12th INTERNATIONAL SCIENTIFIC CONFERENCE ON DEFENSIVE TECHNOLOGIES
OTEH 2026
Serbia, Tara, 21 - 24 October 2026

COMPARATIVE ANALYSIS OF DIFFERENT SYSTEMS FOR PROJECTILE VELOCITY MEASUREMENT IN BALLISTIC TESTING

ALEKSA ANIČIĆ
Agency for Testing, Stamping and Marking of Weapons, Devices and Ammunition, Kragujevac, tehnika@aiz.rs

NEBOJŠA HRISTOV
Military Academy, University of Defence, Belgrade, nebojsahristov@gmail.com

LAZAR BLAGOJEVIĆ
Agency for Testing, Stamping and Marking of Weapons, Devices and Ammunition, Kragujevac, proofhouse@aiz.rs

MILOŠ JONČIĆ
Ministry of Foreign Affairs, Arms Control Department, Belgrade, milos.joncic@mfa.rs

ILIJA LJUJIĆ
Zastava Arms, Quality Control Department, Kragujevac, kkvaliteta@zastava-arms.rs

DAMIR JERKOVIĆ
Military Academy, University of Defence, Belgrade, damir.jerkovic@va.mod.gov.rs

Abstract: *The paper presents the comparative analysis of projectile velocity measurement results obtained using different types of measuring equipment in ballistic testing. The considered velocity measurement systems include infrared barriers and various types of radar systems, with the aim of assessing their applicability, accuracy, reliability, and limitations under different test conditions. In addition to the comparative analysis of experimentally obtained results, the paper also provides an overview of different types of measuring equipment, their structural design, operating principles, and basic technical characteristics relevant to their application in ballistic testing. The tests were carried out using a ballistic barrel receiver, a test barrel, and accompanying measuring equipment, for several different calibers within the category of small-arms ammunition. The comparison of the measured projectile velocity values obtained by different measuring systems was performed, together with the analysis of the influence of the type of measuring equipment, measuring position, test configuration, and test conditions on the obtained results. Particular attention was given to the analysis of the estimation of measurement uncertainty in order to evaluate the validity and repeatability of the obtained data. Based on the obtained results, the assessment of the applicability of different measuring systems in ballistic testing of small arms was given.*

Keywords: *Projectile Velocity, Ballistic Testing, Measuring Equipment, Ammunition.*

1. INTRODUCTION

In the field of ballistics, measuring projectile velocity is one of the most important tasks. Projectile velocity directly determines kinetic energy, stability, and terminal effectiveness. Without precise velocity data, it is impossible to develop modern weapons, control the quality of gunpowder and ammunition, or test the resistance of ballistic protective equipment.

In the past, mechanical and electrical methods, such as the ballistic pendulum or wire grids, were used to measure projectile velocity. With older systems, the projectile had to physically hit the pendulum or cut wires at a precisely defined distance to calculate the projectile's velocity. The procedure was complicated to set up, required constant replacement of destroyed wires, and often yielded inaccurate results. Today, technology has completely changed this process and shifted to non-contact measurement. Modern devices allow the projectile to pass through the measurement point without any physical contact, while electronic measurement stations instantaneously read data on the screen with extremely high precision [5, 6, 8, 9].

In this study, two such modern but technologically completely different measuring systems were used: a ballistic chronograph based on infrared barriers *Top Trend V2.205* (Figure 1), and a portable Doppler radar *Garmin Xero C1 Pro* (Figure 2). The ballistic chronograph based on IR barriers (hereinafter referred to as the optical chronograph) operates on an optical principle – it measures the time required for a projectile to pass between two invisible IR light beams [3, 6, 9]. On the other hand, the Garmin (hereinafter referred to as the radar chronograph) utilizes radar technology, where the device emits radio waves that bounce off the flying

Corresponding author: A. Aničić;
E-mail: tehnika@aiz.rs
DOI: 10.5937/OTEH26155A

projectile, thereby continuously tracking its velocity.

