Calibration of velocity light screens

J.P.F. Broos BSc[1)], W.E.T. Spruit BSc[1)]

[1)] TNO Defence, Security and Safety, P.O. Box 480, NL-2501 Rijswijk, the Netherlands, hans.broos@tno.nl

Abstract. Correct projectile velocity measurement is essential for shooting ranges, in order to determine the ballistic performance of sample materials. It determines the accuracy of the provided measurement result and therefore requires flawless and precise functioning of the velocity measurement system, including light screens, counters and calculations. A regular, traceable calibration of the velocity measuring instrumentation is mandatory for ISO 17025 accredited laboratories. This could be achieved by returning the complete system to the manufacturer for calibration. At TNO, infrared (IR) light screens are mounted on the wall inside the shooting ranges at a fixed position. Removing and re-installing the light screens could induce small deviations in the distance between the light screens, causing an error in the velocity measurement. For this reason it was chosen to calibrate the light screens in their original position. With this approach potential effects of outdoors calibration, like transportation and re-positioning are prevented.

Because a constant projectile velocity cannot be generated over the measurement range, considering the effect of drag resulting from variance of air pressure, temperature and humidity, a high speed video system is used for calibration. The in-house developed and precise velocity measurement device visualizes the projectile position during its flight. With the known projectile position over time and the resulting displacement between two recordings, the projectile velocity can be accurately measured. It results in an accurate average velocity over the distance between infrared light screens, for comparison with the reading obtained with the to be calibrated device.

The results of different sets of calibrations with two different projectiles show that projectile shape and velocity can influence the velocity measurements of the IR light screen. Also effects potentially resulting from vibrations due to moving of mobile velocity measurement equipment to different locations have been found.

1. INTRODUCTION

At TNO's Laboratory for Ballistic Research, ballistic tests according to standards are performed on daily basis. As an ISO17025 accredited laboratory, regular traceable calibration of measuring equipment is mandatory. Velocity screens are one of the most important devices since they determine the projectile impact velocity and decide together with the end result whether the sample has passed or failed the test. Since there is no such thing as a 'precise projectile velocity generator' that also corrects for drag for the given air pressure, temperature and humidity, TNO has developed a precision velocity measurement instrument to accurately calibrate their light screens.

Although it will be used mainly for light screens a variety of velocity systems can be calibrated, for example:

- Light screens
- Laser screens
- Contact foil/wires
- Doppler radar

Calibrating the velocity measurement instruments is an action which takes place on a regular basis. The outcome is important to monitor, not only to make sure that the readings are ok but also because the yearly gathered information could provide information about the possible causes for deviating readings.

This paper describes the method TNO is using for calibrating their velocity measuring instruments as performed on regular basis. A description of the system together with the outcomes of the measurements and lessons learned are presented.

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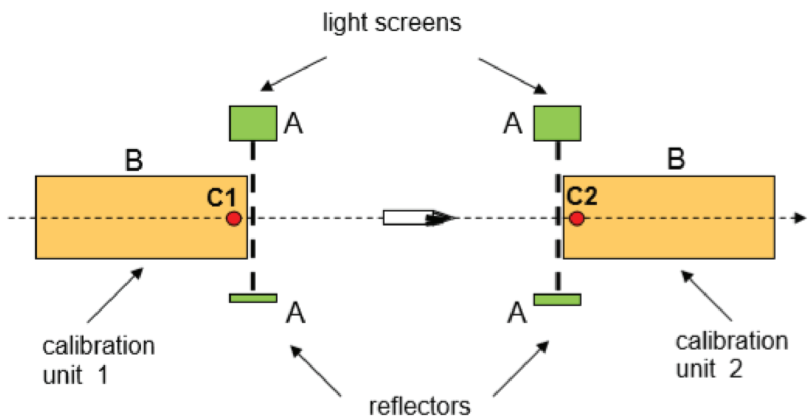
2. CALIBRATION PRINCIPLE

