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Time measurement and uncertainty in Galileo's inclined plane: From water clocks to electronic timing

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ABSTRACT
A reconstruction of Galileo Galilei's experimental apparatus used to investigate the dynamics of motion along an inclined plane is presented. The study not only replicates the measurements of distance and motion described in Galileo's manuscripts, but also emphasizes the central role of time measurement in the formulation of the laws governing uniformly accelerated motion. The experiment is first reproduced using historically plausible instruments, including a reconstructed water clock, in order to assess the feasibility and precision of time measurements available in the seventeenth century. In addition, a comparative analysis is performed using modern measurement techniques: an electronic timing system based on LED–phototransistor pairs has been developed to acquire transit times with millisecond resolution. The comparison between historical and modern methods allows a quantitative evaluation of measurement uncertainty, and highlights the metrological limitations and capabilities of early experimental practices, while offering a contemporary verification of Galileo's law of motion.

Section: RESEARCH PAPER

Keywords: cultural heritage; ancient instrument; physics education; optical system; time measurement

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1. INTRODUCTION

In his experiments, Galileo Galilei aimed to demonstrate that all bodies in free fall experience the same acceleration regardless of their mass, thereby introducing a deep change in the understanding of motion. Among his most significant experimental contributions, there is the study of the inclined plane, conceived to investigate uniformly accelerated motion through a controllable experimental procedure. Since free fall involves accelerations that are too large to be directly measured with the instruments available at the time, Galileo adopted a slightly inclined surface along which a sphere could roll, thus reducing the effective gravitational acceleration and making the relevant kinematic quantities measurable. The determination of time intervals, carried out using rudimentary yet repeatable measurement techniques, such as water clocks and approximations based on pendulum motion, made it possible to reveal the uniform character of gravitational acceleration, thereby laying the foundations of classical mechanics.

Despite the intrinsic limitations of 17th-century time-measuring instruments, Galileo's experimental approach introduced fundamental principles of controlled experimental conditions, repeatability of measurements, and quantitative comparison of results, anticipating key concepts of modern metrology. These innovations significantly contributed to the subsequent development of instruments and methodologies for time measurement with ever-increasing accuracy and resolution.

In the present work, building upon Galileo's legacy, we propose a reconstruction of the inclined-plane experimental apparatus with the aim of critically analysing the measurement of travel times and the associated kinematic quantities. Measurements of space and time are performed using both historically reconstructed instruments and contemporary electronic devices, allowing a comparison in terms of accuracy, precision, and measurement uncertainty. By integrating historical methodology with modern experimental practices, and by conducting a geometric and kinematic analysis of the motion, this work aims to provide a quantitative assessment of the validity of Galileo's conclusions from a metrological perspective.

The study of the inclined plane in university courses promotes the development of skills in accurate measurement, uncertainty management, and a systematic approach to experimentation. This training provides future scientists and engineers with a solid

Figure 1. Galileo Galilei (1564–1642) demonstrating the laws of motion using the inclined plane, in the presence of Giovanni de' Medici (1543–1621). Fresco by Giuseppe Bezzuoli (1784–1855), Tribuna di Galileo, Florence, Italy.

foundation for addressing complex problems in both experimental and theoretical physics [1].

In order to highlight the relevance of historical experimentation in the light of current metrological criteria, the article is organized as follows. Section 2 presents the historical and technical reconstruction of the experimental apparatus, based on the analysis of Galileo Galilei's manuscripts. Section 3 describes the adopted measurement methodology, with particular attention to the determination of time intervals and the evaluation of measurement uncertainties, including a comparison between historical and modern instruments. Section 4 analyses the experimental results and compares them with Galileo's law of uniformly accelerated motion. Section 5 provides the uncertainty analysis associated with the time and distance measurements. Finally, the last section presents the conclusions.

2. HISTORICAL AND TECHNICAL RECONSTRUCTION OF THE EXPERIMENTAL APPARATUS

2.1. Analysis of historical sources

The experiment, as illustrated in Figure 1, in the fresco by Giuseppe Bezzuoli, located in the Tribuna of Galileo in Florence, Italy, is described in detail in the manuscripts of Galileo Galilei. In order to replicate the inclined-plane experiment with the highest possible degree of historical fidelity, the passages in which Galileo presents the experimental procedure and the constructional features of the apparatus were carefully analyzed. The excerpt considered in this study is reported below [2]–[4].

