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A simple experimental setup for measuring microparticle diameters with a smartphone and an LED

Andrea Zamboni, Alessandro Salmoiraghi*, Luigi M Gratton and Pasquale Onorato

Department of Physics, University of Trento, Povo (TN), Italy

E-mail: a.salmoiraghi@unitn.it

Abstract

We present a simple and low-cost experimental setup for quantitatively measuring the size of microparticles in powders. The method requires only inexpensive, readily available materials and can be easily reproduced at home, making it particularly suitable for distance learning applications. The theoretical framework relies on Babinet's principle, which states that, to very good approximation, a particle generates a diffraction pattern equivalent to that of a circular aperture. In practice, the powder sample is placed on a glass slide and positioned directly over the camera of a smartphone. A small piece of a diffraction grating is attached over the slide, and the resulting diffraction images are captured with the smartphone camera. The images are then quantitatively analysed using the open-source software Tracker. As light sources, light emitting diodes of different colours are employed. This accessible setup provides a robust and reproducible approach to introducing students to diffraction phenomena and particle size measurement.

* Author to whom any correspondence should be addressed.

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Keywords: wave optics, low-cost experiments, microplastics, microparticles, diffraction, distance learning

1. Introduction

Microparticles are particles with sizes ranging from 1 to 1000 micrometres (μm). When properly controlled, their use can greatly benefit humanity, as they are employed in fields such as medicine, environmental science, and technology due to their unique properties [1–4]. On the other hand, certain microparticles are considered among the most hazardous pollutants [5]. A notable example is microplastics, defined as plastic fragments smaller than 5 mm, typically originating from the degradation of larger plastic materials. These particles pose serious threats to ecosystems and human health, as they infiltrate soil, water, and air, can be ingested by living organisms, enter the food chain, and act as carriers of toxic substances. Another critical category is particulate matter such as PM10, with diameters smaller than 10 μm, which remain suspended in the atmosphere and can penetrate the upper respiratory tract. These particles arise both from natural sources (e.g. dust, pollen) and anthropogenic activities (e.g. industry, heating, traffic, agriculture). The latter are widely recognized as major contributors to urban pollution [6].

One of the most established techniques for rapidly measuring particle size is laser diffraction analysis, which exploits the diffraction patterns produced when a laser beam interacts with particles ranging from nanometres to millimetres in size [7]. This method is originally based on Fraunhofer diffraction theory, which states that the scattering angle of the laser beam is inversely proportional to the particle size: the scattering angle increases as particle size decreases, and vice versa [8]. Consequently, laser diffraction spectrometry is often said to rely on Fraunhofer diffraction. However, this is strictly valid only when particles are significantly larger than the wavelength of light; otherwise, Mie theory should be applied. Fraunhofer theory considers only diffraction effects at the particle boundaries, and thus it should be applied exclusively to opaque particles or to samples with known optical properties, where the expected particle diameter is at least ten times greater than the wavelength of the illuminating source [9, 10].

From the perspective of physics education, diffraction represents a key topic within curricula at both the high school and undergraduate levels [7, 11]. Numerous studies in physics education, including recent ones, have examined this subject from theoretical [12], experimental [8, 13–17], and pedagogical [9, 10, 18–20] perspectives. Nevertheless, practical implementation in teaching laboratories is often limited by the high cost of equipment and the use of potentially hazardous laser sources.

In this paper, we present an alternative experimental approach to Fraunhofer diffraction that employs commercially available light emitting diodes (LEDs) as illumination sources, a low-cost holographic diffraction grating film, and a smartphone for capturing diffraction patterns. The simplicity, affordability, and safety of this setup make experiments easily reproducible at home, thus offering a valuable tool for distance learning [21, 22]. The resulting images are quantitatively analysed with the open-source software Tracker [23]. To determine the size limit down to which this measurement method can be used, we performed the experiment on powders ranging from 30–35 μm down to 1 μm in diameter. The simplicity, affordability, and safety of this setup make the experiments easily reproducible at home, thus offering a valuable tool for distance learning.

2. Theory

Fraunhofer diffraction describes the pattern produced by large, opaque spherical particles, where the particle's edge acts as a circular obstacle. When the particle size is much larger than the wavelength of light, this situation can be approximated by Fraunhofer diffraction from a circular aperture, yielding the characteristic ring-shaped

structure. This equivalence between diffraction by an obstacle and by an aperture is a direct consequence of a principle formulated by Jacques Babinet in 1837 [24], which states that the sum of the fields scattered by an obstacle and its complementary aperture is equal to the unobstructed incident wave [25, 26].

