Research of the Photo-Optical Method Application for Measuring Selected Data on the Movement of a Parachute for Type M-282

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Abstract: Testing in the field of parachute technology provides space for the application of new and innovative methods of measuring operating and functional parameters. The main aim of the paper is to present the results of research for the verification of the photo-optical method of measuring the vertical speed of the M-282 parachutes, and for its use in testing, collecting, and investigating motion data in parachuting. As part of this measuring technology, twelve jumps were performed. It was verified that the experiment was completed for the M-282 parachute according to the regulation of SAE AS 8015B “Minimum Performance Standard Parachute Assemblies and Components”. An analysis of the influencing factors and quantification of their influence on the uncertainty of the measurement results was also performed. The results of the measurement achieved by using the photo-optical method were compared with the measurement with the electronic variometer FLYTEC 4030. The vertical speed of the M-282 parachute (4.655 m·s⁻¹) defined by the photo-optical method is significantly similar to the vertical speed of the M-282 parachute (4.662 m·s⁻¹) defined by FLYTEC 4030. We can state that the process of identifying the vertical speed of the parachute by the photo-optical method was correct. This is a suitable method of evaluating motion data in the operation of M-282 type parachutes. In the following research for generalization of the methodology, we assume the performance of more than 60 experimental jumps using different types of parachutes, digital sensors (cameras), and a photo-optical method to examine motion data and formulate recommendations for testing, investigative applications, individualized training programs, and aspects of parachuting injury prevention.

Keywords: safety; parachute; vertical speed; jump; measurement; testing; accident; investigation; digital motion data; individualized training; injury prevention

1. Introduction

Based on the focus of the journal’s Special Issue, measurement systems and methods provide many solutions for controlling and monitoring sports performance and collecting movement data. The data analysis can thus help to obtain relevant metrics supporting different digital scenarios (for training or accident investigation) or, for example, provide an additional level of coaching and individualized training programs based on performance and injury prevention aspects, including parachuting. The vertical descending speed of a parachutist (skydiver)–parachute composition (i.e., parachute vertical speed) is the most significant parachute flight parameter. This eventuation has been gained from a fundamental utilization of the parachute: To slow a free-fall down to an acceptable value until a fall/touchdown on the ground is safe and does not harm a human body. Articles [1–3], based on statistical indicators, point to this issue. Medicine and occurring injuries are also highlighted in relation to this issue [4,5]. When performing B.A.S.E. jumps (jumps from...
fixed points: Building, Antenna, Span, and Earth), the risk of injury due to the excessive vertical speed is also high [6]. Furthermore, this issue is key [7,8] when pilots perform emergency jumps from a low altitude and desire to slow to an acceptable vertical speed.

The main aim of the work is to present the results of the research on the photo-optical method for measuring selected data on the movement of a parachute for the type M-282 Parachute, and its usability in testing, collecting, and investigating motion data in parachuting. The M-282 parachute is designed to be used as the main canopy for sport jumps. Basic parameters of the M-282 parachute are as follows [9]:

- Canopy area: 26.9 m².
- Number of cells: 7.
- Descent rate at the weight of 100 kg depending on the braking mode: 2.5–5 m·s⁻².
- Gliding ratio: 2.5–3:1.
- Forward speed at the weight of 100 kg: max. 12 m·s⁻¹.

The research question is as follows: Is the photo-optical measurement method suitable for measuring the vertical speed of the M-282 parachute with the potential for general use for other types of parachutes and digital cameras for motion recording? The working hypothesis is as follows: Test parachute jumps confirm that the photo-optical method is a suitable method for measuring the vertical speed of a parachute. The results of the experiment verified the answer to the research question and confirmed the suitability of the photo-optical method for the M-282 parachute type. The differences in the results with the compared technical devices will be statistically insignificant.

The novelty of our work lies in the application of the photo-optical method for the purpose of measuring the vertical speed of a parachute. This was fulfilled by the development and verification of measurement procedures and measurement schematic diagrams.

The principal conclusions from the research undertaken for the topic are as follows:

- The photo-optical method in the application area of parachuting, for measuring the rate of descent of the M-282 parachute, within the investigation of movement data;
- Verification of the use of the photo-optical method in the application area of parachuting, within the research of the issue, by performing twelve test jumps with the M-282 parachute;
- Integration of knowledge from the investigation of a parachutist’s accident using the photo-optical method, with knowledge from research parachute jumps, within the research of the topic, for the formulation of the following research;
- The results of the M-282 parachute research of the topic showed the potential use of the photo-optical method for the design of recommendations for testing, investigative applications, individualized training programs, injury prevention aspects, and reduction of the risk of injury in parachuting. The process of identifying the vertical speed of the parachute by the photo-optical method was correct. It is a suitable method of evaluating M-282 parachute motion data in parachuting.

The remaining sections are arranged as follows. Section 2 describes the measurement of the parachute vertical speed by the photo-optical method. Section 3 states the main results of the M-282 test jumps. Section 4 provides a discussion of the verified theoretical results. Section 5 concludes the M-282 preliminary research focused on the photo-optical method for collecting and investigating motion data in parachuting.