"A piece of wooden moulding or scantling, about 12 cubits long, half a cubit wide, and three finger-breadths thick, was taken; on its edge was cut a channel a little more than one finger in breadth; having made this groove very straight, smooth, and polished, and having lined it with parchment, also as smooth and polished as possible, we rolled along it a hard, smooth, and very round bronze ball. Having placed this board in a sloping position, by lifting one end some one or two cubits above the other, we rolled the ball, as I was just saying, along the channel, noting, in a manner presently to be described the time required to make the descent. We repeated this experiment more than once in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse-beat. Having performed this operation and having assured ourselves of its reliability, we now rolled the ball only one-quarter the length of the channel; and having measured the time of its descent, we found it precisely one-half' of the former. Next, we tried other distances, comparing the time for the whole length with that for the half, or with that for two-thirds, or three-fourths, or indeed for any fraction; in such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times, and this was true

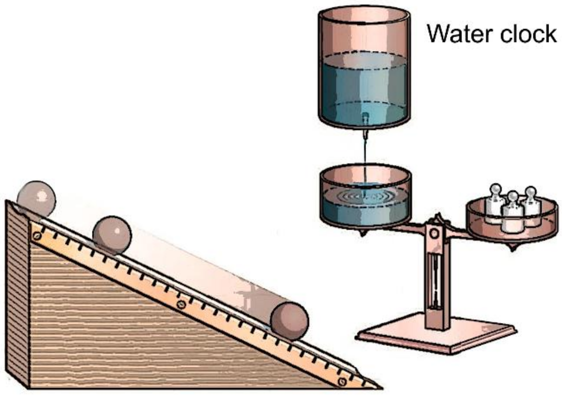

Figure 2. Schematic representation of Galileo Galilei's inclined-plane experiment with a water clock for time measurement.

for all inclinations of the plane, i.e., of the channel; along which we rolled the ball. We also observed that the times of descent, for various inclinations of the plane, bore to one another precisely that ratio which, as we shall see later, the Author had predicted and demonstrated for them. For the measurement of time, we employed a large vessel of water placed in an elevated position; to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent, whether for the whole length of the channel or for a part of its length; the water thus collected was weighed, after each descent, on a very accurate balance; the differences and ratios of these weights gave us the differences and ratios of the times, and this with such accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results".

Figure 2 is a schematic illustration of Galileo Galilei's inclined-plane experiment. A sphere rolls along a slightly inclined wooden plane, while the elapsed time is measured using a water clock by collecting and weighing the discharged water. The figure highlights the spatial reference marks along the plane and the synchronization between the release of the sphere and the start of the time measurement.

The account provided by Galileo allows for the reconstruction and replication of the experiment without significant operational ambiguities. It is also noteworthy that the scientist emphasizes the importance of repeating experimental trials, thereby demonstrating an early awareness of the repeatability of measurements, a concept that is central both to modern metrology and to the study, preservation, and valorisation of scientific cultural heritage.

The motion of a body along an inclined plane involves fundamental aspects, such as measurement techniques, measurement accuracy and precision, the communication of experimental results, and the inductive reasoning underlying the experiment. These elements make the inclined plane a crucial topic for the teaching of physical measurements. Furthermore, efforts aimed at reconstructing Galileo's experiments—particularly those involving the inclined plane—seek to deepen the understanding of historiographical and epistemological issues related to the emergence of the modern scientific method [5]–[7].

Nevertheless, among historians of science, there remain doubts as to whether the experiment was actually carried out as described by Galileo [8]–[10]. In particular, his ability to measure time intervals with a precision on the order of one tenth of a second has been questioned. It is generally argued that the time-measurement methods employed by Galileo, such as counting heartbeats or using a water clock, were not sufficiently accurate or precise at this temporal scale. Moreover, in the absence of a statistical analysis of the data, the assessment of measurement accuracy would be further limited when evaluated according to modern metrological criteria.

Galileo, however, coming from a family of musicians, also made use of small bells placed along the inclined plane, exploiting rhythmic patterns for temporal control. By appropriately adjusting the positions of the bells, he was able to identify points along the plane at which sounds occurred at short and equal time intervals, effectively introducing a form of relative time measurement based on auditory perception [11]. This method can be interpreted as an early attempt to measure frequency, in which the periodicity of motion is inferred from a sequence of equal time intervals perceived acoustically.

In this article, we aim to reconstruct Galileo's experiment on the motion of a heavy body along an inclined plane, based on the descriptions provided by Galileo himself [2]–[4]. In particular, the focus is on assessing the feasibility of measuring time with a precision on the order of one tenth of a second, using a water clock similar to that considered historically plausible, and on comparing these measurements with those obtained using modern time-measurement technologies.

2.2. Reconstruction of Galileo's inclined plane

The reconstruction of the inclined plane was carried out based on the descriptions provided by Galileo Galilei, and was guided by criteria of historical fidelity, experimental functionality, and reproducibility of measurements.

