the placed triggering angle φ.

The MTRV distance measurement is based on the principle of TOF, as is shown in Figure 2. The MTRV transmits the radar signal at time τ_a, then the target vehicle received the transmitted signal by MTRV and reflected the echo signal, and finally, the MTRV received the echo signal at time τ_b. It has a time delay between τ_a and τ_b, which is due to the distance between the MTRV and the target vehicle. The beat signal can be obtained by mixing the echo signal and transmitted signal, and the frequency f_d of the beat and the time delay τ of the echo signal meet the following requirements:

$$\tau = \tau_b - \tau_a, \quad (4)$$

$$f_{\text{bu}} = f_\tau - f_d = \frac{B}{T} \cdot \frac{2 \cdot R}{C} - \frac{2 \cdot f_0 \cdot v_r}{C},$$
$$f_{\text{bd}} = f_\tau + f_d = \frac{B}{T} \cdot \frac{2 \cdot R}{C} + \frac{2 \cdot f_0 \cdot v_r}{C}, \quad (5)$$

where τ_a is the time that MTRV transmits the radar signal, τ_b is the time that MTRV received the echo signal, τ is the delay time between τ_a and τ_b, B is the sweep bandwidth of signal, τ is the sweep period of signal, R is the distance between the MTRV and the target vehicle, and f_d is the frequency change caused by the target distance.

According to Equations (4) and (5), in measuring the delay time between the transmitted signal and the received echo signal, the distance of target vehicle can be calculated as follows:

$$R = \frac{(f_{\text{bu}} + f_{\text{bd}})}{4} \cdot \frac{T}{B} \cdot C. \quad (6)$$

There is an included angle θ between the echo signal and the normal direction of the radar antenna array when the position of the target is not on the same axis as the normal direction of radar antenna array. The angle measurement of MTRV is usually realized by the interference principle of multiple receiving antennas [21]. Array antenna is one of the most common antenna forms used in the radar system. As shown in Figure 3, the radar can detect the included angle θ by measuring the phase difference $\Delta\varphi$ between the adjacent elements of the antenna array, and the angle θ and the phase difference $\Delta\varphi$ meet the following requirement:

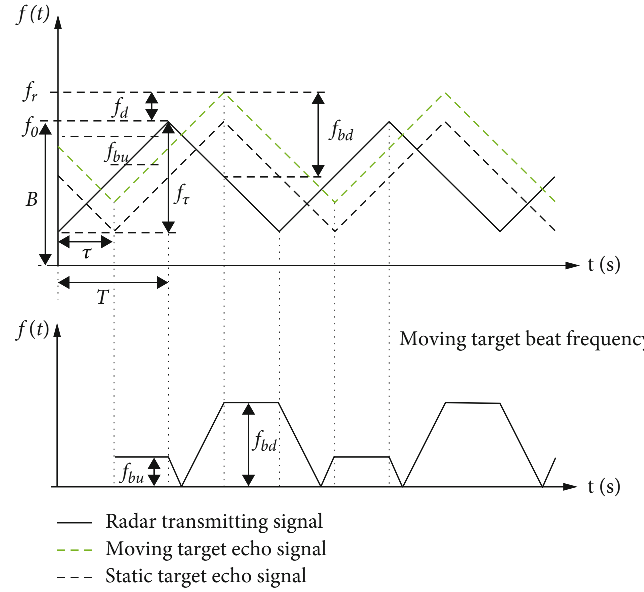

Figure 2: Principle of MTRV distance measurement.

$$\Delta\varphi = \frac{2\pi}{\lambda} \cdot D \sin\theta, \quad (7)$$

where λ represents the wavelength of the transmitting signal and D is the range of the adjacent elements of the antenna array.

4. Verification Method and Device Development

To ensure the accuracy and reliability of the MTRV measurement results, MTRV must be annually verified or calibrated in the laboratory and in the field to examine and test its velocity measurement performances. In this paper, a simulation verification method based on echo simulation technology is proposed to verify the measurement performance of MTRV.

As shown in Figure 4, the radar signals are emitted by MTRV based on the principle of echo simulation. When the radar signals are received by the antennas of the verification device, the echo radar signal is processed by signal processing module (target generate, Doppler signal shift, time delay, power attenuator, etc.). Thus, the multitarget simulation signals with velocity and distance information are generated. Rotate the swing arm by preset target angle to make the signal have angle information. Finally, the echo signal with simulated nominal parameter values is received by MTRV.

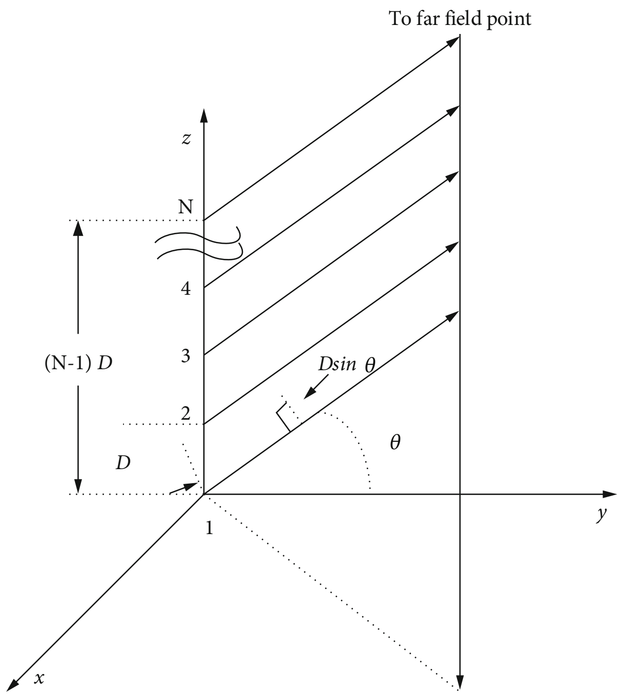

Figure 3: Principle of MTRV angle measurement.

The MTRV can measure the running velocity of more than two motor vehicles, and the information of the two target motor vehicles includes velocity, distance, and angle which are simulated through the MTRV verification device. Thus, the measurement performance (velocity, distance, and angle) of the MTRV can be verified by the verification device.

4.1. Radar Signal Processing Module. The radar signal processing module mainly includes upper/lower frequency converter, delay module, Doppler frequency modulation, and power attenuator. The MTRV received transmitting radio frequency (RF) signal $f_{\mathrm{RF\,RX}}$ with high frequency and is difficult to adjust and process the signal. It is necessary to convert the signal frequency into intermediate frequency (IF) signal f_{IF} that can be normally processed by the Doppler frequency modulation. The composition of down frequency converter is shown in Figure 5, and the local oscillator (LO) signal f_{LO} of the MTRV verification device is mixed with the received RF signal $f_{\mathrm{RF\,RX}}$ of the MTRV. Therefore, the IF signal converted by received signal is successfully generated by the down frequency converter and named $f_{\mathrm{RX\,IF}}$.