The calibration system and its components consists of two instrumented units which are capable to measure the projectile velocity with high accuracy. The units are triggered by a projectile passing a (laser) screen in the units. At the trigger, a shadowgraph picture of the projectile in flight is made by means of a short duration flasher. The position of the projectile imaged by both units is then measured with a calibrated ruler. By placing the units just in front and behind the velocity measuring instruments, the readings of both systems will give the same (average) velocity. In figure 1 a schematic setup of the device is shown. Boxes 'A' represents the velocity measuring instrument to be calibrated and 'B' the calibration system. The red dots C1 and C2 are the positions where the cameras are located. The distance between C1 and C2 is calculated using a calibrated aluminum ruler. The ruler contains several small holes (markers) at calibrated distances over the length of the ruler. With this tool different velocity measuring devices with varying distances between start and stop trigger can be calibrated.



A = device to be calibrated
B = calibration system
C1, C2 = camera position

Figure 1. Schematic top view of the setup for calibrating a velocity instrument (A in this case).

To ensure a sharp image of the projectile in flight, a short duration flash is combined with a parallel collimated optical system. The two lenses that provide the image and background illumination of the projectile have a double function. These imaging lenses used in the calibration units are based on the combination of the 2 lenses mounted in each cone holder in the units (see Figure 2). Thus, each lens in the speed calibrator is a combination of the large spherical lens located in the front of the cone holder and the small correction lens located in the back of the cone. This large lens is a spherical lens and therefore has spherical aberration. I.e. that the focus point of the light rays passing through the edge of the lens does not coincide with that of the light rays passing through the lens near the center. To correct for this, a correction lens is included in the back of the cone. The lens in the speed calibrator is therefore an aspherical lens. With this lens, the focus point of the edge rays does coincide with the focus point of the more central rays.

However, the result is that there is a quality difference in the depicted image. This is corrected in image processing. The dual function of these imaging a-spherical lenses consists on the one hand of creating as smooth a background illumination as possible and on the other hand of creating a good sharp image of the projectile. These are two different functions combined in one lens system. The beam path in this lens system is as follows. The flash emits a diverging beam during the flash. The spectrum of this beam ranges from UV to over 750 nm. This causes problems when focusing on the camera because it is not an a-chromatic lens and this a-spherical lens is therefore not corrected for this. A filter is used to correct for this and is discussed later. 50% of the light is transmitted through the 50R / 50T mirror and falls on the first large lens via the 100

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% mirror. The flash electrodes are exactly in the focal point (f = 30cm) of this lens. This creates a parallel beam behind this lens (in the pipe). This very wide spectrum beam is then focused by the second large lens on the side towards the camera (see Figure 2). Due to the wide spectrum and the non-chromaticity of this lens, the location of the focal point depends on the wavelength. This is the reason that a narrowband filter is placed in front of the camera. This filter is composed of two colored glass filters, namely a band filter and a long pass filter. The choice of these filters is determined by the final bandwidth and thus the resulting amount of light (energy) required to create adequately exposed images with current flashes. The bandwidth is preferably chosen as narrow as possible because the better the focus point for the background lighting is determined and the image of the projectile (shadow recording) is sharper the narrower this bandwidth. The focus point of the beam that is now very well determined should exactly coincide with the aperture in the camera lens.

If the beam path is optimally aligned, the aperture hole can be small and there is still sufficient background lighting. Because the aperture hole is small (F≈11 to 16), the image of the projectile is also as sharp as possible after focusing. The latter is therefore the second function of the lens system. Only the second large lens is involved in imaging the projectile. The first large lens ensures that a parallel light beam is present in the pipe. A sharp image of the projectile can now be captured during a flash against a well-lit background.