The inclined plane consists of a wooden board, consistent with 17th-century technologies, smoothed and treated with petroleum jelly to reduce frictional effects. A straight groove was carved along the surface to guide the rolling sphere, ensuring as uniform rolling conditions as possible.

The inclination angle was made adjustable in order to test different motion conditions and select configurations in which friction was minimal. The moving body is a metal sphere, chosen to promote stable and reproducible rolling while minimizing dissipative effects.

In Galileo's original experiment, markers were placed along the plane at distances corresponding to the sequence of odd numbers: 1, 3, 5, 7, 9, forming an arithmetic progression in which each successive spatial interval increases by two units. In this way, he could verify that progressively larger spatial intervals were traversed in equal time intervals, demonstrating uniformly accelerated motion and providing the basis for formalizing the law of free fall, according to which the distance travelled under constant acceleration, is proportional to the square of the elapsed time.

In our setup, markers were placed along the inclined plane at known distances: 11 cm, 33 cm, 55 cm, and 77 cm, for a total length of 176 cm. The overall length of the plane was chosen to ensure sufficient spatial resolution of the measurements, consistent with the constraints of the laboratory.

The reconstructed inclined plane is shown in Figure 3.

Although in Galileo's time the use of sound rhythms to measure equal time intervals was neither an objective nor standardized method, he arranged small 'bells' along the plane, exploiting his musical expertise to identify equal time intervals based on the regularity of their sound. In our experiment, analogous bells were positioned along the plane, and timing was performed by recording the sounds.

Special attention was paid to the alignment of the plane and the stability of the apparatus, in order to reduce systematic uncertainties associated with the geometry of the experiment.

Overall, the reconstruction of the inclined plane aims to faithfully reproduce the experimental conditions described by Galileo, while preserving the possibility of a quantitative evaluation of the results according to modern metrological criteria. This approach combines historical fidelity with experimental analysis, providing an effective tool for studying the laws of motion and valorising historical scientific heritage.

2.3. Galileo's water clock time measurement

In the historical context, the use of a water clock represented one of the few available solutions for measuring short time intervals. The proposed reconstruction therefore allows not only an evaluation of the metrological feasibility of the time measurements attributed to Galileo, but also the valorisation of the water clock as a scientific instrument of historical and cultural interest, establishing a dialogue between 17th-century experimental practices and contemporary measurement criteria.

The reconstructed water clock consists of a glass vessel equipped with a regulating valve located at the bottom. The vessel was initially filled completely and connected to a continuous water supply, in order to ensure a constant inflow. Subsequently, the lower valve was opened until a continuous and approximately constant water stream was obtained. This configuration allows the water level inside the vessel to be maintained at an approximately constant value, a necessary condition to ensure the stability of the outflow rate.

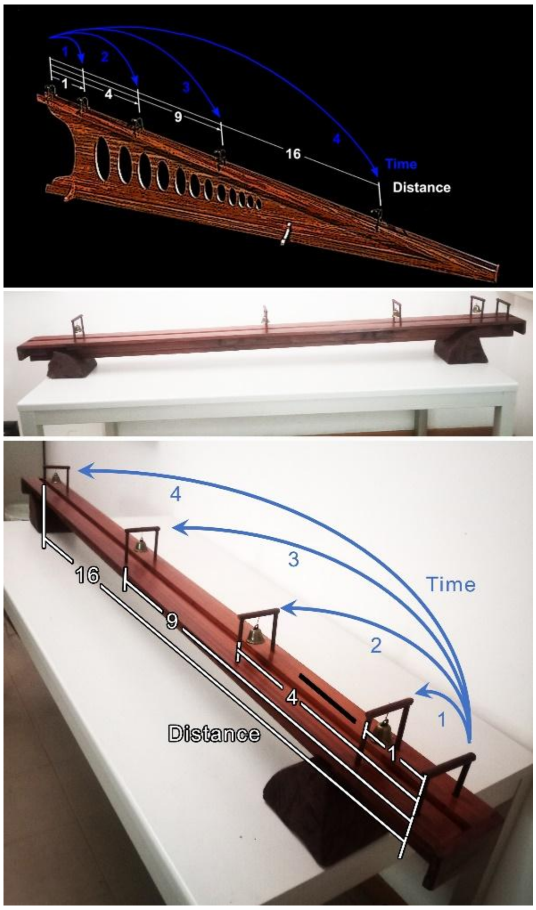

Figure 3. Reconstruction of Galileo's inclined plane.

Figure 4. a) Hydraulic apparatus for water-clock time measurements. b) Balance used to assess the accuracy of mass measurements achievable in Galileo's time.