As shown in Figure 6, the IF signal generated by down frequency converter $f_{\mathrm{RX\,IF}}$ is entered in the delay module. Firstly, the radar signal $f_{\mathrm{RX\,IF}}$ is processed by photoelectric conversion, optical fiber delay, and electrooptical conversion. Secondly, the amplitude of radar signal is changed by attenuator. Finally, the DDS technology is used to shift the radar signal for Doppler frequency. At this point, the transmitted signal is called $f_{\mathrm{TX\,IF}}$, and it has carried the parameters of Doppler shift, time delay, and power amplitude. Finally, as shown in Figure 7, the transmitted signal $f_{\mathrm{TX\,IF}}$ is mixed with the LO f_{LO} by down frequency converter to generate an emission signal $f_{\mathrm{RX\,TX}}$ with high frequency and sent to MTRV by the antenna. The physical diagram of radar signal processing module is shown in Figure 8.

4.2. Angle Control Module. The angle control module is realized by rotating the swing arm, which is mainly composed of the swing arm and the turntable controller, as shown in Figure 9. The turntable is considered the center of angle controller, and the sending and receiving antennas of the two targets are installed at the end of the swing arm. According to the simulated target angle information set by the system software, the two stepping motors are controlled by the table to complete the rotation of the double swing arm and realize the emission angle adjustment of the two target radar signals.

4.3. Technical Parameter and Verification Process. The main technical parameters of MTRV verification device are shown in Table 1. The verification device can generate two simulated targets of vehicles. The verification device of MTRV is realized to verify the accuracy and reliability of the MTRV measurement results. The simulated velocity range of the verification device is up to (-300~300) km/h. The simulated distance range of the verification device is up to (10~45) m when the simulated incident angle range was within the range of (-60~60)°.

To achieve better interpersonal interaction performance, the MTRV verification device is equipped with a software test system. The software includes test system parameters and radar target simulation parameters, and the verification process is shown in Figure 10. The system parameter setting part mainly includes the center frequency, dark room distance, and antenna gain. The target simulation parameter setting part mainly includes the simulation target distance mode, distance, and velocity.

5. Simulation Experiment and Results

To verify the developed MTRV verification method by using verification device, a set of high-precision measuring instruments (including the signal generator, spectrum analyzer, and network analyzer) was used to verify the simulation accuracy including velocity, distance, and angle. Since the simulated velocity and distance accuracy are decided by the accuracy of the Doppler shift frequency and echo delay time generated by the target simulator, the simulated angle accuracy is decided by the accuracy of the swing arm angle controller, and the performance evaluation of the simulated target parameters was taken into account in the verification device by measuring the Doppler shift frequency corresponding to the simulated velocity value, the echo delay time corresponding to the simulated distance value, and the actual angle of the swing arm corresponding to the simulated angle value.

5.1. Velocity Simulation Test. The simulated velocity test can be evaluated by the Doppler shift frequency error. Firstly, the signal generator is used to generate standard RF signal, and the center frequency f_0 is 24.125 GHz and the distance is 10 m through the software. Secondly, the simulation velocity v_s was set by the control software, and the theoretical

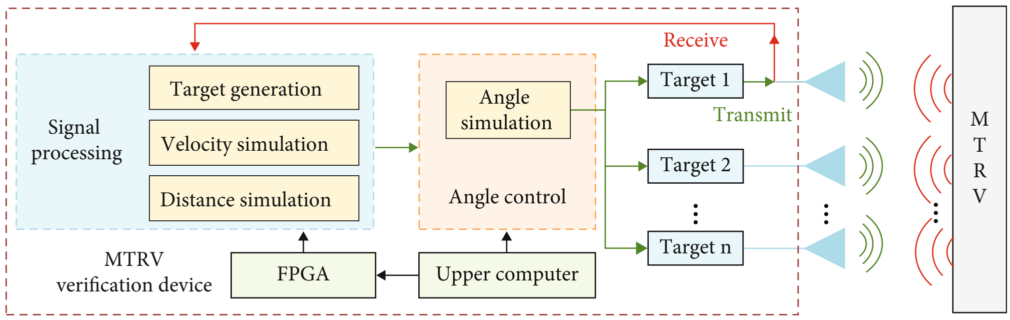

Figure 4: The box diagram of simulation verification device.

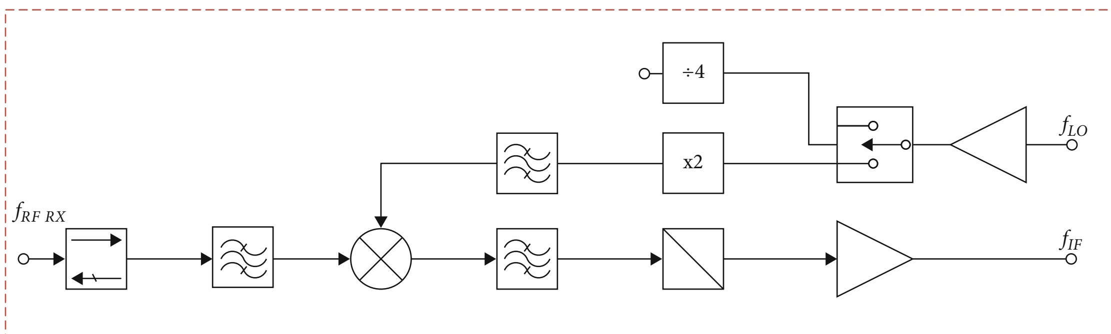

Figure 5: Composition of the down frequency converter.

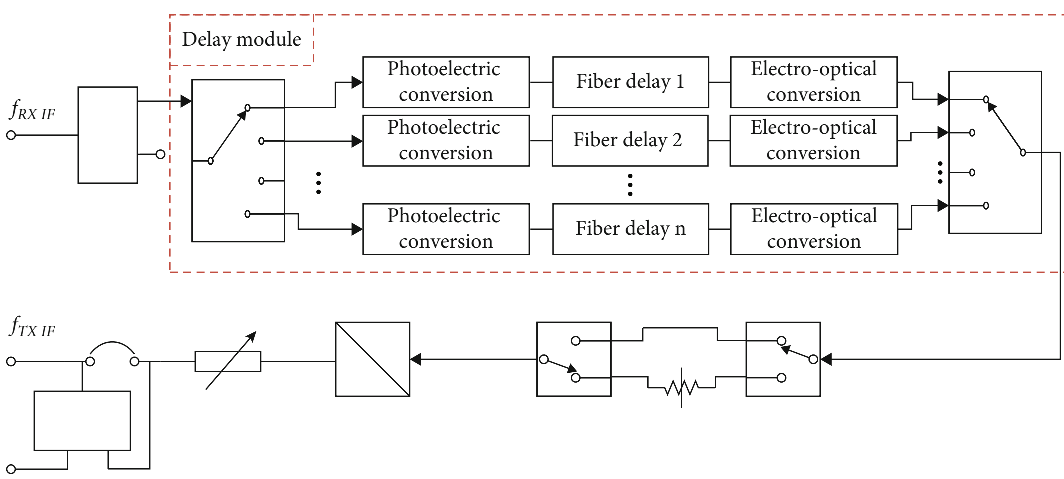

Figure 6: Composition of delay module.

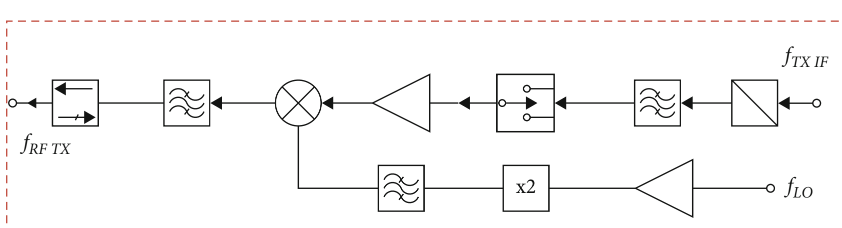

Figure 7: Composition of down frequency converter.