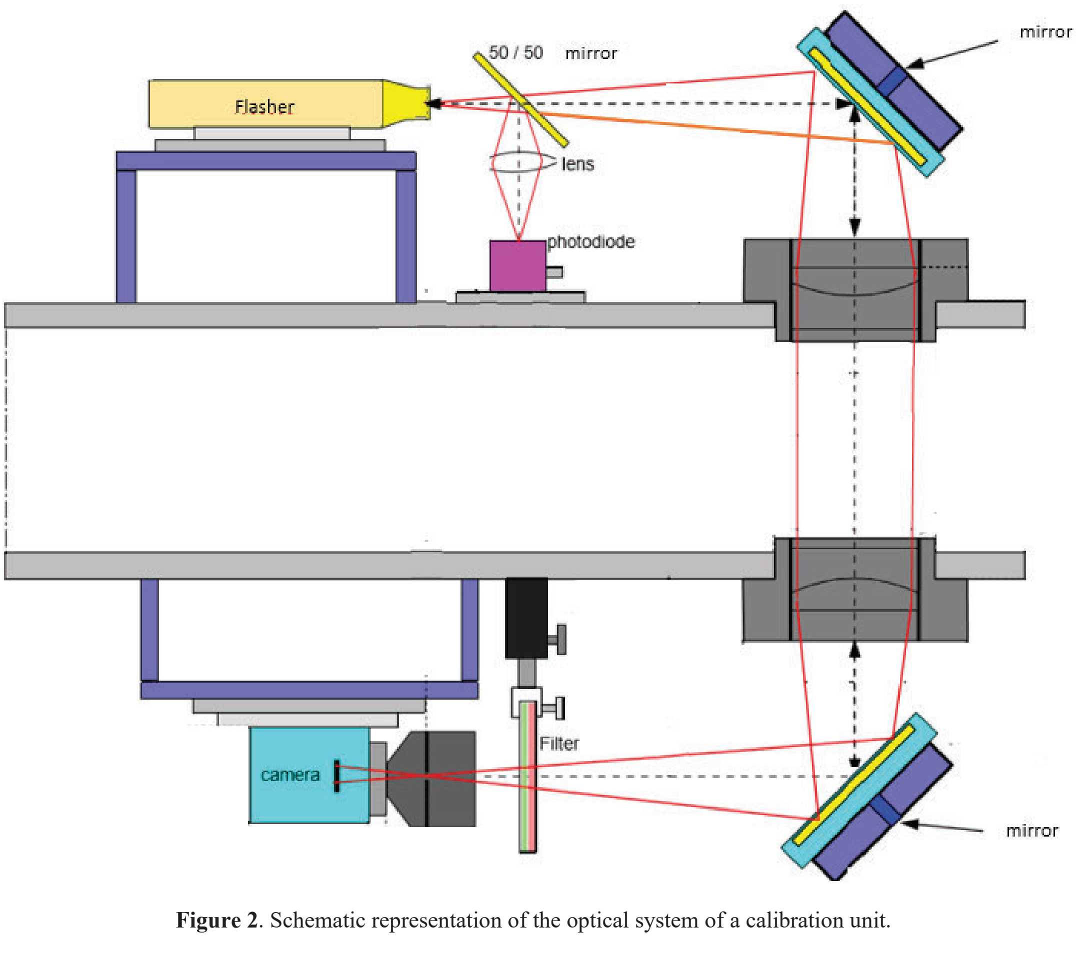

Figure 2. Schematic representation of the optical system of a calibration unit.

Figure 3 shows the calibration set-up in one of TNO's small caliber ranges. The calibration units are placed just in front and behind the light screens that are mounted on the wall.

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Figure 3. Overview of the setup in one of the small caliber ranges. The red boxes on the right are wall mounted IR light screens, the black boxes on the left are the reflectors. The calibration units are positioned in the line of fire and just in front of light screen 1 and behind light screen 2.

To resume: the two calibration units are identical and combined create a precise velocity measurement system. The spacing between the units can be accurately varied by using the calibrated ruler. In that way different velocity measurement instruments with varying spacing (up to 2 m) can be calibrated. Figure 4 shows two pictures of both the calibration units seen from two sides.

Figure 4. Side view of the unit with camera (left) and flasher on the opposite side (right)

The calibration system is composed of two identical units containing:

- Optical components
- Lasers
- High speed flash units
- Light detection components
- Cameras
- Optical filters
- Laser light detector system

Used additional equipment consists of:

- Electronic counter (externally calibrated)

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- Reference distance ruler (externally calibrated)
- Delay units
- Linux PC
- Image analysis software

Specifications of the system:

- Velocity range: 20 – 3500 m/s
- Distance over which the system can measure the average velocity: 800 – 2000 mm

The measurement accuracy depends on:

- Distance over which the measurement is carried out
- The projectile velocity (a very small contribution)
- The used camera lenses (our 35mm objective increases the accuracy 1.8 times)

The above variables results for a typical projectile velocity in a measurement accuracy of 0.019% at 1 meter distance between units and 0.009% at 2 meter distance between units.