The volumetric flow rate Q is related to the height of the water column above the outlet orifice according to:

$$Q = C\,A\,\sqrt{2\,g\,h}\,, \tag{1}$$

where C is the discharge coefficient, A is the area of the outlet orifice, g is the acceleration due to gravity, and h is the height of the water column above the orifice. Maintaining a constant value of h minimizes temporal variations in the flow rate, a condition essential for ensuring that the collected water mass is proportional to the considered time interval.

Figure 4 shows the experimental apparatus. After a short transient following the opening of the valve, the system reaches a steady-state condition in which the inflow rate balances the outflow rate, stabilizing the water level in the vessel.

Under these conditions, time is measured indirectly by determining the mass of the collected water, assuming a constant water density under laboratory ambient conditions.

2.4. Electronic timing and data acquisition

Subsequently, in order to compare time measurements obtained using manual methods with those based on modern technologies, an electronic apparatus was developed consisting of LED–phototransistor pairs positioned at each reference mark along the inclined plane [12]. Infrared light-emitting diodes (IR LEDs, wavelength ≈ 940 nm) were used as light sources, coupled with silicon NPN phototransistors (SPD8406 [13]), selected for their fast temporal response and high sensitivity in the infrared spectral range. The passage of the sphere interrupts the light beam, generating a signal used for the automatic determination of the transit times.

The sensors are managed by an Arduino platform [14], programmed to acquire the transit times with a resolution on the order of milliseconds.

Figure 5 shows the schematic diagram of the electronic timing circuit.

Prior to the experimental measurements, the system underwent a calibration procedure and repeatability verification, aimed at assessing the accuracy of the temporal triggering and estimating the uncertainty associated with the data acquisition system. The overall uncertainty in the electronic time measurement was found to be dominated by the resolution of the microcontroller's internal clock and by the temporal response of the phototransistors.

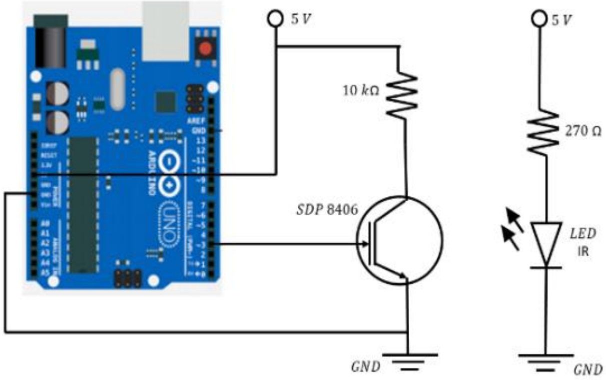

Figure 5. Schematic diagram of the electronic timing circuit used for the optical detection of the sphere's transit along the inclined plane.

The system enables the automatic recording of time intervals corresponding to the different segments of the inclined plane, allowing both the experimental verification of the law of uniformly accelerated motion and a direct comparison between time measurements obtained using historically plausible instruments and modern measurement devices.

3. METHODS

Time measurements were performed using three distinct methods: a reconstructed water clock, a manual stopwatch, and an electronic timing system based on optical sensors.

This approach, characterized by different levels of instrumental complexity and temporal resolution, enabled a direct comparison between historically plausible measurement techniques and modern technologies for time measurement.

3.1. Time measurement using the water clock

Time intervals were measured indirectly by collecting the water discharged from the outlet and determining its mass. By exploiting the constancy of the water flow and maintaining a constant water level in the reservoir, the mass of water exiting through the outlet is proportional to the elapsed time according to the relation:

$$\mathrm{d}m = \rho\,Q\,\mathrm{d}t\,, \tag{2}$$

where Q is the volumetric flow rate and ρ is the density of the liquid, assumed to be 1.0 g cm^{-3}.

Water was collected by two different operators in separate trials, using a graduated cylinder for nominal time intervals of 5, 10, and 15 s, measured with a digital stopwatch. For each time interval, 50 independent measurements were performed. The collected water was subsequently weighed using a precision balance, adopting the double-weighing method to reduce systematic errors (Figure 4b).

The main sources of uncertainty are attributable to residual fluctuations in the flow rate, the resolution of the mass measurement, the repeatability of the measurements, and the reproducibility of the valve opening. In addition, the overall accuracy of the measurements is affected by the manual procedures used to start and stop the timing, as well as by the operators' reaction time during water collection, which introduce an intrinsic contribution to the measurement uncertainty.

Table 1. Mean values and standard deviations of collected water masses for different time intervals.