To compare the performance of the aforementioned measuring systems, three calibers were selected for this research, covering a wide range of applications.



Figure 1 Ballistic chronograph based on infrared barriers, Top Trend V2.205 (optical chronograph)



Figure 2 Garmin Xero C1 Pro

The calibers used during the ballistic testing are as follows:

- 9 mm Luger (Figure 3a)
- 7.62x39 mm (Figure 3b)
- .308 Winchester (7.62x51 mm) (Figure 3c)

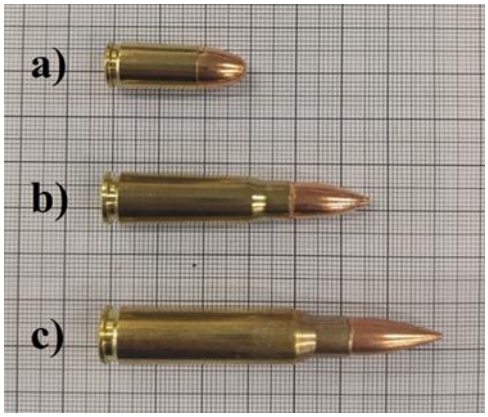


Figure 3 Ammunition: a) 9 mm Luger; b) 7.62x39 mm; c) .308 Winchester (7.62x51 mm)

Figure 4 shows the test barrels used for the testing.

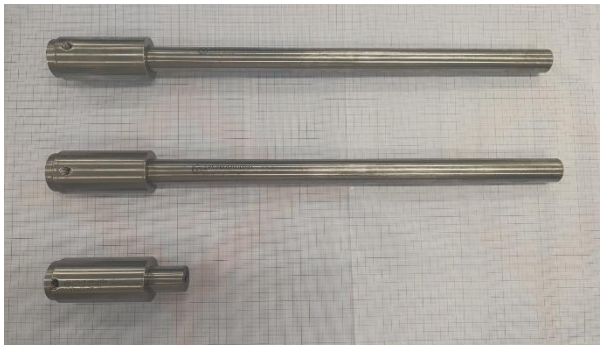


Figure 4 Test barrels (in order): 7.62x39 mm; .308 Winchester; 9 mm Luger

This study aims to perform a comparative analysis of the measuring systems through experimental testing. Through statistical processing of the measured velocity values for the specified three calibers, the paper aims to determine the level of measurement uncertainty for both systems, identify their operational advantages and limitations, and provide recommendations for their optimal application in research, development, and testing ballistic processes.

2. EXPERIMENTAL PERFORMANCE TESTING

This chapter details the method of executing the test, the spatial layout of the measuring components in the ballistic tunnel, as well as the basic physical principles on which the operation of the applied measuring systems is based.

For the purpose of measuring the muzzle projectile velocities of the selected calibers (9 mm Luger, 7.62x39 mm and .308 Winchester), specialized ballistic barrels were used. These barrels were manufactured, mounted, and calibrated in strict accordance with the international C.I.P. standard (*Commission internationale permanente pour l'épreuve des armes à feu portatives*). According to the C.I.P. standard, projectile velocity is measured at a distance of 2.5 m from the muzzle, with the chronograph positioned to determine the projectile velocity at that reference distance [1].

The use of standardized barrels in ballistic testing is crucial because they eliminate the influence of mechanical tolerances, wear and gas losses characteristic of service weapons. This ensures controlled, maximally repeatable initial conditions and allows the generated pressures and projectile velocities to be solely a function of the propellant charge characteristics and the geometry of the cartridge itself.

Ammunition conditioning was also performed in a temperature control chamber to prevent external environmental factors from negatively affecting the test. The temperature inside the chamber was 21°C, while the air humidity was 65%. The ammunition was stored in the chamber for 24 hours prior to the test itself. Table 1 shows the characteristics of the tested ammunition.