Figure 8: Physical diagram of radar signal processing.

frequency shift is calculated according to Equation (3). The same RF signal is divided into two channels through the power divider: one is connected to channel 1 of the spectrum analyzer, and the other is connected to channel 2 of the spectrum analyzer through the verification device. The Doppler frequency shift is obtained by measuring the frequency difference of the signals received between two channel signals, and the simulated velocity value is calculated.

The velocity simulation test results are shown in Table 2, with the verification simulation target velocity range of (-300~300) km/h. The maximum permissible error (MPE) of the velocity simulation is expressed by absolute error. The MPE of the simulation velocity of the two targets is both ±0.05 km/h as shown in Figure 11, which can meet the requirements of laboratory simulation verification.

5.2. Distance Simulation Test. The simulation of distance is realized through the actual time delay which can be measured by the vector network analyzer. Firstly, the center frequency f_0 is set to 24.125 GHz and the velocity v_s is set to 0 km/h. And set simulation distance R_s (including the test physical distance of 1 m) through the MTRV verification device software.

The standard RF signal is generated by the signal generator, and the standard RF signal is divided into two signals through the power divider. One signal is directly connected to the vector network analyzer channel 1 as the transmission signal. The other signal is used as the receiving signal, which is connected to the vector network analyzer channel 2 after the fiber delay processing of the verification device. The time delay between channel 1 signal and channel 2 signal can be measured by vector network analyzer, and the simulation distance R can be calculated according to the following equation: $R_r = C \cdot \tau/2$.

The measurement results are shown in Table 3. The simulation target distance range of the verification device is 10~45 m, which meets the detection distance range of MTRV. The simulation test error of target distance is shown in Figure 12, and MPE of the two targets is both ±0.3 m, which can meet the requirements of laboratory simulation.

5.3. Angle Simulation Test. The test of the simulated angle is realized by the laser tracker. First of all, the swing arm angle set by the software measures the rotation angle of the swing arm and verifies the target angle simulation performance.

The test results are shown in Table 4. The simulation target angle range of the verification device is (-60~60)°, which meets the detection distance range of MTRV. The target angle test error results are shown in Figure 13, and the MPE of the two targets is both ±0.2°, which can meet the requirements of laboratory simulation verification.

According to the simulation test results in Sections 5.1, 5.2, and 5.3, the MPE of simulated velocity was ±0.05 km/h, the MPE of simulated distance is ±0.3 m, and the MPE of simulated angle is ±0.2°. The simulation target generation for two targets of the device is also verified. This shows that the simulated echo signal with speed, distance, and angle information has a high accuracy.

6. Verification Results and Uncertainty Evaluation

To validate the effectiveness and feasibility of the proposed simulation verification method based on echo simulation technology, a typical multitarget radar velocimeter was chosen to verify the developed MTRV verification device to evaluate its technical performance in this section. The typical sample is iDS-TDI900-A manufactured by Hikvision.

6.1. Verification Results. The central frequency of the sample iDS-TDI900-A is 24.125 GHz. According to JJG 528-2015 “Mobile Radar Vehicle Speed Measurement Devices” and JJG 771-2010 “Test Equipment for Vehicle Speed Radar Measurement Meters,” the environmental requirements of the laboratory are that the temperature is within the range of (15~25)°C and the humidity is less than 85% RH. Moreover, the distance, velocity, and angle of the sample can be measured in the 24 GHz frequency band without mechanical vibration and electromagnetic interference. In order to avoid signal interference and ensure the accuracy of measurement data, the verification test needs to be carried out in a microwave anechoic chamber. During the test, the sample is placed on the turntable tooling platform, and the laser sight is used to ensure that the sample and antenna are in the same normal direction.

6.1.1. Velocity Verification Results. During the velocity verification, the simulated velocity points were set to several typical values from 20.0 km/h to 180.0 km/h through control software on the MTRV verification device and each velocity point was measured 10 times, respectively.

The numerical verification results of the sample at various simulated velocity points are shown in Table 5. Then, the average of ten independent velocity measurement values was taken as the measured value of the simulated velocity to calculate the simulated velocity measurement error and standard deviation. It can be seen from Table 5 that within the velocity range, the maximum simulated velocity measurement errors of target 1 and target 2 at the above simulated velocity points were 0.46 km/h and 0.51 km/h, respectively, which meet the velocity measurement requirements.

6.1.2. Distance Verification Results. The distance verification method is similar to the velocity, six typical distance values from 15.0 m to 45.0 m are set through control software on the MTRV verification device, and each distance point was measured 10 times, respectively.

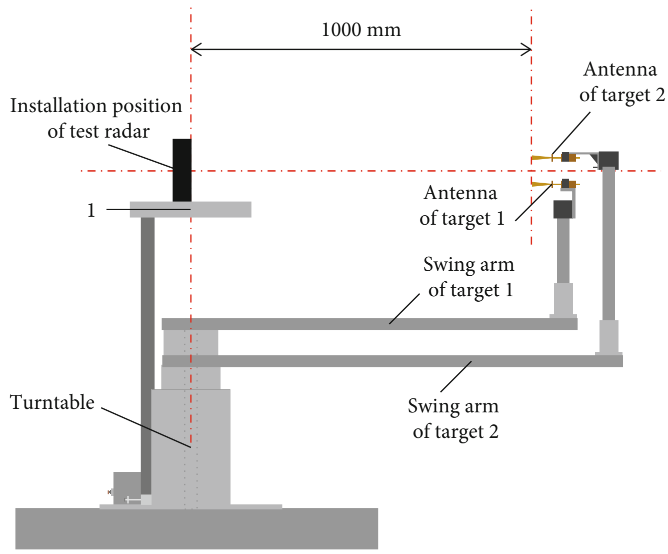

Figure 9: The structure of the swing arm and turntable controller.

Table 1: MTRV verification device technical parameters.

Description	Specification
Frequency simulation	24~24.25 GHz
Bandwidth	250 MHz
Number of simulated targets	2
Velocity	
Simulation range	(-300~300) km/h
Simulation step	0.01 km/h
Simulation maximum permissible error	±0.05 km/h
Distance	
Simulation range	(10~45) m
Simulation step	5 m
Simulation maximum permissible error	±0.3 m
Angle	
Simulation range	(-60~60)°
Simulation step	0.1°
Simulation maximum permissible error	±0.2°

The numerical verification results of the sample at various simulated distance points are shown in Table 6. The average of ten independent distance measurement values was taken as the measured value of the simulated distance to calculate the simulated distance measurement error and standard deviation. As shown in Table 6, the maximum simulated distance measurement errors of the two targets at the above simulated distance points were 1.1 m and 1.0 m, respectively, which meet the distance measurement requirements.

6.1.3. Angle Verification Results. The angle verification points are set from -30° to 30° with step of 10°, and each angle point was measured for 10 times, respectively. The numerical verification results of the sample at various simulated angle points and the average of ten independent angle measurement values are listed in Table 7. It can be seen from Table 7 that the maximum simulated angle measurement errors of the two targets at the above simulated angle points were -0.5° and -0.7°.