Time (s)	Mass (g)	σ (%)	$\sigma/\sqrt{N}$ (%)
2.5	16.5	5.4	0.8
4.9	31.1	3.6	0.5
10.0	56.5	1.9	0.3
14.9	93.7	1.7	0.2

3.2. Time measurement using a manual stopwatch

As an intermediate reference and to verify the temporal consistency with the electronic timing system (i.e., to compare manually measured times with those obtained automatically), time measurements were also performed using a digital manual stopwatch operated by different users.

The stopwatch was started at the first acoustic event generated by the impact of the sphere on the reference bell, and stopped at the subsequent acoustic signal, corresponding to the passage of the sphere at the designated markers along the inclined plane.

3.3. Time measurement with LED–phototransistor method

Finally, time intervals were measured using an electronic timing system based on LED–phototransistor pairs positioned at each marker along the inclined plane. When the sphere passes through a marker, the interruption of the optical beam generates an electronic signal that defines the corresponding transit time [15], [16].

The acquisition system allows the recording of time intervals with a temporal resolution on the order of milliseconds.

4. DATA ANALYSIS AND RESULTS

4.1. Experimental results with the water clock

In the measurements performed using the water clock, water was collected by two different operators in independent trials, using a graduated cylinder for several predefined time intervals, determined with a digital stopwatch. For each interval, 50 independent measurements were performed to evaluate the repeatability of the method and estimate the statistical dispersion of the data.

The experimental results are reported in Table 1.

As shown in Figure 6, the collected water mass is proportional to the elapsed time, following a linear relationship of the form:

$$m = \dot{m}\, t\,, \tag{3}$$

where $\dot{m}$ is the mass flow rate measured in g/s.

Fitting the experimental data via linear regression yields a relationship of the form:

$$m(t) = \alpha\, t + \beta\,, \tag{4}$$

where α represents the estimated mass flow and β accounts for initial conditions and potential systematic contributions. The coefficient of determination, $R^2 = 0.99$ indicates a high linear correlation between the variables, confirming the adequacy of the adopted model and the stability of the flow during the measurements.

In a second set of measurements, the nominal 10 s interval was repeated while intentionally varying the outflow rate from the valve, in order to assess the influence of flow fluctuations on the proportionality between collected mass and elapsed time. For each set of measurements, the standard deviation was calculated,

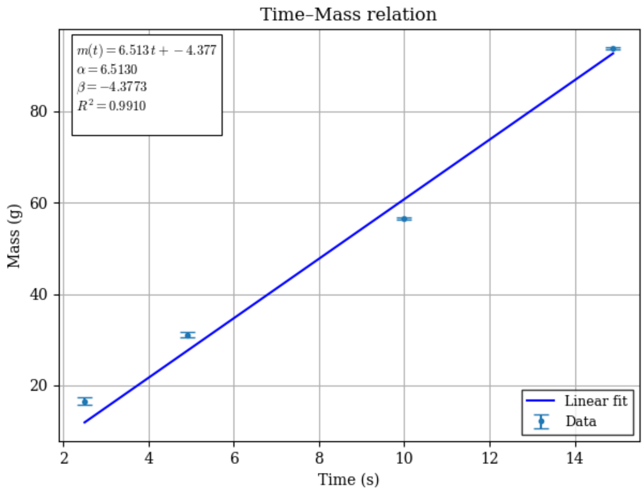

Figure 6. Linear fit of water mass versus time, showing high correlation (R^2 = 0.99) and stable flow.

resulting between 0.2 % and 0.3 % relative to the mean value, confirming the high repeatability and precision of the experimental system. The results are reported in Table 2.

Analysis of the collected data shows that the adopted method provides sufficient precision for experimental time measurement. The measurements exhibited high repeatability, with a relative uncertainty between 0.2 % and 0.3 %. The flow rate remained essentially constant within the limits of experimental uncertainty, indicating that the hydraulic system was properly calibrated and maintained near-ideal conditions. These results confirm the reliability of the method, making it suitable for subsequent experiments, in particular for verifying the quadratic relationship between distance travelled and time during the descent of a body along the inclined plane, in agreement with the model of uniformly accelerated motion.

4.2. Experimental results with the manual stopwatch

Time intervals were measured using a digital stopwatch by multiple operators, with a set of 50 measurements per interval to increase statistical significance, assess the reproducibility of the method and to compare manually measured times with electronic time.

The distribution of the collected data is shown in Figure 7. Statistical analysis indicates that the distribution is not Gaussian (p-value = 1.2 %), likely due to the difficulty of data acquisition, particularly in coordinating the start and stop of the stopwatch with the passage of the sphere and the sound of the bells along the inclined plane. This introduces deviations from an ideal distribution and reduces the goodness of fit.

For the 55 cm distance, the measured mean time is:

$$t = (0.62\ \pm 0.09)\ \mathrm{s}\,. \tag{5}$$

Table 2. Measurements at 10-second intervals with varied flow rates.