Table 1 Characteristics of the ammunition used for testing

Caliber	Projectile type	Bullet mass (gr)	Projectile mass (g)	Nominal muzzle velocity (m/s)
9 mm Luger	FMJ	124	8,00	~340
7,62x39	FMJ	123	8,00	~715
.308 Win	FMJ BT	145	9,40	~850

Before starting the test, the measuring devices were placed in specific positions to ensure simultaneous recording of the velocity of the same projectile during a single firing. Figure 5 shows the spatial configuration of the measuring systems, with the optical chronograph positioned on the right side, while the radar chronograph is positioned on the left side. They are located at a distance of 2.5 m ± 5 cm from the muzzle.



Figure 5 Spatial configuration of measuring systems: infrared barrier (right) and Garmin Xero C1 Pro (left)

The applied measuring devices represent two fundamentally different technological solutions in the field of experimental kinematics. The optical chronograph (Figure 1) functions as a passive-active optoelectronic discrete system for measuring passage time. Its operation is based on forming a continuous light curtain in the infrared spectrum within a rigid metal frame. When an opaque body (projectile) cuts through the first light plane, an instantaneous change in light intensity occurs at the photodetectors, which electronically activates a high-resolution time counter (timer). Passage through the second light plane, located on a factory-calibrated measuring base, generates a second pulse that stops the counting. The projectile velocity is subsequently interpreted as the average velocity over that fixed distance [3, 6, 9]. Table 2 provides the technical specifications of the optical chronograph.

Table 2 Technical specifications of ballistic chronograph based on infrared barriers, *Top Trend V2.205[3]*

Effective measuring area	1000x1000 mm
Caliber	4 – 40 mm
Velocity measurement range	30 – 3000 m/s
Fixed mesurement base	2000 mm
Measurement error	±0,1%
Spectral range	790 – 1050 mm (IC – A)
Detection maximum	940 nm
Output signal: square wave pulse	≤5V DC
Operating range	-10°C do +50°C
Power supply	230 V AC, 50 – 60 Hz
Weight	35 kg

The radar chronograph (Figure 2) functions as an active continuous-wave high-frequency radar system. The device continuously emits electromagnetic waves of a defined frequency in the direction of the projectile's movement. When the emitted wave encounters a projectile in flight, it reflects and returns to the device's receiving antenna. Given that the projectile moves at a velocity significant relative to the wave propagation velocity, the frequency of the reflected signal shifts proportionally to the body's velocity (Doppler shift). The system performs real-time frequency analysis (FFT) of the received signal, transforming the measured frequency shift directly into the instantaneous velocity of the projectile [2, 5, 8]. Table 3 provides the technical specifications of this measuring system.

Table 3 Technical specifications of the Garmin Xero C1 Pro [2]

Measuring range	30 do 1600 m/s
Dimension	77 x 60,5 x 34,44 mm
Weight	105,6 g
Water rating	IPX7
Display type	Sunlight-visible, monochrome
Display size	133 x 44 mm, diagonal 55 mm
Battery type	Internal rechargeable lithium-ion battery; non replaceable

Battery life	Up to 2000 shots or up to 6 hours
Operating range	-10°C to +55°C (14°F to 131°F)
Memory/history	50 sessions at max 100 shots per round before a Xero Core app sync is required to save data to phone
Interface	USB-C

3. RESULTS AND DISCUSSION

After setting up the measurement configuration, testing was conducted for each caliber individually. For each caliber, 20 shots were fired in a single group, during which the results provided by the optical chronograph were read alongside the muzzle velocity value measured by the radar chronograph. The tables presented below, in addition to the muzzle velocity values of each individual projectile, contain the average measured velocity value, maximum velocity, minimum velocity, spread of values (extreme spread) and standard deviation.

The first test was conducted for the 9 mm Luger caliber, and the obtained values read from the measuring systems are compared in Table 4.