6.1.4. Multitarget Distinguish Verification Results. Base on the above velocity, distance, and angle verification experiment results of the two targets, the repeatability of ten independent measurement values was quite good. In order to verify the accuracy of multitarget distinguish of MTRV, four groups of nominal target values within the range of speed (20~180) km/h, distance (15~45) m, and angle (0~30)° of the two targets are set by MTRV verification device, and the combination of measurement values is listed in Table 8.

As shown in Table 8, through 10 groups of verification tests, the two targets with simulated nominal parameter values are correctly distinguished by MTRV. It is proved that the verification device can simulate the two target signals well. The verification experiment includes velocity, distance, and angle, and the multitarget distinguish validates that the technical performance of the simulation device and the verification method based on echo simulation technology is an effective verification method for MTRV.

6.2. Uncertainty Evaluation. Referring to the international standard for the uncertainty of measurement [22] and China's national standard for the evaluation and expression of uncertainty in measurement [23], the uncertainty of the verification results in Sections 6.1.1, 6.1.2, and 6.1.3 is evaluated in this subsection.

6.2.1. Velocity Uncertainty Evaluation. In the uncertainty evaluation for velocity calibration, the mathematical model for

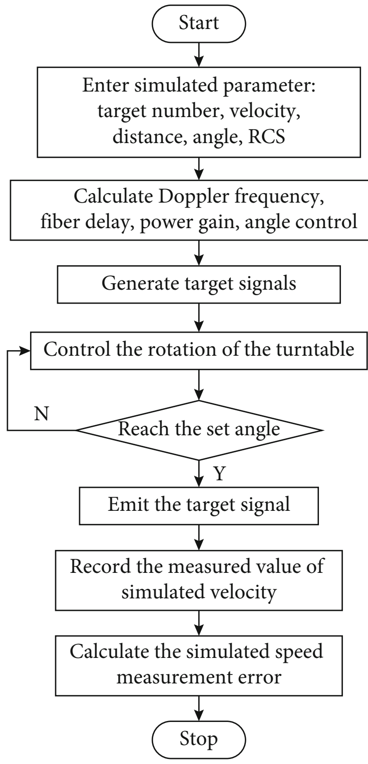

Figure 10: Verification flow chart.

simulated velocity measurement error Δv is given as follows:

$$\Delta v = v - v_0, \tag{8}$$

where v is the measured velocity value of sample and v_0 is the simulated velocity value of the MTRV verification device.

In the mathematical model, the components are independent of each other. According to Equation (8), the uncertainty model can be expressed as

$$u_c(\Delta v) = \sqrt{c_1^2 u^2(v) + c_2^2 u^2(v_0)}, \tag{9}$$

where $u_c(\Delta v)$ is the standard uncertainty of the velocity measurement error Δv, $u(v)$ is the standard uncertainty component associated with the measured value of simulated velocity v, $u(v_0)$ is the standard uncertainty component associated with nominal value of simulated velocity v, and c_{v1} and c_{v2} are the sensitivity coefficients, which are equal to

$$\begin{aligned} c_{v1} &= \frac{\partial \Delta v}{\partial v} = 1, \\ c_{v2} &= \frac{\partial \Delta v_0}{\partial v_0} = -1. \end{aligned} \tag{10}$$

Therefore, the standard uncertainty $u_c(\Delta v)$ in Equation (9) can be simplified as

$$u_c(\Delta v) = \sqrt{u^2(v) + u^2(v_0)}. \tag{11}$$

(A) The standard uncertainty component associated with the measured value of for simulated velocity $u(v)$

The standard uncertainty component $u(v)$ associated with the measured value of the simulated velocity v includes two subcomponents $u_a(v)$ and $u_b(v)$. $u_a(v)$ is the standard uncertainty subcomponent associated with the repeatability velocity measurement results in Table 5, and the standard deviation can be calculated by the Bessel formula as follows:

$$s(x_n) = \sqrt{\frac{\sum_{i=1}^{m} \left(x_n^i - \bar{x}_n\right)^2}{m-1}}, \tag{12}$$

where x_n denotes the nominal value of the n^{th} simulated velocity point, x_n^i denotes the i^{th} measurement value of the n^{th} simulated velocity point, $\bar{x}_n$ denotes the average value of ten independent measurement values of the n^{th} simulated velocity point, and m is number of repeated measurements, $m = 10$.

Since the average value of ten independent velocity measurement values was taken as the measured value of the simulated velocity to calculate the simulated velocity measurement error, the standard deviation of arithmetic mean can be calculated by Equations (12) and (13):

$$s(\bar{x}_n) = \frac{s(x_n)}{\sqrt{m}}. \tag{13}$$

Each velocity measurement point has the same number of repeated measurements; therefore, the standard uncertainty subcomponent associated with the velocity measurement repeatability can be expressed as the standard deviation of combined samples and can be calculated by

$$u(v) = s_p = \sqrt{\frac{\sum_{j=1}^{n} s_j^2(\bar{x}_n)}{n}}. \tag{14}$$

Therefore, the standard uncertainty subcomponent associated with the repeatability velocity measurement results $u_a(v)$ about target 1 and target 2 can be calculated by Equation (14) as follows:

$$\begin{aligned} &\text{Target 1}: u_{a1}(v) = s_{p(a1)} = 0.033\,\text{km/h}, \\ &\text{Target 2}: u_{a2}(v) = s_{p(a2)} = 0.039\,\text{km/h}, \end{aligned} \tag{15}$$

where $u_b(v)$ is the standard uncertainty subcomponent associated with the velocity measurement resolution of sample MTRV, which is 0.1 km/h and estimated by rectangular distribution, as shown in Table 5, and therefore can be calculated as follows:

Table 2: Velocity simulation test results.

Set simulation velocity value v_s (km/h)	Theoretical frequency shift f_s (Hz)	Measurement of the frequency shift f_d (Hz) Target 1	Target 2	Actual simulation velocity v_r (km/h) Target 1	Target 2	Simulation velocity error v_e (km/h) Target 1	Target 2
0 (Ref)	0	0	0	0	0	0	0
-300	-13412.08	-13412.50	-13412.90	-300.01	-300.02	-0.01	-0.02
-280	-12517.94	-12516.60	-12517.00	-279.97	-279.98	0.03	0.02
-240	-10729.66	-10730.10	-10730.10	-240.01	-240.03	-0.01	-0.03
-200	-8941.38	-8942.70	-8943.20	-200.03	-200.04	-0.03	-0.04
-180	-8047.25	-8046.80	-8046.40	-179.99	-179.98	0.01	0.02
-140	-6258.97	-6258.97	-6258.50	-139.95	-139.99	0.05	0.01
-100	-4470.69	-4469.80	-4469.80	-99.98	-99.98	0.02	0.02
-80	-3576.55	-3576.10	-3575.70	-79.99	-79.98	0.01	0.02
-60	-2682.42	-2683.50	-2683.80	-50.03	-50.03	-0.03	-0.03
-40	-1788.28	-1786.90	-1787.80	-39.97	-39.99	0.03	0.01
-20	-894.14	-893.20	-893.20	-19.98	-19.98	0.02	0.02
-10	-447.07	-448.10	-448.40	-10.02	-10.03	-0.02	-0.03
-1	-44.71	-43.10	-43.70	-0.96	-0.98	0.04	0.02
1	44.71	43.30	43.40	1.01	0.97	0.03	-0.03
10	447.07	448.40	448.10	10.03	10.02	-0.03	0.02
20	894.14	893.20	893.20	19.98	19.98	-0.02	-0.02
40	1788.28	1787.30	1789.60	39.98	40.03	0.02	0.03
60	2682.42	2683.30	2683.70	60.02	60.03	0.02	0.03
80	3576.55	3577.00	3578.30	80.01	80.04	-0.01	0.04
100	4470.69	4469.80	4492.95	99.98	100.05	-0.02	0.05
140	6258.97	6259.90	6260.30	140.02	140.03	0.02	0.03
180	8047.25	8048.60	8046.80	180.03	179.99	0.03	-0.01
200	8941.38	8943.30	8942.30	200.00	200.02	0.00	0.02
240	10729.66	10730.60	10731.40	240.02	240.04	0.02	0.04
280	12517.94	12518.40	12519.70	280.01	280.04	0.01	0.04
300	13412.08	13412.70	13410.70	299.98	299.97	-0.02	-0.03