Flight efficiency and personnel parachute limits are measured and verified in compliance with the technical standards order number TSO-C23D and due regulation of SAE AS 8015B “Minimum Performance Standard for Parachute Assemblies and Components” [10] (or TSO-C23e and PIA TS 135 [11]). In the chapter “The Test of Descending”, these regulations constitute maximum figures for the vertical speed, the minimum number of test jumps, and the minimum height interval of measuring (above the earth). SAE AS 8015B requires that the measurement of the vertical rate of descent of reserve and rescue parachutes be performed by a minimum of six test jumps/landings at maximum operating weight. Measuring procedures for the vertical speed have not been defined. The free-fall
parachutist speed and the vertical speed of an emergency parachute have been measured by a barograph [12] at Parks College Parachute Research Group of Saint Louis University. The principle of this method lies in the scanning of an air compression per time, subsequently in defining the height per time, and calculation of the vertical speed after the height change per time. This test method is given without uncertainty of the measurement result. The Skydiver Flight Parameters Recorder is also used to measure free-fall parameters [13]. Flight performances and emergency parachute limits for paragliding are measured and verified in compliance with STN EN 12491 [14] standards. These include maximum vertical speed values, minimum number of testing flights, and testing conditions, in the chapter “The Testing of Decline Speed and Stability”. The normal specified testing procedures for the vertical speed measurement note: “Any direct, exact, and repeatable practice can be applied for the vertical speed measurement. For example, the vertical speed can be calculated by derivation of a height recorded by a barograph in the context of time. Or the vertical speed can be determined by a load hung on a rope”. These presented testing results appear doubtful, and a measuring procedure is not given. An emergency parachute vertical speed measurement [15] performed at laboratories for paragliding speed (LTF certification—German airworthiness requirement, DHV—German Hang Glider Association) is conducted by fixing a ballast to an emergency parachute that is consequently thrown from a bridge to the ground. Parachute opening time and descending motion speed are measured. The laboratories do not take the parachute stability into consideration. The limiting vertical speed is 6.8 m·s⁻¹. This experimental method is assigned without determination of measuring results or measuring technique. A method for the measurement of the vertical speed [15] is undertaken in laboratories of paragliding engineering DHV, in which a pilot flies a parachute glider above a lake and opens an emergency parachute. After the emergency parachute is opened, the pilot detaches the main parachute. A 30-m-long rope is used with a ball attached and fixed to a seat. As soon as the ball touches the water’s surface, a stopwatch is set, which is then stopped after the pilot touches the water’s surface. These measured data become the basis for the calculation of the vertical descending speed. The maximum deviation against the vertical axis is 10° and the limiting vertical speed is 5.5 m·s⁻¹. This experimental method is assigned without a determinate result in measuring or a measuring technique. In terms of operational parameters, requirements for an emergency parachute used for hang gliding are restricted to the vertical descending speed and a minimum parachute opening height. However, the vertical descending speed can be determined relatively accurately [16]. Computer simulations and modeling can be used for parachute testing, but only in the development phase; these approaches include numerical methods [17], modeling [18–20], and simulation [21,22]. We can study experience from other projects [23,24], but it is necessary to perform real flight tests to demonstrate compliance with the requirements of the standards. This brief insight into the normative sources concerning the measurement of the vertical parachute speed illustrates that the current testing procedures are insufficient. Hence, for the testing of personnel parachute equipment in relation to the current most-utilized measurement methods of the vertical parachute speed (the classic method and an approach using an electronic variometer), measuring procedures, technological conditions, and analysis of influencing factors, and the quantification of their impact on measuring results, were investigated in this study. Essential information about these methods is presented in the following text.

1.1. Theoretical Background

The parachute vertical speed is a vertical element of the final parachute speed by which a parachute moves during stabilized gliding flight in the atmosphere. The speed is determined by the constructional composition of the parachute, the atmosphere conditions, and weight of the skydiver–parachute system (\(G = m \cdot g\), where \(m\) is mass and \(g\) is gravity
where:

- \( G \) — Weight of the system skydiver-parachute [N];
- \( c_x \) — Drag coefficient;
- \( \rho_H \) — Air density that depends on the height \( H \) [kg·m\(^{-3}\)].

\[
\rho_H = \frac{p_H}{R \cdot T_H}
\]

- \( p_H \) — Air pressure that depends on the height [Pa];
- \( T_H \) — Air temperature that depends on the height [K];
- \( S \) — Reference surface of the parachute [m\(^2\)].

The measurement of the parachute vertical speed can be divided into:

- Operational measurement for practical in-flight use (for example, a terminal flight with a parachute glider in the case of paragliding).
- Measurement to verify the functional parameters of the parachute before its release for in-flight operations. These can also be used in the area of investigation of parachute accidents. This article focuses on both of these areas.

1.1.1. Measurement of the Vertical Parachute Speed Using the Classic Method

The principle of this method (Figure 1) has been reposed on the measurement of the time interval between the impact of the load and the impact of a parachutist (ballast), whereby a long string of a given length (generally 35 m) holds the load and the whole formation is fixed to the parachutist (ballast). In this case, the vertical speed is defined as a moderate parachute speed during the last 35 m above the earth [27].

![Figure 1. Measurement of the parachute vertical speed using the classic method (source: The authors of this article).](image-url)
Determining the actual value of the vertical speed is a challenge due to the measuring doubts caused by the deviation between the existing height and length of the rope as a result of:

- The impact of the characteristics of the fiber that the rope is made of and current meteorological conditions (objective atmospheric temperature and moisture) on the objective string length.
- The impact of several of windings on the rope at the moment of load fall on the rope length.
- The impact of load diversion from the vertical axis due to the horizontal direction of the parachute movement.

A significant benefit of this method is that it can be used without the exercise of a parachutist jump. The method is dedicated to the parachutes only. The utilization of the method to determine the parachute glider’s vertical speed is not possible. The uncertainty of the vertical speed measurement results of a parachute using the classic method is 15–20% [27]. The Technical Metrological Regulation of TPM 0051-93—Designating the measurement of indeterminateness [28] was applied to determine the extended uncertainty of the measuring results (this is applicable for all of the measuring methods mentioned in this study Appendix A).

1.1.2. Measurement of the Vertical Parachute Speed Using a FLYTEC 4030 Variometer

This variometer (vertical speed indicator) is dedicated to the operational measurement of the vertical speed of hang-gliders and parachute gliders for paragliding. The above-mentioned facts result in some limits for its utilization for skydiving parachutes. Predominately, it has limited resistance against free-fall conditions, and a powerful effect during the parachute opening and landing. All of these are performed with a higher vertical descending speed. Generally, the FLYTEC 4030 was used for the specification of the vertical speed parachute value that had been previously achieved using the classical method, and for the specifications of the whole flight envelope of the parachute. The method is applicable for parachutes and parachute gliders [27].

The measurement of the vertical parachute speed using the FLYTEC 4030 device has significant disadvantages:

- Uncertainty resulting from turbulence of agitated air that causes the device to be blown over.
- Inlet of a dynamic air compression into a pressure sensor cannot be completely avoided during the functional flight.

2. Materials and Methods of the Measurement of the Parachute Vertical Speed Using the Photo-Optical Method

The basic principle of this measurement method lies in assembling a compilation of sequential snapshots of the parachute movement trajectory with a noted time interval between shots [27] (Figures 2 and 3).

The detailed procedure for defining the vertical parachute speed by the photo-optical method is as follows [27].

2.1. Conditions for Testing

Before a testing jump, a parachutist–parachute set must be trimmed to the weight for which the vertical parachute speed was defined. The measurement of the capacity uses the settled atmosphere and maximum wind speed up to 3 m·s⁻¹.
Figure 2. Photomontage from the measurement of the parachute vertical speed using the photo-optical method (source: The authors of this article).

Figure 3. The measurement of the parachute vertical speed by the photo-optical method (source: The authors of this article).
2.2. Demarcation of a Basic Scheme

Demarcation of a basic scheme for scanning of the reference length according to Figures 4 and 5.