Table 4 Muzzle velocity of the 9 mm Luger projectile measured by two different measuring systems

9 mm Luger		
No.	Optical chronograph	Radar chronograph
1.	387,60	388,40
2.	391,54	392,80
3.	381,97	380,40
4.	388,73	386,10
5.	384,76	383,00
6.	384,17	384,20
7.	386,03	386,60
8.	387,22	387,90
9.	383,29	384,60
10.	375,38	377,00
11.	377,71	376,00
12.	387,37	387,90
13.	381,61	380,40
14.	389,11	390,30
15.	380,01	381,00
16.	381,90	379,20
17.	381,61	382,60
18.	388,50	390,70
19.	385,73	387,80
20.	373,13	373,80
Avg.val.	383,87	384,04
Max:	391,54	392,80
Min:	373,13	373,80
Spread:	18,41	19,00
St. dev.	4,79	5,21

Based on the 20 performed measurements, it was determined that the average measured velocity for the optical chronograph is 383.87 m/s, while for the radar chronograph it is 384.03 m/s. The difference between the average values is only 0.16 m/s, indicating very good agreement between the results.

The spread of measured values for the optical chronograph is 18.41 m/s, and for the radar chronograph it is 19 m/s, which shows that both devices record almost identical velocity variations. The standard deviation for the optical chronograph is 4.79 m/s, while for the radar it is 5.21 m/s, implying low dispersion of results and good measurement repeatability for both systems.

The obtained results show that the radar chronograph yields almost identical results to those provided by the optical chronograph. The small difference in average values, as well as the similar values for spread and standard deviation, indicate that the radar chronograph provides reliable and stable measurements of the muzzle velocity for the 9 mm Luger projectile.

Following the 9 mm Luger caliber, the muzzle velocity measurement was performed for the 7.62x39 mm caliber. Table 5 presents the measurement results.

Table 5 Muzzle velocity of the 7.62x39 mm projectile measured by two different measuring systems

7,62x39 mm		
No.	Optical chronograph	Radar chronograph
1.	725,16	725,40
2.	736,38	737,10
3.	738,28	738,70
4.	737,46	736,80
5.	737,46	737,40
6.	735,56	735,50
7.	736,11	736,40
8.	738,55	738,30
9.	736,92	737,90
10.	731,26	731,70
11.	737,46	737,60
12.	736,11	736,70
13.	742,39	744,30
14.	737,74	737,90
15.	736,65	736,30
16.	739,64	740,60
17.	745,71	746,10
18.	741,02	741,30
19.	737,46	738,60
20.	737,19	737,50
Avg.val.	737,23	737,61
Max:	745,71	746,10
Min:	725,16	725,40
Spread:	20,55	20,70
St. dev.	4,04	4,20

Based on the 20 performed measurements, it was determined that the average measured velocity for the optical chronograph is 737.23 m/s, while for the radar it is 737.60 m/s. The difference between the average values is

only 0.38 m/s, indicating very good agreement between the results obtained by both measuring systems.

The spread of measured values for the optical chronograph is 20.55 m/s, and for the radar it is 20.70 m/s, which shows that both devices record almost identical velocity variations. The standard deviation for the optical chronograph is 4.04 m/s, while for the radar chronograph it is 4.20 m/s, implying low dispersion of results and good measurement repeatability for both systems.

The obtained results show that the radar chronograph yields almost identical results to those provided by the optical chronograph. The small difference in average values, as well as the similar values for spread and standard deviation, indicate that the radar chronograph provides reliable and stable measurements of the muzzle velocity for the 7.62x39 mm projectile.

The next measurement was performed for the .308 Winchester (7.62x51 mm) caliber.

Table 6 Muzzle velocity of the .308 Winchester projectile measured by two different measuring systems

.308 Winchester		
No.	Optical chronograph	Radar chronograph
1.	847,10	838,70
2.	858,00	866,60
3.	862,07	859,70
4.	853,24	852,80
5.	856,53	855,40
6.	868,43	867,30
7.	852,88	853,80
8.	862,07	862,00
9.	859,85	859,50
10.	867,30	866,70
11.	861,70	861,20
12.	867,30	871,80
13.	848,90	848,10
14.	853,97	855,50
15.	856,16	854,00
16.	862,44	861,80
17.	854,70	854,10
18.	862,44	861,80
19.	849,98	850,10
20.	857,63	855,70
Avg.val.	858,13	857,83
Max:	868,43	871,80
Min:	847,10	838,70
Spread:	21,33	33,10
St. dev.	6,15	7,65

Based on the 20 performed measurements, it was determined that the average measured velocity for the optical chronograph is 858.13 m/s, while for the radar chronograph it is 857.83 m/s. The difference between the average values is only 0.30 m/s, indicating very good agreement between the results obtained by applying both measuring systems.