$$u_{b1}(v) = u_{b2}(v) = \frac{0.1}{2\sqrt{3}} = 0.029\,\text{km/h}. \quad (16)$$

Since the two subcomponents $u_1(v)$ and $u_2(v)$ are independent and uncorrelated, the standard uncertainty component $u(v)$ of the two targets can be calculated as

$$\text{Target 1}: u_1(v) = \sqrt{u_1^2(v) + u_2^2(v)} = \sqrt{(0.033)^2 + (0.029)^2} = 0.044\,\text{km/h},$$
$$\text{Target 2}: u_2(v) = \sqrt{u_1^2(v) + u_2^2(v)} = \sqrt{(0.039)^2 + (0.029)^2} = 0.049\,\text{km/h}. \quad (17)$$

(B) The standard uncertainty component associated with nominal value of simulated velocity $u(v_0)$

The standard uncertainty component $u(v_0)$ associated with the nominal value of the simulated velocity v depends on the simulated velocity error of the verification device. According to the simulation velocity test of the verification device given in Table 1, the MPE of the simulated velocity was ±0.05 km/h and is estimated by rectangular distribution. Then, the standard uncertainty component $u(v_0)$ of the two targets can be calculated as

$$u_1(v_0) = u_2(v_0) = \frac{0.05}{\sqrt{3}} = 0.029\,\text{km/h}. \quad (18)$$

(C) The expanded uncertainty $U(\Delta v)$ of the velocity measurement error Δv

The uncertainty component associated with velocity measurement error Δv is summarized in Table 9. According to the calculation results of Equations (17) and (18), the standard uncertainty $u_c(\Delta v)$ of the two targets can be calculated by Equation (11):

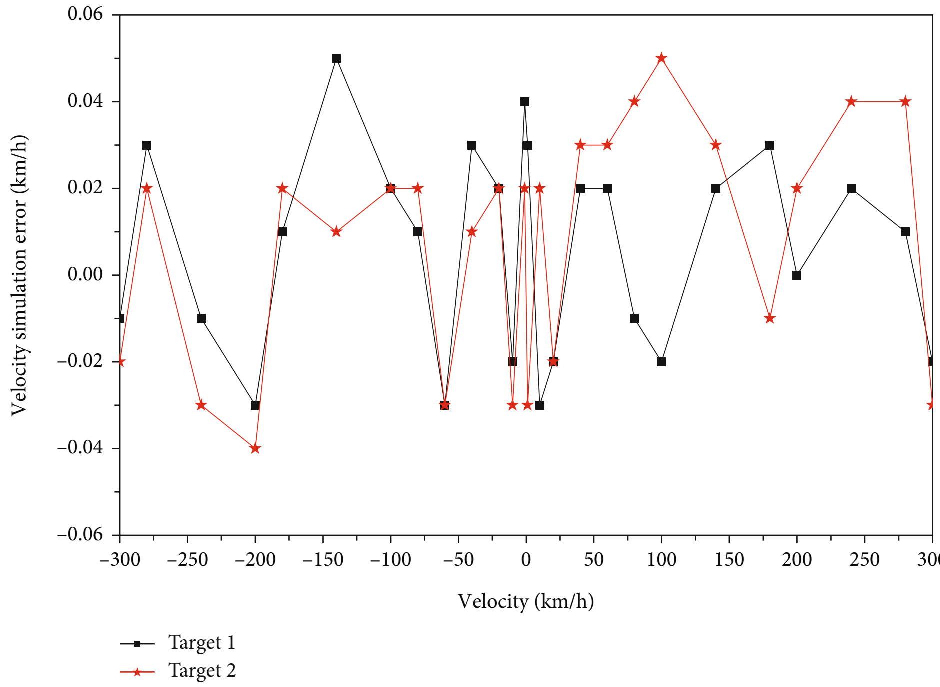

Figure 11: Results of the target velocity simulation error.

Table 3: Distance simulated measurement results.

Set the simulation distance R_s (m)	Measurement of the time delay τ (ns)		Actual simulation distance R_r (m)		Simulated distance error R_e (m)	
	Target 1	Target 2	Target 1	Target 2	Target 1	Target 2
10.0	64.7	65.0	9.7	9.8	-0.3	-0.2
15.0	99.5	98.3	14.9	14.7	-0.1	-0.3
20.0	130.5	131.8	19.8	19.8	-0.2	-0.2
25.0	165.7	165.0	24.8	24.7	-0.2	-0.3
30.0	197.3	198.0	29.9	29.9	-0.1	-0.1
35.0	232.2	231.8	34.8	34.8	-0.2	-0.2
40.0	263.9	264.8	39.9	39.8	-0.1	-0.2
45.0	296.5	298.3	44.8	44.7	-0.2	-0.3

$$\text{Target 1}: u_{c1}(\Delta v) = \sqrt{u^2(v) + u^2(v_0)} = \sqrt{(0.044)^2 + (0.029)^2} = 0.053\ \text{km/h},$$
$$\text{Target 2}: u_{c2}(\Delta v) = \sqrt{u^2(v) + u^2(v_0)} = \sqrt{(0.049)^2 + (0.029)^2} = 0.057\ \text{km/h}. \quad (19)$$

The expanded uncertainty $U(\Delta v)$ of the velocity measurement error Δv, where the coverage factor k is 2, can be expressed as follows:

$$\text{Target 1}: U_1(\Delta v) = k \cdot u_{c1}(\Delta v) = 0.11\ \text{km/h} \quad (k = 2),$$
$$\text{Target 1}: U_2(\Delta v) = k \cdot u_{c2}(\Delta v) = 0.11\ \text{km/h} \quad (k = 2). \quad (20)$$

6.2.2. Distance Uncertainty Evaluation. The standard uncertainty of the distance measurement error can be calculated by the uncertainty evaluation method of velocity error introduced in Section 6.2.1.

In the uncertainty evaluation for distance calibration, the mathematical model for simulated distance measurement error ΔR is given as follows:

$$\Delta R = R - R_0, \quad (21)$$

where R is the measured distance value of sample and R_0 is the simulated distance value of the MTRV verification device.