![Figure 4. Basic scheme for reference length (RL) scanning—view from above (source: The authors of this article).](image)

![Figure 5. Basic scheme for reference length scanning—side view (source: The authors of this article).](image)

2.3. Requirements for the Deckle Strap

The plane of projection requires that the trajectory of the parachute movement over the earth must be delineated by a clearly visible deckle strap. The deckle strap must be marked in a contrasting color against the earth. This deckle strap serves as an orientation point for a parachutist who strives to land as close to it as possible. The jump must be in the agreed direction and from the desired height (that reaches a photo objective shot).
2.4. Requirements for the Reference Length

The reference length must be coincident with an even level because a perpendicular axis is necessary for identification of the vertical distance $s_{\text{vertphoto}}$ of the parachute reference point from which individual shots are derived.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

2.5. Taking into Account the Direction of the Wind and the Position of the Sun

When constructing a basic scheme for scanning of the reference length, we must consider:

- The wind direction according to the parachute parameters. During the measurement of the vertical speed of the parachutist–parachute set, the landing must be against the wind (or rarely with a wind) and never with a side wind. During the measurement of the vertical speed of the set load, the parachute will move in the direction of the least resistance, i.e., with the wind.
- The sun position (i.e., never scan against the sun).

2.6. Scanning the Reference Length

The objective axis must be directed to the middle of the reference length and the camera focused to the infinity mode. Then, the reference length (at least three pictures) should be scanned in a sequence mode and the same model should be used for scanning of the parachutist–parachute set. The previously used camera mode setting must not be subsequently changed.

2.7. Camera Readiness for Scanning of Parachute Movement

The camera axis is then adjusted according to the basic scheme for the measurement of the vertical parachute speed using the photo-optical method (Figure 6).

![Figure 6](source: The authors of this article)
2.8. Required Procedure for the Test Parachutist

The parachutist performs a maneuver to land as accurately as possible on the plane of the required projection of the trajectory of the parachute movement on the ground, which is demarcated by the deckle strap. The flight regime (i.e., that for which the vertical speed is measured) must be set at least 3 to 4 s before measurement so that the effects of the temporary flight regime dissipate (with the exception of a flattening out before landing). The ground personnel execute the sequence scanning by the camera (a KYOCERA FINECAM M410R was used in this research). For the purpose of investigation of a real trajectory of the M-282 parachute movement on the ground (Figure 7), the parachutist releases the auxiliary load at the beginning of the demarcated plane projection. Thus, point A of the real projection of the parachute movement trajectory on the ground can be determined. This auxiliary load must be released perpendicularly under the parachutist without a side impulse. The parachutist’s touchdown spot on the ground will be marked as point B of the real projection of the real trajectory of the parachute movement on the ground.

![Diagram](image)

**Figure 7.** Determining the projection of the actual trajectory of the parachute movement on the earth’s surface—view from above (source: The authors of this article).

2.9. Determination of the Perpendicular Distance of the Points A and B

Following the jump, we determine the perpendicular distance of the points A and B from the plane of projection of the required trajectory of the parachute movement on the ground, i.e., \( s_A \) and \( s_B \). We also determine the distance between points A and B from the middle of the reference length RL, i.e., \( s_A' \) and \( s_B' \).

2.10. Photo Montage Construction

A photo montage is then constructed using an appropriate computer environment (Figure 3), including the graphical position of the reference point and the center of the designated parts, for which the average parachute speed is calculated (Figure 8).
2.11. The Correction of the Reference Length for the Selected Parts’ Center

We calculate the dimension of the reference length, $RL_{\text{distance}}$, that results from the correction of the dimension $RL_{\text{photo}}$ by the dimension change caused by the non-zero distance of the perpendicular plane of the projection of a point $S_{n,n+1}$ (on the axis of the objective) from the $RL_{\text{photo}}$ position (Figure 9).

The experiment has revealed (valid for the KYOCERA FINECAM M410R only) that, based on a selective correlation coefficient, we can consider the dependency $RL_{\text{distance}}$ from the distance $k_{\text{distance}}$ as linear, and hence the regression axis can be used to formulate the relationship as follows:

$$RL_{\text{distance}} = a \cdot k_{\text{distance}} + b [\text{mm}]$$  \hspace{1cm} (2)

where:
We have calculated the dimension of the reference length, $RL_{hor}$, that originates from a correction of the $RL_{distance}$ dimension of the objective defect in the view caused by a horizontal shift of the object from the center of the objective by the distance $k_{hor}$ (Figure 10).

\[ a = -0.74855714285; \]
\[ b = +35.8198095238. \]

The experiment has revealed (valid for the KYOCERA FINECAM M410R only) that, based on a selective correlation coefficient, we can consider the dependency $RL_{distance}$ from the distance $k_{distance}$ as linear, and hence the regression axis can be used to formulate the relationship as follows:

\[ RL_{distance} = m \cdot RL_{distance} + a + b \]

where:
\[ a = -0.74855714285; \]
\[ b = +35.8198095238. \]

Calculation of the correction of the reference length in the horizontal direction is as follows:

\[ RL_{hor} = c \cdot RL_{hor} + c \cdot (k_{hor}) \]

Table 1 presents the values of the coefficient $c_{hor}$ achieved in experiments (camera KYOCERA FINECAM M410R), by which we calculated the dimension $RL_{hor}$ that originates from a horizontal movement $RL_{distance}$ from the center of the photomontage increased by the distance $k_{hor}$. Intervals (columns) are provided in the following tables. For the distance $k_{hor}$, Table 1 defines the quotient $k_{hor}$ as half of the horizontal dimension of the photomontage.

Table 1. Dependence of coefficient $c_{hor}$ on the interval of distance $k_{hor}$.

| $k_{hor}$ | 0–0.066 | 0.067–0.132 | 0.133–0.265 | 0.266–0.397 | 0.398–0.529 | 0.530–0.618 | 0.619–0.779 | 0.780–0.897 |
|-----------|---------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|
| $c_{hor}$ | 1.0     | 1.0       | 1.0         | 0.99911     | 0.99866     | 0.99822     | 0.99755     | 0.99666     |

We have calculated the dimension of the reference length $RL_{vert}$, which is caused by the correction of the dimension $RL_{hor}$ by the lens error in the display due to the vertical displacement of the object from the center of the lens by the distance $k_{vert}$. The correction of the reference length in the vertical direction can be calculated as follows:

\[ RL_{vert} = c \cdot RL_{vert} + c \cdot (k_{vert}) \]

Table 2 shows the experimentally achieved values of the coefficient $c_{vert}$ (camera KYOCERA FINECAM M410R), by which we can calculate the dimension $RL_{vert}$ that originates from a horizontal movement of $RL_{hor}$ from the center of the photomontage increased by the distance $k_{vert}$. Indexes (columns) for the distance $k_{vert}$ are reported in Table 2, which indicate a quotient $k_{vert}$ as half of the vertical photomontage dimension.