The spread of measured values for the optical chronograph is 21.33 m/s, while for the radar chronograph it is 33.10 m/s. The standard deviation for the optical chronograph is 6.15 m/s, and for the radar it is 7.65 m/s, indicating less dispersion of results and slightly better measurement repeatability for the optical chronograph compared to the radar chronograph during this test.
Although a slightly larger spread of measured values and a larger standard deviation were recorded for the radar chronograph, the average values obtained by both devices are practically identical. Based on the obtained results, it can be concluded that the radar chronograph provides reliable and stable measurements of the muzzle velocity for the 7.62x51 mm projectile, with the results agreeing very well with those obtained using the optical chronograph.

4. RESULTS ANALYSIS

Following the testing and the obtained data, it is necessary to analyze the results, which is done in this chapter. An analysis of the results obtained from the measurements of the optical chronograph and the radar chronograph was conducted. The aim of the analysis is to compare the results obtained with the two measuring systems, evaluate their mutual agreement, and examine the repeatability and reliability of the measurements. The analysis is based on a comparison of average velocity values, spreads of measured values, standard deviations, percentage deviations, and measurement uncertainty for all three tested ammunition calibers.

4.1 Analysis of average values

Figure 5 shows a comparative diagram of the average velocity values for all three calibers (both measurement systems).

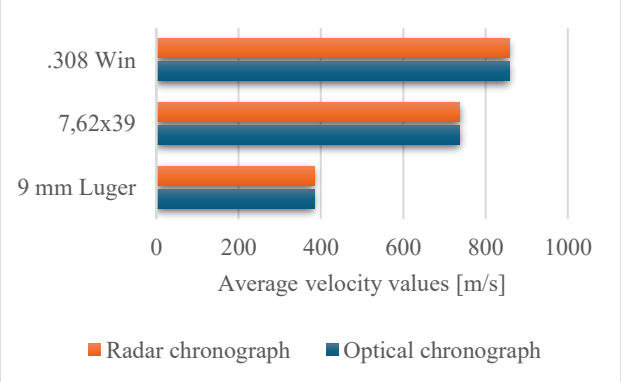


Figure 5 Comparative presentation of the obtained average velocity values using different measuring systems for three different calibers

The diagram clearly shows that the average velocity values of both measuring systems are almost identical, indicating consistency between the two systems.

4.2 Analysis of measurement repeatability

Figure 6 shows the comparative values of the standard deviation obtained by measuring with both systems for three different calibers.