3. CALIBRATION PROCEDURE

The units are accurately positioned in the line of fire and at each side of a velocity measurement instrument. The ruler is then placed in between the calibration units (see figure 5). A picture is taken by the cameras in the units, identifying and storing the ruler marker positions using the image analysis software. After that, the ruler is removed and a projectile is fired through the holes in the units. At the moment the projectile passes a laser screen at point C1 (see figure 1) a shadowgraph picture is taken with a short duration (nanoseconds) flasher. The same procedure holds for point C2.

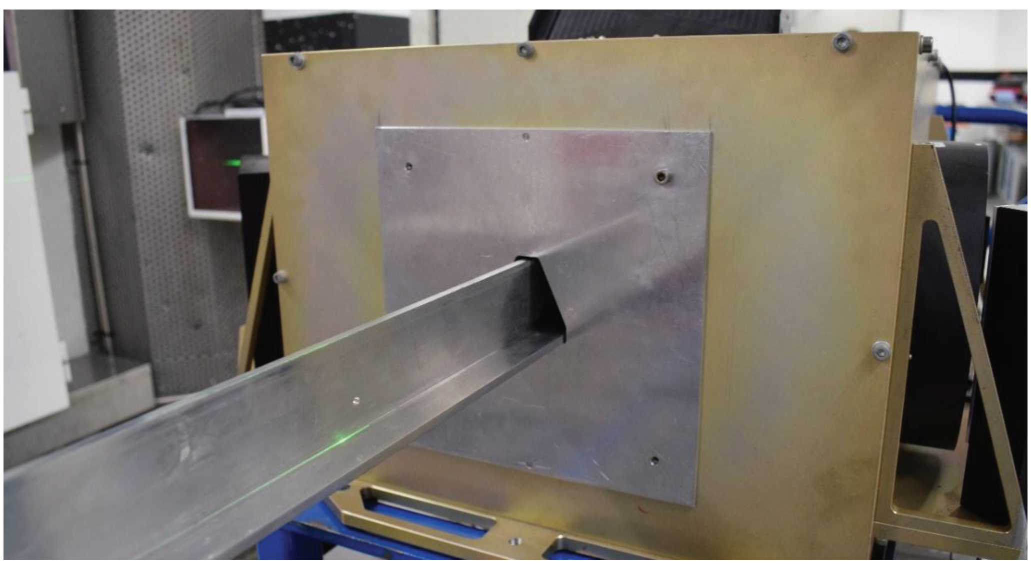

Figure 5. The ruler with a marker (hole) positioned in one of the calibration units.

The projectile position is determined from the exact center of the projectiles in flight, eliminating the influence of yaw on the measured projectile position. With image analysis software the contour of the projectile is determined and from that also the center of the projectile. The center is digitally marked with a cross. The two pictures of the projectile in flight are combined with the digitally stored marker positions that are now visualized as dots in the photograph (see figure 6). The software is now able to determine the exact position of the projectiles relative to the marker positions.

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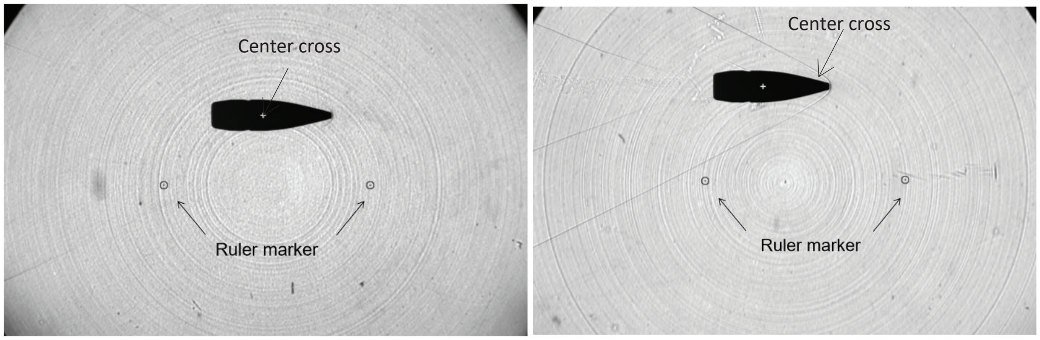