Flow rate	Mass (g)	σ (%)	$\sigma/\sqrt{N}$ (%)
1	27.7	1.8	0.2
2	51.8	1.7	0.2
3	56.5	1.9	0.3
4	153.6	1.9	0.3

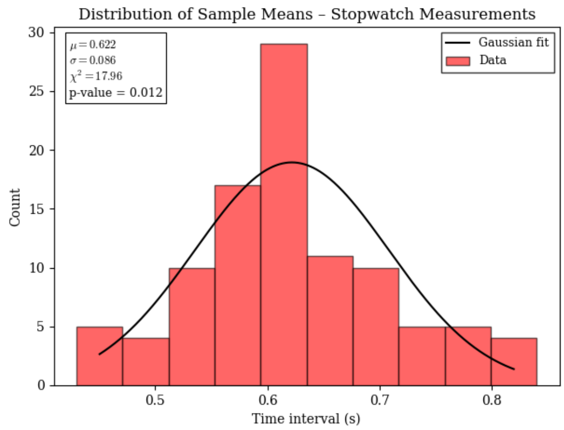

Figure 7. Time interval distribution measured with a manual stopwatch, showing non-Gaussian behaviour due to operator reaction and coordination with bell signals.

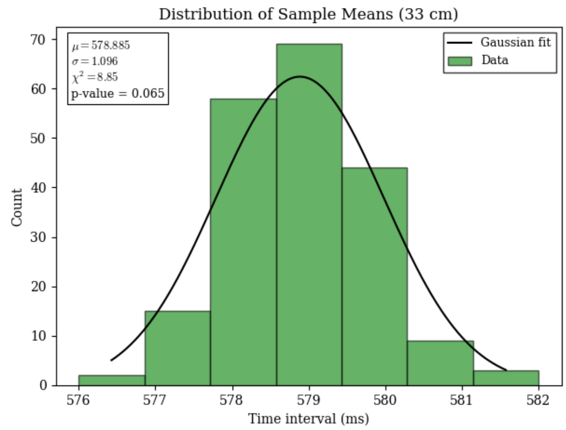

Figure 8. Measured time distributions for the 33 cm interval using the electronic timing system.

The main sources of uncertainty associated with the manual stopwatch method are:

- Operator reaction time, causing delays in starting and stopping the stopwatch, which represents the dominant contribution to the measurement uncertainty;
- Coordination with the bell signals, the variability of which introduces systematic errors in recording the sphere's passage;
- Interpretation variability of visual or auditory signals, which may produce discrepancies between different operators.

These contributions dominate the overall uncertainty and explain the non-Gaussian shape of the time distribution.

4.3. Experimental results with LED–phototransistor method

In measurements performed using the electronic timing system based on LED–phototransistor pairs, time intervals were acquired with a set of 100 measurements for each reference position, with a temporal resolution on the order of milliseconds. The sphere was released at the beginning of the inclined plane without the intentional application of external forces.

Data corresponding to the first interval of 11 cm were excluded from the analysis, since in this initial region, the motion of the sphere may be influenced by external forces introduced by the operator during release, thus compromising the assumption of reproducible initial conditions.

The data distributions for the 33 cm, 55 cm, and 77 cm intervals are shown in Figure 8, Figure 9, and Figure 10, respectively.

The measured mean times for the three intervals are:

$$t_{33} = (579 \pm 1)\ \mathrm{ms}\,, \tag{6}$$

$$t_{55} = (600 \pm 1)\ \mathrm{ms}\,, \tag{7}$$

$$t_{77} = (606 \pm 1)\ \mathrm{ms}\,. \tag{8}$$

Statistical analysis indicates that, for the first two intervals, the time distributions are compatible with a Gaussian distribution, although with relatively low probability values (p-value = 6.5 % and p-value = 9.8 %). In contrast, for the longest interval the distribution is non-Gaussian.

Since the resolution of the microcontroller clock and the temporal response of the optical sensors are significantly finer

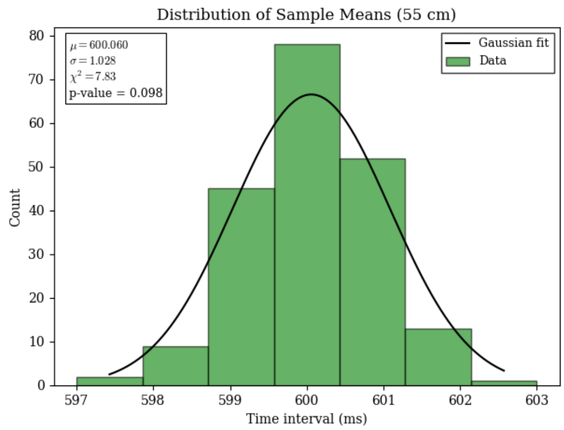

Figure 9. Measured time distributions for the 55 cm interval using the electronic timing system.