Table 2. Dependence of the coefficient $c_{vert}$ on the interval of distance $k_{vert}$.

| $k_{vert}$ | 0–0.086 | 0.087–0.171 | 0.172–0.343 | 0.344–0.390 | 0.391–0.429 | 0.430–0.514 | 0.515–0.686 | 0.687–0.800 |
|------------|---------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $c_{vert}$ | 1.0     | 0.99844     | 0.9971      | 0.98552     | 0.98463     | 0.98418     | 0.97171     | 0.95678     |

We have calculated the dimension of the reference length $RL_{n,n+1}$, which originates from the correction of the dimension $RL_{vert}$ after its rotation to the perpendicular axis (Figure 11).

Figure 9. Correction of reference length in the distance (source: The authors of this article).

Figure 10. Correction of the reference length in the horizontal direction (source: The authors of this article).
Calculation of the correction of the reference length in the horizontal direction is as follows:

\[ RL_{\text{hor}} = c_{\text{hor}} \cdot RL_{\text{distance}} \text{[mm]} \]

\[ c_{\text{hor}} = f(k_{\text{hor}}) \] (3)

Table 1 presents the values of the coefficient \( c_{\text{hor}} \) achieved in experiments (camera KYOCERA FINECAM M410R), by which we calculated the dimension \( RL_{\text{hor}} \) that originates from a horizontal movement \( RL_{\text{distance}} \) from the center of the photomontage increased by the distance \( k_{\text{hor}} \). Intervals (columns) are provided in the following tables. For the distance \( k_{\text{hor}} \), Table 1 defines the quotient \( k_{\text{hor}} \) as half of the horizontal dimension of the photomontage.

**Table 1.** Dependence of coefficient \( c_{\text{hor}} \) on the interval of distance \( k_{\text{hor}} \).

| \( k_{\text{hor}} \) [1] | 0–0.066 | 0.067–0.132 | 0.133–0.265 | 0.266–0.397 | 0.398–0.529 | 0.530–0.618 | 0.619–0.779 | 0.780–0.897 |
|-------------------------|---------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \( c_{\text{hor}} \) [1] | 1.0     | 1.0         | 1.0         | 0.99911     | 0.99866     | 0.99822     | 0.99755     | 0.99666     |

We have calculated the dimension of the reference length \( RL_{\text{vert}} \), which is caused by the correction of the dimension \( RL_{\text{hor}} \) by the lens error in the display due to the vertical displacement of the object from the center of the lens by the distance \( k_{\text{vert}} \). The correction of the reference length in the vertical direction can be calculated as follows:

\[ RL_{\text{vert}} = c_{\text{vert}} \cdot RL_{\text{hor}} \text{[mm]} \]

\[ c_{\text{vert}} = f(k_{\text{vert}}) \] (4)

Table 2 shows the experimentally achieved values of the coefficient \( c_{\text{vert}} \) (camera KYOCERA FINECAM M410R), by which we can calculate the dimension \( RL_{\text{vert}} \) that originates from a horizontal movement of \( RL_{\text{hor}} \) from the center of the photomontage increased by the distance \( k_{\text{vert}} \). Indexes (columns) for the distance \( k_{\text{vert}} \) are reported in Table 2, which indicate a quotient \( k_{\text{vert}} \) as half of the vertical photomontage dimension.

**Table 2.** Dependence of the coefficient \( c_{\text{vert}} \) on the interval of distance \( k_{\text{vert}} \).

| \( k_{\text{vert}} \) [1] | 0–0.086 | 0.087–0.171 | 0.172–0.343 | 0.344–0.390 | 0.391–0.429 | 0.430–0.514 | 0.515–0.686 | 0.687–0.800 |
|-------------------------|---------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \( c_{\text{vert}} \) [1] | 1.0     | 0.99844     | 0.9971      | 0.98552     | 0.98463     | 0.98418     | 0.97171     | 0.95678     |

We have calculated the dimension of the reference length \( RL_{n,n+1} \), which originates from the correction of the dimension \( RL_{\text{vert}} \) after its rotation to the perpendicular axis (Figure 11).

Angle \( \beta \) can be located from a tripod scale using an incline objective axis from the basic scheme for scanning of the reference length (Figure 5) in the basic scheme for the measurement of the vertical parachute speed using the photo-optic method (Figure 6). Angle \( \beta \) can be also determined by calculation. A correction of the reference length by its rotation to the perpendicular axis can be calculated as follows:

\[ RL_{n,n+1} = RL_{\text{vert}} \cdot \cos \beta \text{[mm]} \] (5)

A coefficient scale of a reduction of \( SC \) measures that object at a point \( S_{n,n+1} \) against the real measure, and can be calculated as follows:

\[ SC = \frac{RL_{n,n+1}}{RL} \] (6)

The perpendicular distance between the reference point \( RP_n \) and \( RP_{n+1} \) in the photomontage \( s_{\text{vertphoto}} \) can be determined by measurement in the photomontage. The distance \( s_{\text{vertphoto}} \) must be adjusted by a correction that originates from its rotation in the perpendicular axis by the angle \( \beta \) (Figure 12).
Angle $\beta$ can be located from a tripod scale using an incline objective axis from the basic scheme for scanning of the reference length (Figure 5) in the basic scheme for the measurement of the vertical parachute speed using the photo-optic method (Figure 6).

Angle $\beta$ can be also determined by calculation. A correction of the reference length by its rotation to the perpendicular axis can be calculated as follows:

$$c_0 = \cos m \cdot n_{vertRL} \beta +$$

(A5)

A coefficient scale of a reduction of $SC_{measures}$ object at a point $S_{n,n+1}$ against the real measure, and can be calculated as follows:

$$RL_{vert} = RL_{n,n+1}$$

(6)

The perpendicular distance between the reference point $RP_n$ and $RP_{n+1}$ in the photomontage $s_{vertphoto}$ can be determined by measurement in the photomontage. The distance $s_{vertphoto}$ must be adjusted by a correction that originates from its rotation in the perpendicular axis by the angle $\beta$ (Figure 12).

The real vertical distance between the reference points $RP_n$ and $RP_{n+1}$ $s_{vertreal}$ can be determined as follows:

$$s_{vertreal} = s_{vertphoto} \cdot \cos \beta \cdot \frac{1}{SC}[mm]$$

(7)

Figure 11. Correction of the reference length for a rotation in the vertical axis (source: The authors of this article).