In the mathematical model, the components are independent of each other. According to Equation (21), the uncertainty model can be expressed as

$$u_c(\Delta R) = \sqrt{c_1^2 u^2(R) + c_2^2 u^2(R_0)}, \quad (22)$$

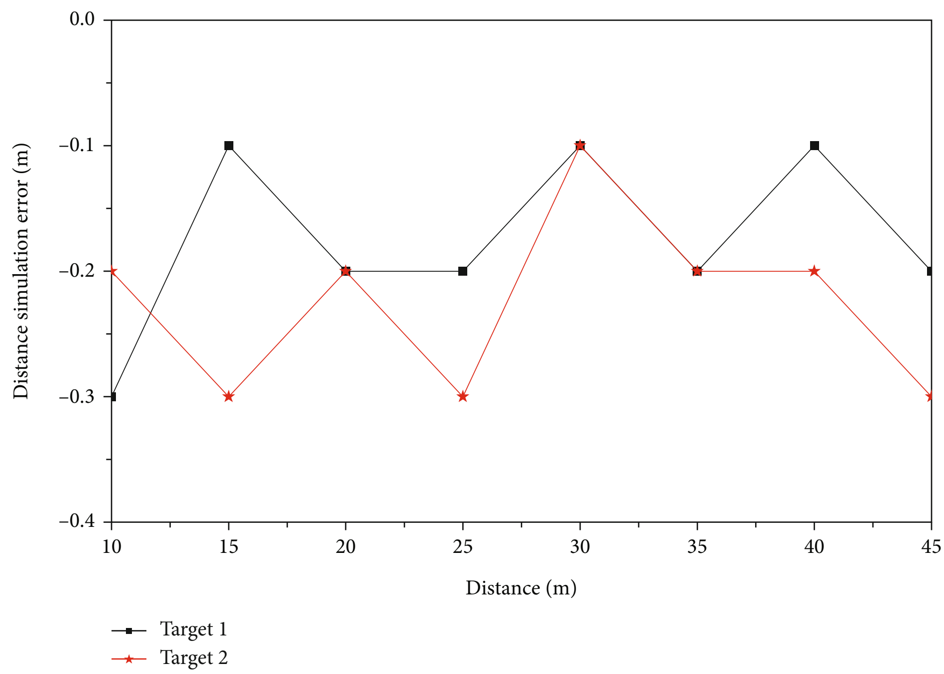

Figure 12: Diagram of distance simulation error.

Table 4: Angle simulated measurement results.

Set the simulation angle A_s (°)	Measurement of the angle A_M (°) Target 1	Measurement of the angle A_M (°) Target 2	Simulation angle error A_e (°) Target 1	Simulation angle error A_e (°) Target 2
-60.0	-60.1	-59.9	-0.1	+0.1
-50.0	-49.8	-50.0	+0.2	0.0
-40.0	-40.1	-39.9	-0.1	+0.1
-30.0	-29.9	-29.8	+0.1	+0.2
-20.0	-20.2	-19.8	-0.2	+0.2
-15.0	-14.8	-15.1	+0.2	-0.1
-10.0	-9.9	-10.2	+0.1	-0.2
-5.0	-5.1	-5.1	-0.1	-0.1
0.0	0.0	0.0	0.0	0.0
5.0	5.1	5.1	+0.1	+0.1
10.0	10.1	10.2	+0.1	+0.2
15.0	14.9	14.8	-0.1	-0.2
20.0	20.1	20.1	+0.1	+0.1
30.0	29.9	30.0	-0.1	0.0
40.0	40.2	40.1	+0.2	+0.1
50.0	50.1	50.0	+0.1	0.0
60.0	60.1	60.1	+0.1	+0.1

where $u_c(\Delta R)$ is the standard uncertainty of the distance measurement error ΔR; $u(R)$ is the standard uncertainty component associated with the measured value of simulated distance R, which includes two subcomponents $u_a(R)$ and $u_b(R)$: $u_a(R)$ is the standard uncertainty subcomponent associated with the repeatability distance measurement results in Table 6, and the standard deviation calculation method is the same as $u_a(v)$ by Equations (12), (13), and (14); $u_b(R)$ is the standard uncertainty subcomponent associated with the distance measurement resolution of sample MTRV, which is 0.1 m and estimated by rectangular distribution, as shown in Table 6, and the calculation method is the same as $u_b(v)$ by Equation (16), where $u(R_0)$ is the standard uncertainty component associated with simulated nominal distance R which depends on the simulated distance error of the verification. The MPE of the simulated distance was ±0.3 m; it can be calculated by Equation (18)

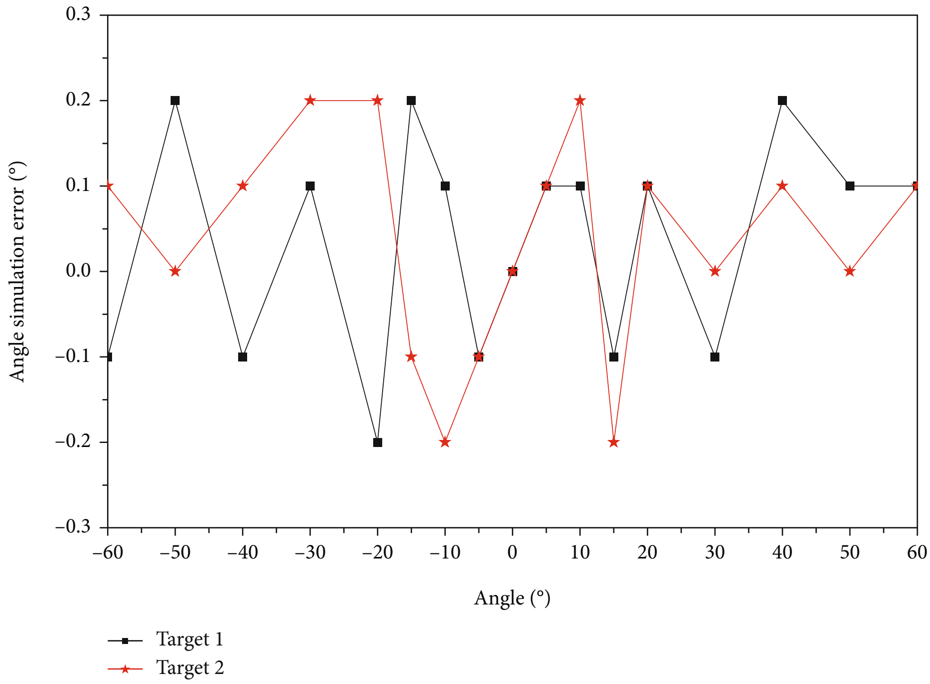

Figure 13: Diagram of angle simulation error.

Table 5: Velocity verification results.