Figure 6. Two recordings of the projectile in flight from unit 1 (left in figure 1) and unit 2 (right). The digitally stored ruler markers are also projected in the pictures.

The time elapsed between taking the two pictures is measured exactly (within 0.2 nanoseconds) with an externally calibrated counter. The counter is started and stopped on C1 and C2 respectively by light sensors that are triggered by the flash. By means of a beam splitter the light is divided 50:50 between the picture and the light sensor. The picture on the left in figure 7 shows the flasher, beam splitter and sensor on one side of the unit. The picture on the right shows the camera on the opposite side looking at the flasher via a lens and mirror.

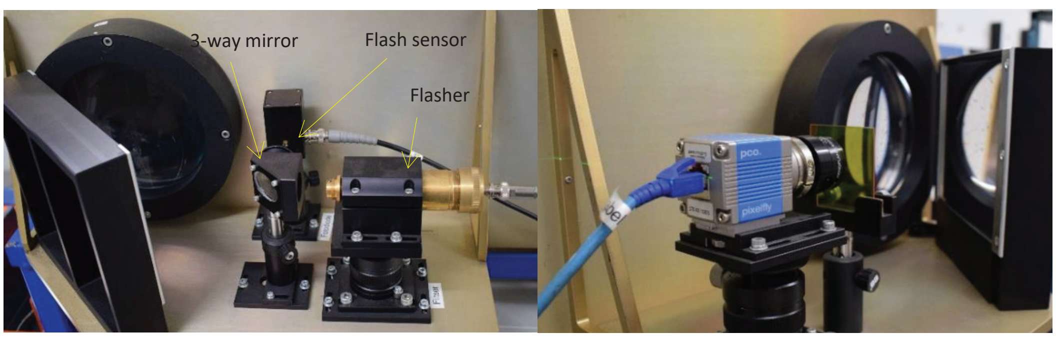

Figure 7. Detail of flasher and sensor for triggering the counter (left) and the camera (right).

The distance between the center of the projectiles on both pictures can be calculated from the distance between C1 and C2 combined with the position of the projectile center relative to each set of ruler markers, see figure 5. These ruler markers are digitally combined on the image of the projectile at C1 and C2.

With the retained information the average projectile velocity between C1 and C2 can now be calculated. Because C1 and C2 are as close as possible to the velocity measuring instrument that is being calibrated, the calculated average speed should be the same for both. When the values deviate, the distance that is used to calculate the velocity for the velocity instrument will be adjusted to a new value.

4. RESULTS

This chapter discusses some of the results found during annual calibrations of velocity light screens. As an ISO 17025 accredited testing institute, TNO must regularly calibrate its velocity measuring equipment. The calibration method described in this article is used for this and has been accepted by the Dutch Accreditation Council [2] (RVA) for application under ISO 17025.

There are mainly two type of velocity measuring systems that are used at TNO: stationary and movable systems. The small caliber shooting ranges have stationary Infrared (IR) light screens. These light screens are mounted on the wall of the shooting range and have a reflector mounted on the opposite wall (see also figure 3).

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The movable systems can be separately installed in a test setup. Examples are wheeled laser units and Doppler radar. An example of a wheeled laser screen device can be seen in figure 8.

Figure 8. Example of a wheeled mobile velocity measurement instrument

Below results are shown for calibration measurements performed with both a stationary and a mobile velocity measurement system. The calibrations were performed for two projectile types:

- 9x19 mm Ball @ 400 m/s
- 7.62x51 mm Ball @ 850 m/s

Nose shape and velocity range are chosen differently, representing realistic conditions during a year of ballistic testing.