Figure 12. Determination of the vertical distance between the reference points $RP_n$ and $RP_{n+1}$ (source: The authors of this article).
2.12. The Time Interval of a Parachute Movement

The time interval of a parachute movement within the specified portion equals the time interval between the shots and is specified for a mode of the camera’s sequence scanning. The mode of the KYOCERA FINECAM M14R camera’s sequence scanning has a time interval between shots:

\[ t = 0.3 \pm 0.01 \text{ [s]} \]  

(8)

2.13. Calculation of the Average Vertical Parachute Speed

Calculation of the average vertical parachute speed in the specified sector is performed. The average vertical parachute speed \( v_{vert} \) in the sector allocated by the reference points \( RP_n \) and \( RP_{n+1} \) is calculated as follows:

\[ v_{vert} = \frac{s_{vert}}{t} \text{ [m/s]} \]  

(9)

2.14. The Transformation of Result in the of Zero Height International Standard Atmosphere

The transformation of the calculated average vertical parachute speed in the specified sector under the conditions of zero height international standard atmosphere (ISA) is performed. It is necessary to check temperature data and air pressure in the measured zone. Then, the air density \( \rho \) is calculated in the measured sector according to the formula:

\[ \rho = \frac{p}{R \cdot T} \text{ [kg·m}^{-3} \text{]} \]  

(10)

where:
- \( p \)—The average value of air pressure in the measured sector [Pa];
- \( T \)—Average air temperature in the measured sector [K];
- \( R \) —Universal gas constant; \( R = 287 \text{ J·kg}^{-1}·\text{K}^{-1} \).

From the calculated air density \( \rho \), we can calculate the relative air density \( \rho_r \) according to the formula:

\[ \rho_r = \frac{\rho}{\rho_{ISA}} \]  

(11)

where:
- \( \rho \)—Air density in the measured sector [kg·m}^{-3} \];
- \( \rho_{ISA} = 1.2257 \text{ kg·m}^{-3} \)—Air density in the height 0 m according to ISA.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

Then, we calculated the average vertical parachute speed \( v_{vertISA} \) in the sector, which is demarcated by the reference points \( RP_n \) and \( RP_{n+1} \):

\[ v_{vertISA} = v_{vert} \sqrt{\rho_r} \text{ [m·s}^{-1} \text{]} \]  

(12)

2.15. Apparatus Used during the Experiment

The digital camera KYOCERA FINECAM M410R was used in the experiment. The basic parameters of this camera, which was borrowed from the company Slovak Aeronautical Institute, are as follows:

- Sequential shooting mode 0.3 s.
- Maximum error in adhering to the time interval during sequential shooting mode 0.01 s.
- Sequential shooting quality 1.0 Mpx.

When using another camera, it is necessary to experimentally detect optical errors for this camera according to Section 2.11 of this article. It also necessary to verify a time interval between shots of the mode of another camera’s sequence scanning mode (Section 2.12 of this article).
Length measuring instrument:
- Measuring range 50 m;
- Accuracy class II.

Tripod for mounting the camera:
- Tripod base with rotating around the vertical axis, with rotation around the longitudinal axis and with rotation around the transverse axis.
- Easy locking of the base position in all three axes.
- Easy adjustment to the horizontal plane.

Parachute M-282 (Figures 13 and 14). Parachute owner: Peter Kalavsky—author of the article and test skydiver.

Figure 13. Landing with parachute M-282 near reference length (source: The authors of this article).

Figure 14. Test jump with parachute M-282 with verification of sequential shooting mode of camera (source: The authors of this article).
3. Results

A total of twelve jumps were performed to verify the photo-optical measurement of the vertical speed of the M-282 parachute. The first six jumps were performed in order to develop a suitable measurement technology. The last six jumps were performed according to this technology and the results of the measurement of these jumps are published as experimental results (test jumps) for the main parachute M-282 in this section. The number of six jumps in the preliminary research was selected in accordance with the SAE AS 8015B standard, as a necessary condition for the certification of parachute technology before its entry into air traffic [10]. The measured data, all input data, partial calculation results, and total results are given for test jump 1 (Table 3). By thoroughly measuring the speed of the M-282 vertical parachute using the photo-optical method, the measurement of the vertical parachute speed using the FLYTEC 4030 device was applied during test jumps (Table 4—results for test jump number 1). Only overall results are shown for test jumps 2 to 6, including test jump 1 (Table 5). The above facts made it possible to compare the measurement results.

3.1. The Photo-Optical Method—Test Jump Number 1

The measured data, all input data, and the procedure for determining the vertical speed of the parachute (for test jump number 1) were in compliance with the procedure described in Sections 2.1–2.14:

\[
\begin{align*}
RL &= 2000 \text{ mm} \\
RL_{\text{photo}} &= 35.604 \text{ mm} \\
\gamma_{\text{vert}} &= 19.0^\circ \\
\beta &= 16.6^\circ \\
S_A &= 1 \text{ m} \\
S_B &= 8.7 \text{ m} \\
k_{\text{real}} &= 12.73 \text{ m} \\

v_{\text{vertISA}} &= 4.718 \text{ m} \cdot \text{s}^{-1}
\end{align*}
\]

Table 3. \(v_{\text{vertISA}}\) using the photo-optical method—test jump number 1.

| \(S_{n,n+1}\) | \(K_{\text{dist}}\) [m] | \(RL_{\text{distance}}\) [mm] | \(k_{\text{hor}}\) [\(\lambda\)] | \(c_{\text{hor}}\) [\(\lambda\)] | \(RL_{\text{hor}}\) [mm] | \(k_{\text{vert}}\) [\(\lambda\)] | \(c_{\text{vert}}\) [\(\lambda\)] | \(RL_{\text{vert}}\) [mm] |
|---|---|---|---|---|---|---|---|---|
| 1,2 | 0.225 | 35.988 | 0.571 | 0.99822 | 35.924 | 0.112 | 0.99844 | 35.868 |
| 2,3 | 0.786 | 36.408 | 0.477 | 0.99866 | 36.359 | 0.195 | 0.9971 | 36.254 |
| 3,4 | 1.685 | 37.081 | 0.379 | 0.99911 | 37.048 | 0.279 | 0.9971 | 36.941 |
| 4,5 | 2.472 | 37.67 | 0.275 | 0.99911 | 37.637 | 0.363 | 0.98552 | 37.092 |
| 5,6 | 3.483 | 38.427 | 0.165 | 1 | 38.427 | 0.446 | 0.98418 | 37.819 |