Target	Nominal value of simulated velocity (km/h)	Velocity measurement value (km/h) 1	2	3	4	5	6	7	8	9	10	Average value (km/h)	Measurement error (km/h)
1	20.00	20.0	20.0	20.0	20.0	19.9	20.0	20.0	20.0	20.0	20.0	20.0	-0.01
	60.00	59.9	60.0	60.0	60.0	60.0	60.0	59.9	60.0	60.0	60.0	60.0	-0.02
	80.00	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	0.00
	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.00
	120.00	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	0.00
	140.00	140.2	140.2	140.2	140.1	140.2	140.2	140.2	140.2	140.2	140.2	140.2	+0.19
	160.00	160.4	160.5	160.4	160.4	160.4	160.5	160.4	160.4	160.4	160.5	160.4	+0.43
	180.00	180.5	180.5	180.5	180.5	180.5	180.4	180.4	180.4	180.4	180.5	180.5	+0.46
2	20.00	20.0	20.0	20.0	19.9	19.9	20.0	20.0	20.0	20.0	20.0	20.0	-0.02
	60.00	60.0	60.0	60.0	59.9	60.0	59.9	60.0	59.9	60.0	60.0	60.0	-0.03
	80.00	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	0.00
	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.00
	120.00	120.0	120.0	120.0	120.0	120.0	120.1	120.0	120.0	120.0	120.0	120.0	+0.01
	140.00	140.2	140.2	140.2	140.2	140.3	140.2	140.3	140.3	140.2	140.2	140.2	+0.23
	160.00	160.4	160.5	160.5	160.5	160.4	160.5	160.5	160.5	160.5	160.5	160.5	+0.48
	180.00	180.5	180.6	180.5	180.5	180.5	180.5	180.4	180.5	180.6	180.5	180.5	+0.51

similarly. And c_{R1} and c_{R2} are the sensitivity coefficients, which are equal to

$$c_{R1} = \frac{\partial \Delta R}{\partial R} = 1, \quad c_{R2} = \frac{\partial \Delta R_0}{\partial R_0} = -1. \tag{23}$$

Therefore, the standard uncertainty $u_c(\Delta R)$ in Equation (22) can be simplified as

$$u_c(\Delta R) = \sqrt{u^2(R) + u^2(R_0)}. \tag{24}$$

The standard uncertainty component associated with distance measurement error ΔR is summarized in Table 10, and

Table 6: Distance verification results.

Target	Nominal value of simulated distance (m)	Distance measurement value (m)										Average value (m)	Measurement error (m)
		1	2	3	4	5	6	7	8	9	10		
1	15.0	15.8	15.8	15.8	15.5	15.8	15.8	15.7	15.8	15.8	15.7	15.8	+0.8
	25.0	25.7	25.7	25.6	25.6	25.9	25.6	25.7	25.7	25.6	25.6	25.7	+0.7
	30.0	31.0	30.9	30.8	30.8	30.8	31.1	31.0	30.9	31.0	31.1	30.9	+0.9
	35.0	41.0	41.0	41.1	40.9	40.9	41.1	41.2	41.0	40.9	41.1	30.9	+0.9
	40.0	45.9	46.0	46.1	45.6	45.8	46.1	45.3	45.6	46.1	46.1	35.7	+0.7
	45.0	46.1	46.2	46.3	45.8	46.0	46.3	45.5	45.8	46.3	46.3	46.1	+1.1
2	15.0	15.7	15.7	15.7	15.7	15.7	15.7	15.6	15.6	15.7	15.7	15.7	+0.7
	25.0	25.9	25.8	25.9	26.0	25.8	25.8	25.9	26.0	25.9	26.0	25.9	+0.9
	30.0	30.8	30.9	30.8	30.9	30.7	30.9	31.0	30.9	30.9	31.0	30.9	+0.9
	35.0	35.8	35.9	36.3	35.7	36.0	35.9	35.9	36.0	35.9	35.9	35.9	+0.9
	40.0	40.9	41.0	41.0	40.9	40.6	40.8	41.0	40.6	40.7	40.9	40.9	+0.9
	45.0	45.9	46.2	46.2	46.1	45.6	46.2	45.5	46.2	46.0	46.2	46.0	+1.0

Table 7: Angle verification results.

Target	Nominal value of simulated angle (°)	Angle measurement value (°)										Average value (°)	Measurement error (°)
		1	2	3	4	5	6	7	8	9	10		
1	-30.0	-30.2	-30.5	-30.6	-30.2	-30.5	-30.5	-30.6	-30.6	-30.5	-30.5	-30.5	-0.5
	-20.0	-20.5	-20.6	-20.3	-20.8	-20.6	-20.3	-20.7	-20.6	-20.3	-20.4	-20.5	-0.5
	-10.0	-10.1	-10.4	-10.5	-10.6	-11.0	-10.6	-10.5	-10.3	-9.4	-10.2	-10.4	-0.4
	10.0	10.7	9.8	9.8	9.6	10.4	10.3	9.9	9.7	10.6	10.4	10.1	0.1
	20.0	20.7	20.4	20.4	20.3	20.7	20.0	20.4	20.4	20.3	20.4	20.4	0.4
	30.0	29.8	30.6	29.8	30.9	30.9	29.7	30.7	30.8	29.7	30.7	30.4	0.4
2	-30.0	-30.7	-30.5	-31.0	-30.8	-30.8	-30.8	-30.5	-30.6	-30.5	-30.4	-30.7	-0.7
	-20.0	-20.4	-20.6	-20.9	-20.7	-20.9	-20.4	-20.6	-20.6	-20.5	-20.4	-20.6	-0.6
	-10.0	-9.8	-10.4	-10.5	-11.1	-11.4	-10.6	-10.4	-10.2	-9.8	-10.3	-10.4	-0.4
	10.0	9.8	9.6	9.6	9.8	10.2	10.3	9.4	9.3	10.3	10.3	9.8	-0.2
	20.0	20.5	19.9	20.3	20.3	19.9	20.0	20.4	20.3	20.3	20.1	20.2	0.2
	30.0	30.6	30.4	30.7	29.4	30.6	30.7	30.3	30.4	30.6	30.4	30.4	0.4

Table 8: Multitarget distinguish results.

Groups	Simulated nominal parameter value						Target distinguish (Success: ○ Fail: ◊)	
	Target 1			Target 2			Target 1	Target 2
	Velocity (km/h)	Distance (m)	Angle (°)	Velocity (km/h)	Distance (m)	Angle (°)		
1	20.0	15.0	0.0	40.0	25.0	15.0	○	○
2	40.0	25.0	15.0	20.0	15.0	0.0	○	○
3	60.0	15.0	0.0	80.0	25.0	15.0	○	○
4	80.0	25.0	15.0	60.0	15.0	0.0	○	○
5	100.0	15.0	0.0	120.0	25.0	15.0	○	○
6	120.0	25.0	15.0	100.0	15.0	0.0	○	○
7	140.0	20.0	5.0	160.0	30.0	5.0	○	○
8	160.0	30.0	20.0	140.0	20.0	25.0	○	○
9	110.0	20.0	5.0	180.0	30.0	5.0	○	○
10	180.0	30.0	20.0	110.0	20.0	25.0	○	○

Table 9: Uncertainty component associated with velocity measurement error Δv.

Standard uncertainty component	Source of uncertainty	Evaluation method	k	Sensitivity coefficient	Value of output standard uncertainty component Target 1	Target 2
$u(v)$	$u_a(v)$: repeatability of velocity result	A	/	1	0.033 km/h	0.039 km/h
	$u_b(v)$: measurement resolution of velocity	B	$\sqrt{3}$	1	0.029 km/h	0.029 km/h
$u(v_0)$	Nominal value of simulated velocity	B	$\sqrt{3}$	-1	0.029 km/h	0.029 km/h

Table 10: Uncertainty component associated with distance measurement error ΔR.