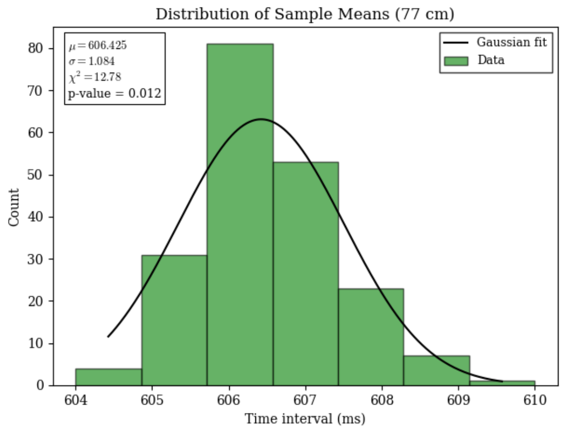

Figure 10. Measured time distributions for the 77 cm interval using the electronic timing system.

than the characteristic timescale of the observed phenomenon, the main sources of uncertainty cannot be attributed to the electronic acquisition system, but rather to the experimental apparatus as a whole.

In particular:

- the inclined plane, constructed using recycled materials, does not present a perfectly smooth surface, introducing non-uniform friction and dissipative forces;

- the sphere may not be perfectly spherical, leading to deviations from pure rolling motion;
- during the release of the sphere, the operator may inadvertently introduce initial forces that alter the motion conditions.

These factors contribute significantly to data dispersion and account for the deviation from Gaussian behaviour observed, particularly for the longer sections of the inclined plane.

4.4. Verification of Galileo's law

The experimental data collected using the electronic timing system based on LED–phototransistor pairs were employed to experimentally verify Galileo's law of uniformly accelerated motion along an inclined plane.

In the experimental context, a sphere rolling down an inclined plane without slipping undergoes a motion that combines translation of the centre of mass and rotation about its own axis. Gravity acts on the body, generating a component along the plane that determines its acceleration, while the perpendicular component is balanced by the normal force. Static friction at the contact point, although performing no work, is essential because it provides the torque required to ensure pure rolling, preventing the sphere from sliding.

Considering a solid sphere of mass m, radius R, and moment of inertia $I = \frac{2}{5}\, m\, R^2$, rolling without slipping along an inclined plane of angle θ, the acceleration of the center of mass is constant and given by:

$$a = \frac{5}{7}\, g \sin\theta\,. \tag{9}$$

Thus, the sphere's descent along the inclined plane occurs with uniformly accelerated motion. This experimental configuration allows a realistic study of this motion regime, overcoming the conceptual limitation of the 'point mass', which represents a mathematical abstraction not experimentally realizable.

Under these conditions, the motion law predicts that the distance travelled Δs is proportional to the square of the traversal time:

$$\Delta s\ \alpha\ t^2\,, \tag{10}$$

a relationship that forms the core of the experimental verification presented in this work.

Measurements acquired with the LED–phototransistor electronic system confirmed this relationship experimentally.

Figure 11 shows the distance travelled as a function of t^2, highlighting a linear relationship with a coefficient of determination close to unity, in excellent agreement with the theoretical model. Deviations observed, particularly in the longer sections of the plane, can be attributed to non-ideal effects, such as rolling friction, surface irregularities, and minor variations in the sphere release conditions.

Overall, the experimental results confirm the validity of Galileo's law of uniformly accelerated motion within the limits of experimental uncertainty.

5. UNCERTAINTY ANALYSIS

This section provides a systematic evaluation of the uncertainties associated with the time and distance measurements along the inclined plane. The main contributions arise from data acquisition, including operator reaction times,

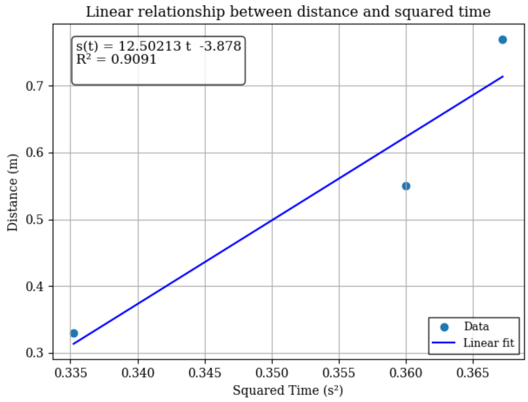

Figure 11. Distance travelled as a function of squared time measured with the LED–phototransistor system, showing linear behaviour consistent with Galileo's law of uniformly accelerated motion.

delays in starting/stopping the stopwatch, water collection, and involuntary forces applied during the sphere release. Minor contributions come from the microcontroller clock resolution and the response time of the phototransistors in the electronic system.