| \(S_{n,n+1}\) | \(RL_{n,n+1}\) [mm] | \(s_{\text{vert\text{photo}}}\) [mm] | \(s_{\text{vert\text{real}}}\) [mm] | \(v_{\text{vert\text{ ISA}}}\) [m \cdot \text{s}^{-1}] |
|---|---|---|---|---|
| 1,2 | 34.368 | 24.476 | 0.017184 | 1.42434 | 4.748 |
| 2,3 | 34.738 | 25.473 | 0.017369 | 1.46658 | 4.889 |
| 3,4 | 35.396 | 25.376 | 0.017698 | 1.43384 | 4.779 |
| 4,5 | 35.541 | 25.282 | 0.01777 | 1.42271 | 4.742 |
| 5,6 | 36.238 | 25.638 | 0.018119 | 1.40009 | 4.667 |

| \(v_{\text{vert\text{ ISA}}}\) [m \cdot \text{s}^{-1}] | \(T\) [K] | \(p\) [Pa] | \(\rho_r\) [\(\lambda\)] |
|---|---|---|---|
| 4.748 | 280.15 | 96600 | 0.9802 |
| 4.889 | 4.742 | 4.695 | 0.9802 |
| 4.779 | 4.621 | 0.097 | 0.9802 |
| 4.742 | 4.621 | 0.097 | 0.9802 |
3.2. Device FLYTEC 4030—Test Jump Number 1

\[ v_{\text{vertISA}} = 4.762 \text{ m} \cdot \text{s}^{-1} \]

Table 4. \( v_{\text{vertISA}} \) using the device FLYTEC 4030—test jump number 1.

| \( v_{\text{vert}} \) [m·s\(^{-1}\)] | \( T \) [K] | \( p \) [Pa] | \( \rho_r \) | \( v_{\text{vertISA}} \) [m·s\(^{-1}\)] | \( v_{\text{vertISA}} - v_{\text{vertISA}} \) [m·s\(^{-1}\)] |
|--------------------------------------|--------|-------|--------|----------------|----------------|
| 4.5                                 |        |       |        | 4.455          | -0.307         |
| 4.9                                 |        |       |        | 4.851          | 0.089          |
| 5.1                                 |        |       |        | 5.049          | 0.287          |
| 5.2                                 |        |       |        | 5.148          | 0.386          |
| 5.1                                 | 280.15 | 96600 | 0.9802 | 5.049          | 0.287          |
| 5.0                                 |        |       |        | 4.950          | 0.188          |
| 4.8                                 |        |       |        | 4.752          | -0.010         |
| 4.6                                 |        |       |        | 4.554          | -0.208         |
| 4.5                                 |        |       |        | 4.455          | -0.307         |
| 4.4                                 |        |       |        | 4.356          | -0.406         |

3.3. Overall Results of the Test Jumps Number 1 to 6

Table 5. Overall results of the test jumps number 1 to 6.

| Test Jump Number | The Photo-Optical Method \( \tau_{\text{vertMSA}} \) [m·s\(^{-1}\)] | FLYTEC 4030 \( \tau_{\text{vertMSA}} \) [m·s\(^{-1}\)] |
|------------------|--------------------------------|----------------|
| 1                | 4.718                         | 4.762          |
| 2                | 4.616                         | 4.526          |
| 3                | 4.640                         | 4.705          |
| 4                | 4.723                         | 4.747          |
| 5                | 4.598                         | 4.622          |
| 6                | 4.636                         | 4.611          |
| average:         | 4.655                         | 4.662          |

4. Discussion

The extended uncertainty of the measured M-282 vertical parachute speed results defined by the photo-optical method of ±6.9% was affected by the coefficient \( k_{UU} \), which allows repeated measurements. For 20 and more repeated measurements, this value equals 1. Based on the extensive measurement results, we can assume that the value of the extended uncertainty of the measurement results of the vertical parachute speed is fixed using the photo-optical method would approximate 5%.

The vertical parachute speed of the M-282 parachute defined by the photo-optical method of \( \tau_{\text{vertISA}} = 4.655 \text{ m} \cdot \text{s}^{-1} \) is similar to that of the vertical parachute speed of M-282 defined by the FLYTEC 4030 of \( \tau_{\text{vertISA}} = 4.662 \text{ m} \cdot \text{s}^{-1} \). Thus, the process of determining the vertical parachute speed by the photo-optical method for the M-282 parachute is correct. This method has been found to be convenient in practice and for the measurement of the parachute mechanism flight capacity in compliance with personnel parachute testing regulations [10,11,14].

Research confirmed the working hypothesis; that is, the test parachute jumps demonstrated that the photo-optical method is a suitable method for measuring the vertical speed of the M-282 parachute.

This research also showed that the photo-optical method of measuring the vertical speed of a parachute is viable, and this method should be further investigated in future
research. Subsequent efforts will focus mainly on obtaining a larger set of measured data and on verifying the method for other types of parachutes. The secondary aim of publishing the results of the research on the M-282 parachute test was also to provide the acquired knowledge for public discussion, and to provide a basis for further research and expert comments.

The classic method [15,27] and the barograph [12] or FLYTEC 4030 [27] methods require the placement of the measuring device on the parachute during flight. On the contrary, the photo-optical method does not require it. However, this method needs measuring equipment on the ground. At present, the photo-optical method of the vertical parachute speed measurement, including its advantages and disadvantages, is a convenient approach for parachute technology testing processes. In future research, our aim will be to perform more than 60 experimental jumps using different types of parachutes, digital cameras, the photo-optical method, and thus specify the extended uncertainty based on many jumps.

5. Conclusions

The research was focused on answering the question of whether it is appropriate to use the photo-optical method to measure selected data on the movement of the M-282 parachute. The performed parachute jumps confirmed that the photo-optical measurement method is a suitable method for measuring the vertical speed of the M-282 parachute with the potential for further work to verify the methodology for general use, other types of parachutes, and digital cameras for motion detection. The photo-optical method (in a modified form) is also suitable for to analyze the trajectory of a parachutist’s movement in the context of a parachutist accident investigation [29].

A major benefit of the photo-optical method application is that measurements can be taken without installing measuring devices on the flying object. An important advantage for practical utilization is that, within the resources presented above, methods for the measurement of a parachute’s vertical speed were processed and developed. These methods can be applied for verification of the parachute capacity before its integration in flight operations. The comparison of results indicates that the process of identifying the vertical speed of the parachute using the photo-optical method was correct.