Standard uncertainty component	Source of uncertainty	Evaluation method	k	Standard uncertainty component	Value of output standard uncertainty component Target 1	Target 2
$u(R)$	$u_a(R)$: repeatability of distance result	A	/	1	0.181 m	0.146 m
	$u_b(R)$: measurement resolution of distance	B	$\sqrt{3}$	1	0.029 m	0.029 m
$u(R_0)$	Nominal value of simulated distance	B	$\sqrt{3}$	-1	0.173 m	0.173 m

the standard uncertainty $u_c(\Delta R)$ about target 1 and target 2 can be calculated by Equation (24):

$$\begin{aligned} \text{Target 1}: u_{c1}(\Delta R) &= \sqrt{u^2(R) + u^2(R_0)} = \sqrt{(0.181)^2 + (0.029)^2 + (0.173)^2} = 0.252\,\text{m}, \\ \text{Target 2}: u_{c2}(\Delta R) &= \sqrt{u^2(R) + u^2(R_0)} = \sqrt{(0.146)^2 + (0.029)^2 + (0.173)^2} = 0.228\,\text{m}. \end{aligned} \tag{25}$$

The expanded uncertainty $U(\Delta R)$ of the distance measurement error ΔR, where the coverage factor k is 2, can be expressed as follows:

$$\begin{aligned} \text{Target 1}: U_1(\Delta R) &= k \cdot u_{c1}(\Delta R) = 0.50\,\text{m} \quad (k = 2), \\ \text{Target 1}: U_2(\Delta R) &= k \cdot u_{c2}(\Delta R) = 0.46\,\text{m} \quad (k = 2). \end{aligned} \tag{26}$$

6.2.3. Angle Uncertainty Evaluation. Furthermore, the standard uncertainty of the angle measurement error can also be calculated by the uncertainty evaluation method of velocity error introduced in Section 6.2.1.

The mathematical model for simulated angle measurement error ΔA is given as follows:

$$\Delta A = A - A_0, \tag{27}$$

where A is the measured angle value of sample and A_0 is the simulated angle value of the MTRV verification device.

In the mathematical model, the components are independent of each other. According to Equation (27), the uncertainty model can be expressed as

$$u_c(\Delta A) = \sqrt{c_1^2 u^2(A) + c_2^2 u^2(A_0)}, \tag{28}$$

where $u_c(\Delta A)$ is the standard uncertainty of the angle measurement error ΔA; $u(A)$ is the standard uncertainty component associated with the measured value of simulated angle A, which includes two subcomponents $u_a(A)$ and $u_b(A)$: $u_a(A)$ is the standard uncertainty subcomponent associated with the repeatability angle measurement results in Table 7; $u_b(A)$ is the standard uncertainty subcomponent associated with the angle measurement resolution of sample MTRV. $u(A_0)$ is the standard uncertainty component associated with the simulated nominal angle value of verification device, the MPE of the

Table 11: Uncertainty component associated with angle measurement error ΔA.

Standard uncertainty component	Source of uncertainty	Evaluation method	k	Standard uncertainty component	Value of output standard uncertainty component Target 1	Target 2
$u(A)$	$u_a(A)$: repeatability of angle result	A	/	1	0.346°	0.333°
	$u_b(A)$: measurement resolution of distance	B	$\sqrt{3}$	1	0.029°	0.029°
$u(A_0)$	Nominal value of simulated distance	B	$\sqrt{3}$	-1	0.115°	0.115°

Table 12: Expanded uncertainty of measurement error.

Target	Expanded uncertainty Velocity	Distance	Angle
Target 1	0.11 km/h	0.50 m	0.73°
Target 2	0.11 km/h	0.46 m	0.71°

simulated angle was ±0.2°, and it can be calculated by Equation (18) similarly. The c_{A1} and c_{A2} are the sensitivity coefficients, which are equal to

$$c_{A1} = \frac{\partial \Delta A}{\partial A} = 1, \quad c_{A2} = \frac{\partial \Delta A_0}{\partial A_0} = -1. \tag{29}$$

Therefore, the standard uncertainty $u_c(\Delta A)$ in Equation (26) can be simplified as

$$u_c(\Delta A) = \sqrt{u^2(A) + u^2(A_0)}. \tag{30}$$

The uncertainty component associated with velocity measurement error ΔA is summarized in Table 11. The standard uncertainty $u_c(\Delta A)$ about target 1 and target 2 can be calculated by Equation (30):

$$\text{Target 1}: u_{c1}(\Delta A) = \sqrt{u^2(A) + u^2(A_0)} = \sqrt{(0.346)^2 + (0.029)^2 + (0.115)^2} = 0.366°, \quad \text{Target 2}: u_{c2}(\Delta A) = \sqrt{u^2(A) + u^2(A_0)} = \sqrt{(0.333)^2 + (0.029)^2 + (0.115)^2} = 0.353°. \tag{31}$$

The expanded uncertainty $U(\Delta A)$ of the distance measurement error ΔR, where the coverage factor k is 2, can be expressed as follows:

$$\text{Target 1}: U_1(\Delta A) = k \cdot u_{c1}(\Delta A) = 0.73° \quad (k = 2), \quad \text{Target 1}: U_2(\Delta A) = k \cdot u_{c2}(\Delta A) = 0.71° \quad (k = 2). \tag{32}$$

According to the above evaluation of Sections 6.2.1, 6.2.2, and 6.2.3, the expanded uncertainty values of sample of the two targets are shown in Table 12. For the velocity verification results, the values of the expanded uncertainty of the two targets were both 0.11 km/h and less than one-third of the simulated velocity MPE of the MTRV verification device. For the distance verification results, the maximum value of expanded uncertainty of the two targets was 0.50 m and less than one-third of the simulated distance MPE of the MTRV verification device. For the angle verification results, the maximum value of expanded uncertainty two targets was 0.73°, also less than one-third of the simulated angle MPE of the MTRV verification device. Therefore, the verification results of sample were effective and reliable [22, 23].

7. Conclusions

A verification device for multitarget radar velocimeter based on the echo signal simulation technology is developed in this paper. The measurement mechanism of MTRV with performance including velocity, distance, and angle is introduced. Then, a verification method based on the echo signal simulation technology is proposed. And the details of the proposed verification method process are illustrated, and the technique on developing the MTRV verification device is presented. Through the echo signal simulation of the verification device, the targets are given simulated nominal values of velocity, distance, and angle. Comparing the measured values of MTRV with the simulated nominal values of the verification device, the measurement error of MTRV is obtained. The verification device of MTRV is realized to verify the accuracy and reliability of the measurement results. The simulated velocity range of the verification device is up to (-300~300) km/h, and the simulated distance range of the verification device is up to (10~45) m when the simulated incident angle range was within the range of (-60~60)°. And the maximum permissible error (MPE) of simulated velocity was ±0.05 km/h, the MPE of simulated distance is ±0.3 m, and the MPE of simulated angle is ±0.2°. The simulation target generation for two targets of the device is also verified. Finally, the verification and uncertainty evaluation results of MTRV sample validated the effectiveness and feasibility of the proposed verification method and the developed verification device of MTRV.

As with the majority of studies, the design of the current study is subject to limitations. Since the performance verification of MTRV includes the accuracy of multiple target judgment, it is necessary to conduct verification test in the microwave anechoic chamber. Therefore, the cost increases due to the construction of darkroom to meet the experimental conditions. For the future work, we will conduct further study on the improvement of validation experimental conditions to improve the stability of analog signals so as to achieve validation under ordinary laboratory conditions. Furthermore, we will study on portable verification for MTRV, especially online verification when the MTRV is installed on the road.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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