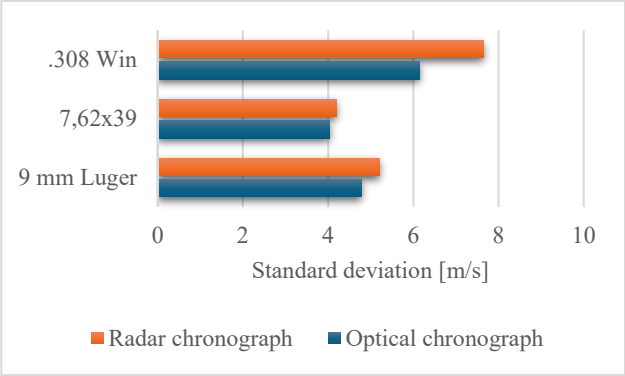


Figure 6 Comparative presentation of the obtained standard deviations

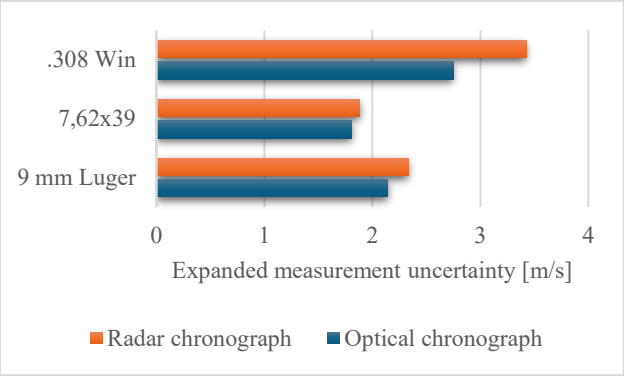


Figure 7 Comparative presentation of expanded measurement uncertainty

A smaller standard deviation value indicates higher measurement repeatability. For all three calibers, it was observed that the standard deviation obtained by measuring with the optical chronograph is smaller. The minimal difference between the two systems is noticed for the 7.62x39 caliber, while the largest difference between the standard deviation values was obtained during the testing of the .308 Winchester caliber.

4.3 Percentage deviation

To show the percentage deviation, the following formula was used:

$$\delta = \frac{\left|V_{avr(optical)} - V_{avr(radar)}\right|}{V_{avr(radar)}} * 100\%$$

Based on the tables from Chapter 3, the following percentage deviations were obtained:

- 9 mm Luger: 0.04%
- 7.62x39 mm: 0.05%
- .308 Winchester: 0.04%

The percentage deviations for all three calibers are approximately equal, indicating very small deviations between the measurement results.

4.4 Measurement uncertainty

Measurement uncertainty is calculated based on the obtained standard deviation[4, 7]. First, it is necessary to calculate the standard uncertainty:

$$u = \frac{Standard\ deviation\ value}{\sqrt{n}}$$

where *n* represents the total number of shots.

After calculating the standard uncertainty, the expanded uncertainty is calculated as follows:

$$U = 2u$$

Based on the aforementioned relations, the obtained results for the expanded measurement uncertainty are presented in the diagram in Figure 7.

4.5 General analysis

Based on all performed measurements, it can be concluded that the optical and radar chronographs provide reliable, stable, and repeatable measurements of muzzle projectile velocity. The analysis of average values, spread, standard deviation, expanded measurement uncertainty, and percentage deviation showed a high degree of consistency between the results obtained by applying both ballistic chronographs for all three tested calibers. The observed differences are small and within the expected measurement uncertainty, indicating that the radar chronograph can be successfully used as an alternative to the optical chronograph for measuring muzzle projectile velocity [5, 8].

CONCLUSION

The aim of this study was to test the measuring systems to see if approximate results are obtained using two different systems. Tests were performed for three different ammunition calibers: 9 mm Luger, 7.62x39 mm, and .308 Winchester, with 20 individual measurements realized for each caliber.

An analysis of the obtained results determined that the average values of the measured velocities are very similar for both measuring systems. Also, the analysis of spread, standard deviation, expanded measurement uncertainty, and percentage deviation showed that the differences between the results are small and within the expected measurement uncertainty. The percentage deviations for all three calibers amounted to approximately 0.04-0.05%, indicating a high degree of agreement between the results.

The calculated values of spread, standard deviation, and measurement uncertainty show that both measuring systems have good measurement repeatability. The obtained results confirm that the optical and radar chronographs can be successfully used to measure initial projectile velocity in laboratory and testing conditions.

The results of this work represent a basis for further research, which may include a larger number of different ammunition types, testing under different environmental conditions, and the analysis of additional factors affecting measurement accuracy. Such research would enable an

even more complete evaluation of the measurement characteristics of the optical chronograph as well as the radar chronograph and their application in ballistic testing.

Based on all conducted tests, it can be concluded that the optical and radar chronographs represent reliable and practical solutions for measuring muzzle projectile velocity, and the obtained results confirm that their application can satisfy the requirements of experimental ballistic testing.

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