Our developed and verified measurement procedures of the photo-optical method, technological conditions for the measurement of the parachute vertical speed, analysis of influencing factors, and quantification of these factors’ influence on the measured results complete the normative documentation for personnel parachute technical testing [10,11,14]. The authors also recommend this method to other researchers, athletes, or sports coaches. The novelty of our work lies in the application of the photo-optical method for the purpose of measuring the vertical speed of a parachute. In general, this method is applicable to any flying object and also to horizontal speed or total speed.

Based on the research results, the photo-optical measurement method can be validated in the future for other types of digital sensors (cameras) to detect the movement of a parachute or to investigate the influence of other devices affecting the results of vertical speed measurements.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Analysis of Influencing Parameters and Quantification of Their Influence on the Uncertainty of Measurement Results

The uncertainty of the measurement results of the vertical parachute speed using the photo-optical method was performed in compliance with the TPM 0051-93 [29] regulation. The measurement of the vertical parachute speed was performed in a practical atmosphere given for the main parachute M-282 flight mode, i.e., under a stable and rectilinear gliding flight by released steering lines. Three testing jumps were performed. Scanning of the parachute movement lasted 3 s, thus the measurement of the vertical parachute speed within one jump was considered to be repeatable. During these 3 s, the vertical speed was measured five times during a single test jump. Because only the vertical distance between the reference points was measured repetitively and all other parameters were measured once, the analysis was executed for the direct measurement of one parameter. Similarly, there was no correlation between the influencing parameters analyzed. The standard uncertainty, type A $u_A$, was calculated additionally for each jump. A total of 20 measurements were performed during the three test jumps to determine the expanded uncertainty of the $U$ measurement result.

Appendix A.1.1. Standard Uncertainty Type A for the 1st Test Jump

In the uncertainty calculation $u_A$, the findings from Table 3 were applied, in which measurement results were processed in compliance with the TPM 0051-93 [29] regulation (so-called processed to lines) in Table A1:

\[
  u_A = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (v_{vertISA_{i}} - \bar{v}_{vertISA})^2} \quad \text{(A1)}
\]

where:

\[
  \bar{v}_{vertISA} = \frac{\sum_{i=1}^{n} v_{vertISA_{i}}}{n} = 4.718 \text{ m} \cdot \text{s}^{-1} \quad \text{(A2)}
\]

$i$—ith measurement.

Appendix A.1.2. Standard Uncertainty Type A for the 2nd Test Jump

\[
  u_A = 0.065 \text{ m} \cdot \text{s}^{-1}
\]

\[
  \bar{v}_{vertISA} = 4.616 \text{ m} \cdot \text{s}^{-1}
\]

Appendix A.1.3. Standard Uncertainty Type A for the 3rd Test Jump

\[
  u_A = 0.05 \text{ m} \cdot \text{s}^{-1}
\]
$\bar{v}_{\text{vert}ISA} = 4.64 \text{ m} \cdot \text{s}^{-1}$

Table A1. Results of the test jump number 1.

| $v_{\text{vert}}$ [m \cdot s$^{-1}$] | $T$ [K] | $p$ [Pa] | $\rho_r$ [] | $v_{\text{vert}ISA}$ [m \cdot s$^{-1}$] | [m \cdot s$^{-1}$] |
|---------------------------------|--------|--------|--------|---------------------------------|----------------|
| 4.748                           |        |        |        | 4.701                           | –0.017         |
| 4.889                           |        |        |        | 4.840                           | 0.122          |
| 4.779                           | 280.15 | 96,600 | 0.9802 | 4.732                           | 0.014          |
| 4.742                           |        |        |        | 4.695                           | –0.023         |
| 4.667                           |        |        |        | 4.621                           | –0.097         |

Appendix A.1.4. Standard Uncertainty Type B

The consequential standard uncertainty type B $u_B$ was determined by following the individual standard uncertainty type B $u_{Bj}$ in Table A2:

- $u_{B1}$—The origin of uncertainty $Z_1$ is an error in defining a time interval between the shots;
- $u_{B2}$—The origin of uncertainty $Z_2$ is an error defining a real scale of the reference length RL, which includes:
  - An error in the linear measurement;
  - Deduction error;
  - Temperature influence on the measuring tool and RL.
- $u_{B3}$—The uncertainty source $Z_3$ is the error in defining the reference length of $RL_{n,n+1}$ for a point $S_{n,n+1}$ and includes:
  - The error in a locating of a position of reference points $RP_n$ and point $S_{n,n+1}$;
  - The error in defining $RL_{\text{distance}}$;
  - The error in defining $RL_{\text{hor}}$ and $RL_{\text{vert}}$;
  - The error in defining the angle $\beta$;
  - The pixel error and deduction error.
- $u_{B4}$—The uncertainty source of $Z_4$ is the error in defining $s_{\text{vertphoto}}$, which includes a pixel error and deduction error;
- $u_{B5}$—Uncertainty of atmospheric pressure (uncertainty in the air pressure measuring device, deduction, temperature impact on the device);
- $u_{B6}$—Uncertainty of the air temperature measurement (uncertainty in the air temperature measuring device, deduction, temperature influence on the device);
- $u_{B7}$—Uncertainty caused by the provision that the air density calculated from the measured air temperature and air pressure above the ground is not changing in the sector of the measurement of the vertical parachute speed (i.e., calculated air density from the ground to 70 m is not changing).

Details regarding the calculation of $u_{B1}$ and the procedure, including comments, are provided in the section below. Calculation results are provided in Table 4 for the uncertainty ranging from $u_{B2}$ to $u_{B7}$.

The calculation of the uncertainty $u_{B1}$ at a specified time interval between shots [29] was carried out as follows: The time interval of the sequence scanning for the KYOCERA FINECAM M410R was $t = 0.3 \pm 0.01$ s. This change of the time interval can cause a change of the interval speed ranging from 3 to 7 m \cdot s$^{-1}$ by a maximum value of $\pm 0.13$ m \cdot s$^{-1}$.

Hence, the uncertainty source $Z_{1_{\text{max}}}$ equals $\pm 0.13$ m \cdot s$^{-1}$, and exceeding this value is not realistic.
The optimal approximation for the process of derivation of these deviations is an equal allocation with a coefficient \( \chi = \sqrt{3} \), which is associated with a predetermined \( Z_{\text{max}} \), which is unlikely to be exceeded.

\[
u_{B1} = \frac{Z_{\text{max}}}{\chi} = \frac{0.13}{\sqrt{3}} = 0.075 \text{ m·s}^{-1}
\]

The TPM 0051-93 standard provides the following approximate distributions of the probability of deviations of the source of uncertainty \( Z_{\text{max}} \), which corresponds to the respective values of the coefficient \( \chi \) [29]:

- Normal Gaussian distribution with \( \chi = 2 \) (selected for sources of uncertainty \( Z_3 \) and \( Z_7 \));
- Triangular Simpson’s distribution with \( \chi = \sqrt{6} \);
- Trapezoidal distribution with \( \chi = 2.32 \);
- Even rectangular distribution with \( \chi = \sqrt{3} \) (selected for sources of uncertainty \( Z_1, Z_2, Z_4, Z_5, \) and \( Z_6 \));
- Bimodal triangular distribution with \( \chi = \sqrt{2} \);
- Bimodal Dirac distribution with \( \chi = 1 \).