4.1 Stationary system

Multiple stationary systems are available in the small caliber ranges. Below calibration results are presented for one set IR light screens in small caliber range 1 (KKW1). Each IR light screen has both IR transmitter and receiver in one box and a reflector opposite of that at 3 m distance. The mutual distance between the IR light screens is 1.5 m.

In total 10 experiments are performed with each projectile. The velocity measurements of the IR light screens were subtracted from the calibration measurements resulting in a deviation ΔV. Therefore a negative value means that the IR light screen measurement was lower than the calibration measurement. A maximum deviation of - 0.6 m/s was found for one experiment with a 7.62mm projectile in 2018. In 2019 a maximum deviation of +0.3 m/s was found also with a 7.62 mm projectile. Figure 9 and 10 show the deviation between the velocity measurements with the IR light screens and the calibration device measured in 2018 and 2019 respectively.

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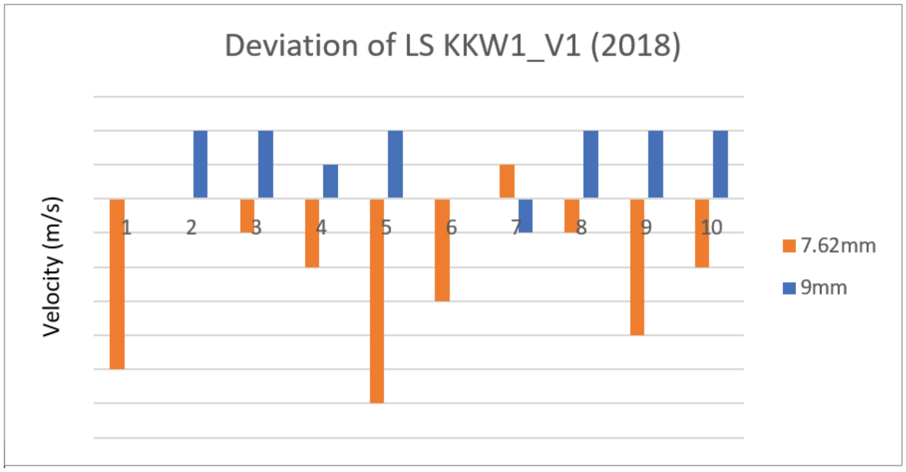

Figure 9. Deviation in velocity between the IR light screens and the calibration device, measured in 2018. A negative value means that the IR light screen measurement was lower than the calibration measurement.

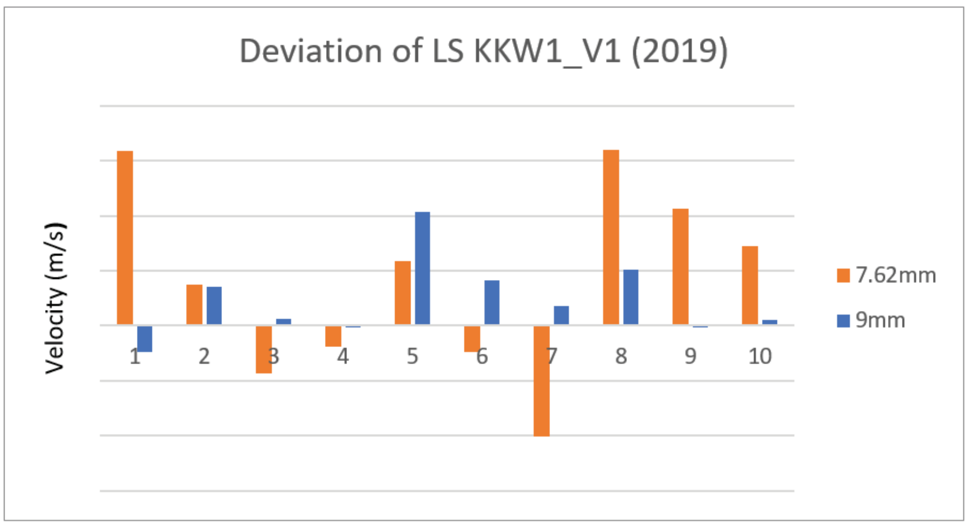

Figure 10. Deviation in velocity between the IR light screens and the calibration device, measured in 2019. A negative value means that the IR light screen measurement was lower than the calibration measurement.