In the following, we make use of the standard textbook expression for the intensity (I) of the Fraunhofer diffraction pattern produced by a circular aperture of diameter D, commonly referred to as the Airy diffraction pattern [25]. This pattern is characterized by a bright central maximum, known as the Airy disc, surrounded by concentric rings of alternating brightness and darkness. The theoretical formula for the intensity is given by

$$I(r) \propto \left[2\frac{J_1\left[\pi Dr/\left(\lambda z\right)\right]}{\pi Dr/\left(\lambda z\right)}\right]^2 \tag{1}$$

where r is the radial distance from the optical axis, D is the aperture diameter (or, for the Babinet's principle, the diameter of the microparticle), λ is the wavelength of light, z is the distance to the screen, and $J_1(x)$ is the first-order Bessel function. Intensity minima, in the limit of large z (small angle), occur when:

$$r_{\mathrm{m}} \sim z\frac{\lambda m}{D} \text{ for } m = 1.22, 2.23, 3.24\ldots. \tag{2}$$

While maxima should be in:

$$R_{\mathrm{m}} \sim z\frac{\lambda m}{D} \text{ for } m = 1.64,\ 2.68,\ 3.69\ldots. \tag{3}$$

From equation (2) we see that the distance between the minima (black rings) is proportional to the wavelength and inversely proportional to the aperture diameter.

To calibrate the distances measured in the pictures, we need to compare the Airy diffraction pattern with the diffraction pattern produced by a diffraction grating with a known distance between the slits. The main formula for a diffraction grating for bright fringes is

$$d\sin\theta = n\lambda \tag{4}$$

where d is the slit separation, θ is the angle of diffraction, is the order of the fringe (an integer), and λ is the wavelength of the light.

When the angle of diffraction θ is small, the further approximation $\tan\theta \approx \sin\theta$ allows for the relation

$$y_{\mathrm{m}} \sim z\frac{n\lambda}{d} \tag{5}$$

to be used for calculating the position of peaks on a screen, where z is the distance from the camera to the screen.

By comparing equation (2) and equation (5), it is possible to derive a linear relationship between the distance R_{m} of the maxima from the centre and the order number of the considered fringe:

$$\frac{R_{\mathrm{m}}}{y_1} = \frac{d}{D}m \text{ for } m = 1.64, 2.68, 3.69\ldots. \tag{6}$$

While, if we considered the distance r_{m} of the minima:

$$\frac{r_{\mathrm{m}}}{y_1} = \frac{d}{D}m \text{ for } m = 1.22, 2.23, 3.24\ldots. \tag{7}$$

When the particles are very small (diameter of the order of μm) just a large black fringe is visible and a luminous ring (the first maximum) surrounding it. Thus, we can evaluate the microparticles diameter as

$$D = 1.64\frac{y_1}{R_1}d. \tag{8}$$

A schematic view of the expected diffraction patterns is shown in figure 1.

3. The experimental setup

As first we put the microparticle powder on a glass slide. We use Lycopodium (diameter about 30–35 μm) and polystyrene powders composed by microparticles with a known diameter (6.00 $\pm$ 0.08 μm, 2.00 $\pm$ 0.03 μm and 1.00 $\pm$ 0.03 μm), as shown in figure 2. The experimental setup consists in placing the glass slide and the diffraction grating of known slits-separation ($\boldsymbol{d = 2\ \mu m}$) directly on the smartphone camera, as shown in figures 3 and 4. This is the most practical way to put the diffracting objects in front of the camera, and moreover the camera lens ensures the validity of the Fraunhofer approximation. Then,