An estimated value of uncertainty \( u_{B1} \) was transformed into a standard uncertainty of the measuring result \( u_B \) and its component \( u_{x1} \) was derived (i.e., an allowance to the uncertainty), which can be calculated in the form:

\[
u_{x1} = A_{x1} \cdot u_{B1} = 1 \cdot 0.075 = 0.075 \text{ m·s}^{-1}
\]

where the conversion coefficient of sensibility is \( A_{x1} = 1 \).

If the estimation \( Z_{\text{max}} \) has the same physical units as the vertical velocity of the parachute, then the gear sensitivity coefficient \( A_{Xj} \) has the value 1 (dimensionless number). If the estimation \( Z_{\text{max}} \) has different physical units than the vertical velocity of the parachute (for example, air pressure \( p \)), then the gear sensitivity coefficient \( A_{Xj} \) is calculated as the ratio \( \Delta v/\Delta p \).

### Table A2. Balance of the standard uncertainty type B of the measurement of the vertical parachute speed.

| Source of Uncertainty \( Z_j \) | Estimation \( Z_{\text{max}} \) \( \text{m·s}^{-1} \) | Selected Disposal | \( \chi \) | \( u_{Bj} \) Uncertainty \( \text{m·s}^{-1} \) | Conversion Coefficient of Sensibility \( A_{Xj} \) | Share to the Resulting Uncertainty Type B \( u_{ej} \) \( \text{m·s}^{-1} \) |
|-------------------------------|-----------------------------|----------------|----------|-----------------------------|-----------------------------|-----------------------------|
| \( Z_1 \) | \( \pm 0.13 \) | universal | \( \sqrt{3} \) | 0.075 | 1 | 0.075 |
| \( Z_2 \) | \( \pm 0.04 \) | universal | \( \sqrt{3} \) | 0.023 | 1 | 0.023 |
| \( Z_3 \) | \( \pm 0.112 \) | standard | 2 | 0.056 | 1 | 0.056 |
| \( Z_4 \) | \( \pm 0.19 \) | universal | \( \sqrt{3} \) | 0.11 | 1 | 0.11 |
| \( Z_5 \) | \( \pm 100 \) | universal | \( \sqrt{3} \) | 57.74 Pa | \( 3 \times 10^{-5} \) | 0.0017 |
| \( Z_6 \) | \( \pm 1 \) K | universal | \( \sqrt{3} \) | 0.58 K | \( 0.01 \) m·s\(^{-1}\)·K\(^{-1}\) | 0.0058 |
| \( Z_7 \) | \( \pm 0.0425 \) kg·m\(^{-3}\) | standard | 2 | 0.02125 kg·m\(^{-3}\) | 1.53 m·s\(^{-1}\) (kg·m\(^{-3}\))\(^{-1}\) | 0.033 |

### Appendix A.1.5. The Final Standard Uncertainty Type B

The final standard uncertainty type B \( u_B \) was defined by a transformation and integration of the estimated uncertainty \( u_{ej} \) by applying Gauss’s Law relating to the distribution of the uncertainty in compliance with TPM 0051-93 [29] (in this case, with no evaluation of correlations).

\[
u_B = \sqrt{\sum_{j=1}^{7} u_{ej}^2} = 0.147 \text{ m·s}^{-1}
\]
Appendix A.1.6. The Combined Standard Uncertainty

The combined standard uncertainty of the measuring results $u_C$ of the vertical parachute speed defined using the photo-optical method was defined by merging the standard uncertainty types A and B by application of Gauss’s Law for the distribution of the uncertainty in compliance with TOM 0051-93 [29]. The combined standard uncertainty of the result was calculated for each testing jump.

$$
\sqrt{u^2_A + u^2_B} = \sqrt{0.036^2 + 0.147^2} = 0.15 \text{ m·s}^{-1}
$$

$u_{C2} = 0.16 \text{ m·s}^{-1}$ $u_{C3} = 0.16 \text{ m·s}^{-1}$

Appendix A.1.7. Extended Uncertainty

The extended uncertainty of a measured result $U$ of the vertical parachute speed defined by the photo-optical method was specified in compliance with TPM 0051-93 [29], where the coefficient $k_U$ provides a number of repeated measurements for $n = 5$ and $k_U = 1.4$:

$$
U_1 = 2 \cdot k_U \cdot \sqrt{u^2_A + u^2_B} = \sqrt{1.4^2 \cdot 0.036^2 + 0.147^2} = 0.31 \text{ m·s}^{-1}
$$

$U_2 = 0.33 \text{ m·s}^{-1}$ $U_3 = 0.32 \text{ m·s}^{-1}$

Thus, the specified extended uncertainty of the measured results of the vertical parachute speed assigned using the photo-optical method has a confidence probability of 95%, assuming a standard Gaussian distribution.

Appendix A.1.8. The Results of the Measurement of the Vertical Parachute Speed M-282 Using the Photo-Optical Method

The final vertical parachute speed was defined as the average value of the results achieved by three measurements:

1st test jump $\overline{v}_{vertISA} = 4.718 \text{ m·s}^{-1} \pm 0.31 \text{ m·s}^{-1}$ ($\pm 6.6\%$);
2nd test jump $\overline{v}_{vertISA} = 4.616 \text{ m·s}^{-1} \pm 0.33 \text{ m·s}^{-1}$ ($\pm 7.2\%$);
3rd test jump $\overline{v}_{vertISA} = 4.640 \text{ m·s}^{-1} \pm 0.32 \text{ m·s}^{-1}$ ($\pm 6.9\%$).

Therefore, the highest extended uncertainty was thus assigned.

The final vertical speed of parachute M-282, including the total weight of 95 kg of the paratrooper-parachute set, defined by the photo-optical method was:

$$
\overline{v}_{vertISA} = 4.658 \text{ m·s}^{-1} \pm 0.32 \text{ m·s}^{-1}$ ($\pm 6.9\%$)

where the extended uncertainty of the measuring result was defined in compliance with TPM 0051-93 [29] and has an assigned confidence probability of $P = 95\%$.

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