The results in figures 9 and 10 show that the measured deviations between IR light screens and the calibration measurement are well within 1 m/s. It also shows a difference in deviation between the 9mm and the 7.62 mm bullet particularly in 2018. Only one 9 mm bullet measurement turns out to be lower than the calibration value. For the 7.62 mm bullet it's the other way around: only one measurement turns out to be higher than the calibration unit. The different results for 7.62 mm and 9 mm projectile calibration is unknown but may be caused by the operating principle of the light screen. When the projectile passes through a light screen, it obscures the IR receivers. This obscuring of the IR receivers and the underlying electronics in the device determine the trigger moment at a certain level. This trigger moment depends on the shape of the projectile and the speed of the projectile. The low-velocity 9 mm projectile's obscuration is more than the smaller, 7.62 mm, fast-flying bullet. Both start light screen and stop light screen probably have no problem with the 9 mm bullet, while for the 7.62 mm bullet it may be more critical because of its high speed and smaller size and therefore less obscuration. This might cause a slight discrepancy in sensitivity between the start light screen and the stop light screen. The results in 2019 show a less pronounced effect.

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4.2 Mobile system

Examples of mobile velocity measurement systems are:

- Doppler radars
- Laser screens (wheeled)
- IR light screens (wheeled)

These systems are used as additional equipment for triggering a yaw measurement system or triggering of High Speed (HS) cameras. Doppler radars are mainly used to measure velocity decrease of small fragments or for more complex test setups.

Below calibration results are obtained for a wheeled laser screen (see figure 7). The system has a laser transmitter in one box and a receiver in the opposite box. The mutual distance between the boxes is 1m.

Also in this case 10 experiments are performed with each projectile type. In figure 11 and 12 the results are shown from the measurements in 2018 and 2019.

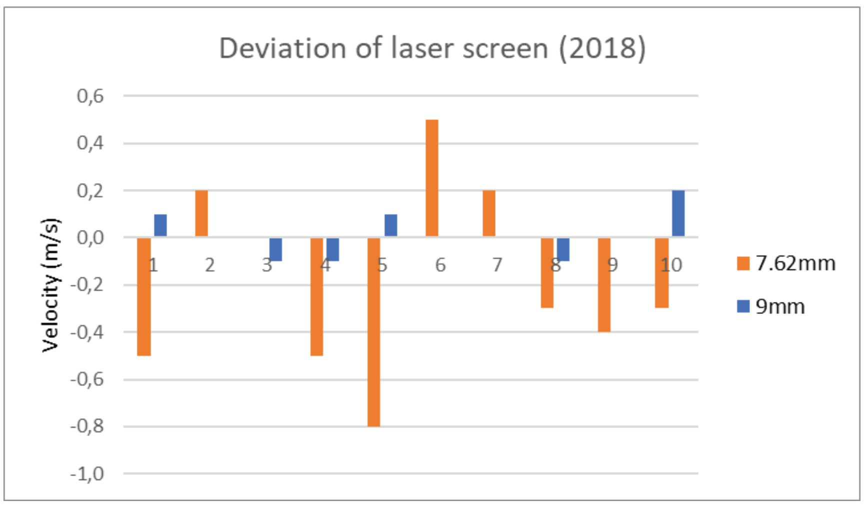

Figure 11. Deviation in velocity between the mobile laser screens and the calibration device, measured in 2018. A negative value means that the IR light screen measurement was lower than the calibration measurement.