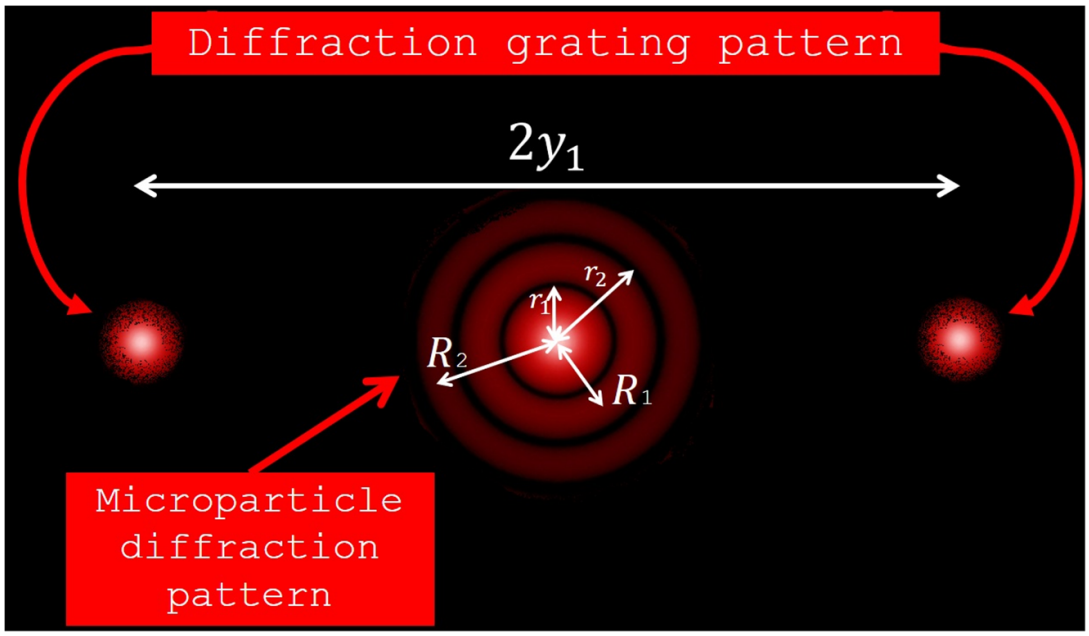


Figure 1. Expected picture of the diffraction patter of the microparticles and the grating.

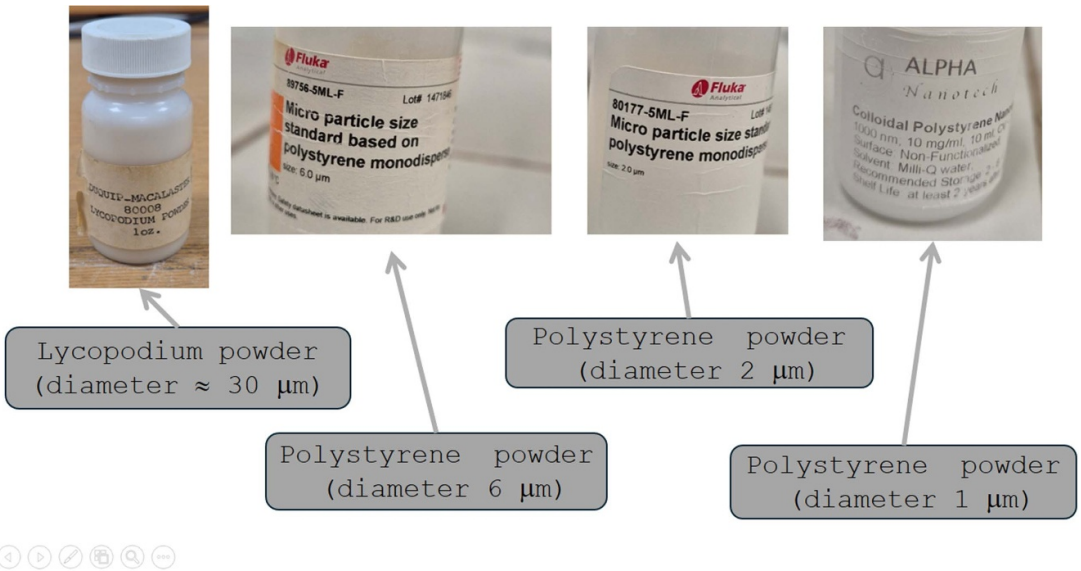


Figure 2. Microparticles powders used for the experiment.

the single LEDs [27] are framed from a distance of 20 cm from the smartphone camera. All measurements are best performed with the room lights off, but we observed that good results are possible even if the lights are on, provided a black cardboard sheet is put behind the LED to enhance contrast (see [14]). The setup of the experiment is reported in figure 5.