Other sources of uncertainty include:

- positioning of the reference marks, affecting the kinematic law verification;
- inclined plane alignment, potentially introducing transverse motion components;
- LED–phototransistor alignment [17];
- local variations in friction due to surface imperfections;
- slight slipping of the sphere, violating the pure rolling condition;
- variations in the inclination angle along the plane;
- mechanical vibrations of the apparatus;
- environmental conditions affecting sensor performance and friction.

These uncertainties influence the verification of the kinematic law: deviations from ideal rolling and non-ideal plane mechanics introduce dispersion in the measured times, resulting in deviations of the experimental points from the theoretical curve. In low-speed sections, where dissipative effects are negligible, the time distributions are approximately Gaussian; in longer sections, where friction and surface irregularities accumulate, dispersion increases and Gaussian decreases.

Other "non-ideal" sources of uncertainty are represented by surface friction and the manual release of the sphere, which lead to non-Gaussian distributions in the longer sections of the plane. To reduce these contributions, several solutions can be adopted:

- the plane was smoothed and treated with petroleum jelly to minimize frictional effects; nevertheless, these measures did not allow for their complete elimination, and residual dissipative forces continue to influence the motion;
- an automatic release system for the sphere could be designed, for example magnetically activated, in order to avoid introducing initial accelerations that may affect the motion of the body along the plane.

Despite these limitations, the overall trend of the data remains consistent with the quadratic dependence of displacement on time, confirming the validity of Galileo's uniformly accelerated motion model within the experimental uncertainty limits.

Finally, the estimated uncertainties, including both random and systematic contributions, are the following:

- Water clock: relative uncertainty ~0.2–0.3 %, dominated by flow fluctuations and manual repeatability;
- Manual stopwatch: relative uncertainty ~2 %, dominated by operator reaction time;
- LED–phototransistor system: relative uncertainty < 0.2 % for short sections ([33–55] cm), up to ~0.2 % for the longest section (77 cm), due to friction, surface irregularities, and variations in sphere release.

6. CONCLUSION

In this work, an inclined plane inspired by the one used by Galileo to experimentally verify the law of motion of bodies subjected to constant acceleration was constructed, adopting three different time-measurement methods: a water clock, a manual stopwatch, and an electronic system based on LED–phototransistor sensors.

The time-measurement tests performed using the water clock indicate that, already in Galileo's time, it was possible to estimate time intervals with a precision of approximately one tenth of a second. However, the obtained results show that such precision can be achieved only through repeated measurements and statistical analysis of the data. Although the concept of standard deviation had not yet been formalized in the 17th-century, it is likely that Galileo implicitly applied criteria of repeatability and consistency of results, which can be regarded as an early form of statistical analysis.

The comparison among the different time-measurement methods highlights how significantly the measurement uncertainty depends on the adopted technique. The LED–phototransistor electronic system provides the highest temporal resolution; however, the overall accuracy is limited by non-ideal mechanical factors. Despite these limitations, the system enabled a quantitative verification of the equation of uniformly accelerated motion.

Overall, the obtained results demonstrate that even simple experimental setups, when properly characterized from a metrological perspective, allow for a quantitative verification of the fundamental laws of kinematics. The adopted approach also emphasizes the educational value of comparing historical and modern measurement techniques, providing a comprehensive view of the evolution of experimental methods for time measurement. For example, Galileo's musical approach, based on the sound of bells, can be considered a precursor to frequency measurement, as it associates the periodicity of sound events with regular time intervals, anticipating the modern concept of frequency as the number of occurrences per unit time.

Future developments of the apparatus could include improved control of the initial conditions and a reduction of dissipative effects, in order to further enhance the agreement between the theoretical model and the experimental data.

In an educational context, it would also be of particular interest to integrate video and audio analysis techniques for a digital verification of the equation of motion [18].

AUTHORS' CONTRIBUTION

Conceptualization, Giuseppe Schirripa Spagnolo (G.S.S.); methodology, Giorgia Satta (G.S.) and Federico Fina (F.F.); validation, Fabio Leccese (F.L.) and Ilaria De Angelis (I.D.A.); formal analysis, G.S. and F.F.; investigation, G.S. and F.F..; resources, F.L.; data curation, G.S.; writing—original draft preparation, G.S.; writing—review and editing, G.S.S. and F.L.; supervision, F.L. and I.D.A. All authors have read and agreed to the published version of the manuscript.

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