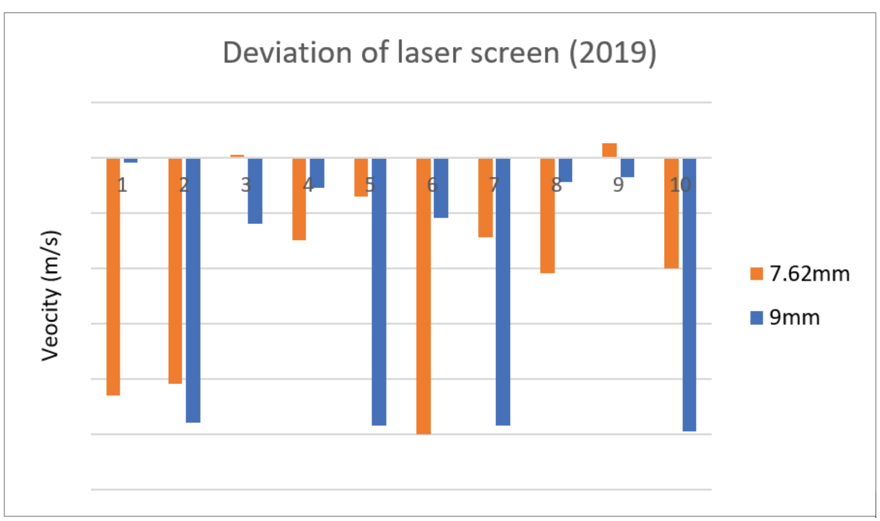

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Figure 12. Deviation in velocity between the mobile laser screens and the calibration device, measured in 2019. A negative value means that the IR light screen measurement was lower than the calibration measurement.

The results show an increase in deviation of the mobile laser screens after one year of usage. The deviations measured in 2019 show all negative values except one. The maximum measured deviation is -1 m/s which is at the limit of what is acceptable according to some standards (like NIJ 0101.06 [1]). The increased deviation could possibly be caused by vibrations that occur by regularly moving of the systems. Since almost all values changed to negative, this can be an indication that the vibrations might have changed the mechanical position of detectors and/or lens systems.

4.3 Damaged optics

When ballistically testing armour materials, fragments are ejected from the target and projectile during impact. These fragments will fly also in lateral directions towards the velocity measurement instruments mounted on the wall and can sometimes damage the optics of the IR light screens. In figure 13 an example of a damaged lens in one of the IR light screens that was caused by a fragment impact is shown. When this damaged velocity measurement system was calibrated, it surprisingly turned out that the deviation was still within 1 m/s. Probably the cracked lens was not influencing the optic path of the IR beam at the projectile line of flight in this particular case. However after replacing the lens with a new one, a major correction had to be made. The position of the lens in its frame turned out to be more critical.

Figure 13. A cracked lens of an IR light screen due to fragment impact.

5. GENERAL EXPERIENCES

Below the main findings of calibrating different types of light screens at TNO are listed:

- No major deviations are witnessed for stationary IR light screens.
- Mobile systems should be aligned accurately in the line of fire since this can influence the velocity reading.
- Doppler radar systems can give fluctuating velocity readings because of software settings.
- A cracked lens from an IR light screen (see figure 8) showed (in this case) to have minor deviation on the velocity reading.
- Replacing a lens can have a major influence on the velocity reading, the deviation can be up to more than 3 m/s.
- Aging of electronics should be monitored and reflectors and lenses should be frequently cleaned to ensure an constant performance of the light screens.
- Calibration of the velocity instruments should be performed at least once a year (but preferably more frequent).

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6. CONCLUSION

TNO has developed a calibration system for velocity measurement devices at ballistic ranges. Using this tool, it was found that our stationary IR light screens showed a small deviation over the past 2 years. It seems that mobile laser screens are more sensitive to vibration as results show a higher deviation after one year of usage. This could be caused by regularly moving the wheeled systems. These vibrations could influence the mechanical position of the detector and/or lens system. Externally calibrated light screens can be seen as mobile velocity systems that could also experience vibration during transport. Other deviations can be caused by:

- ageing of electronics
- dirt/dust or damage to components
- accuracy of installing (alignment)
- replacing of components (lenses)
- incorrect use of device and/or software (Doppler radar)
- rough handling of the equipment

Therefore regular maintenance, careful handling and regular calibration of light screens is necessary to keep the velocity readings reliable.

References

[1] Ballistic Resistance of Body Armor NIJ Standard-0101.06, July 2008

[2] Dutch Accreditation Council, https://www.rva.nl/en/scopes/details/L275

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