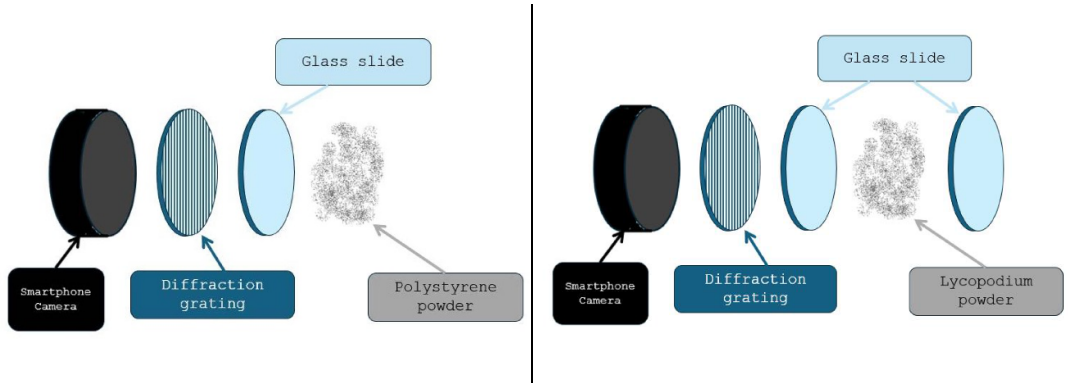


Figure 3. Schematic representation of the sample preparation. The Lycopodium, since it is in powder form, was placed between two slides to prevent the sample from dispersing. The polystyrene powders, on the other hand, being diluted in solution, were placed on a single slide and then the liquid part was allowed to evaporate, thus remaining the powder fixed on the surface of the slide.

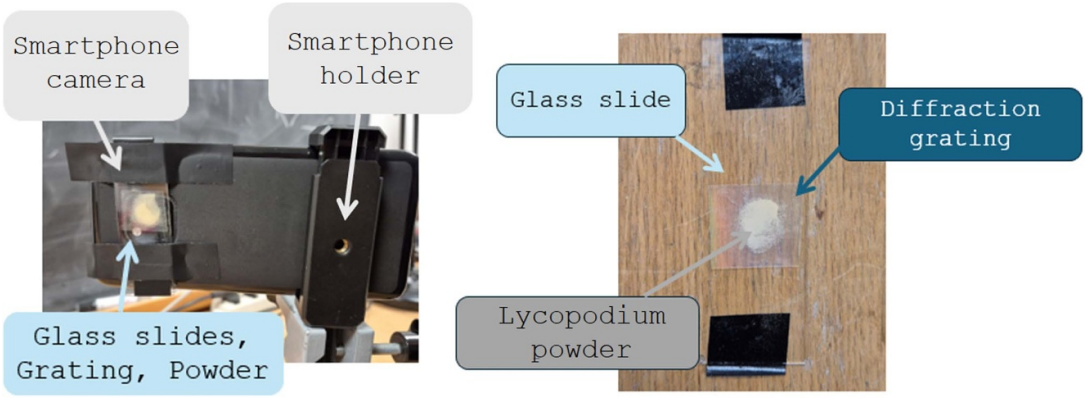


Figure 4. Preparation of the sample on the slide and positioning on the smartphone camera lens.

4. The experiment

We frame red, orange, green, blue and violet LEDs and photograph the diffraction patterns thus obtained. The images were analysed using the open-source software Tracker, employing various tools such as the calibration stick, point mass, 'find circles' and 'line profile' functions. Specifically, the diffraction pattern produced by the grating was utilized as a means of calibration, given the known slit spacing (in our case, we used gratings with 500 lines per millimetre).

4.1. Lycopodium

Diffraction patterns for the Lycopodium are reported in figure 6 for the different LED colours. The resulting particle diameter measurements are shown in table 1. The unit length is given by the half-spacing between the two first-order peaks to the left and to the right of the centre produced by the diffraction grating ($y_1 \equiv 1$); the following higher-order peaks are equispaced with an uncertainty of 5% (which overestimates the angular distortion due to the linearization). Thanks to Tracker we acquire the positions of the minima, that can be interpolated using the linear relations expressed in equation (7). In this way, using a spreadsheet for the linear interpolation of data, we obtain the value of the slope d/D. A detailed breakdown of the data analysis is included in the appendix for illustrative purposes.

The weighted average across the results obtained from the different colour measurements

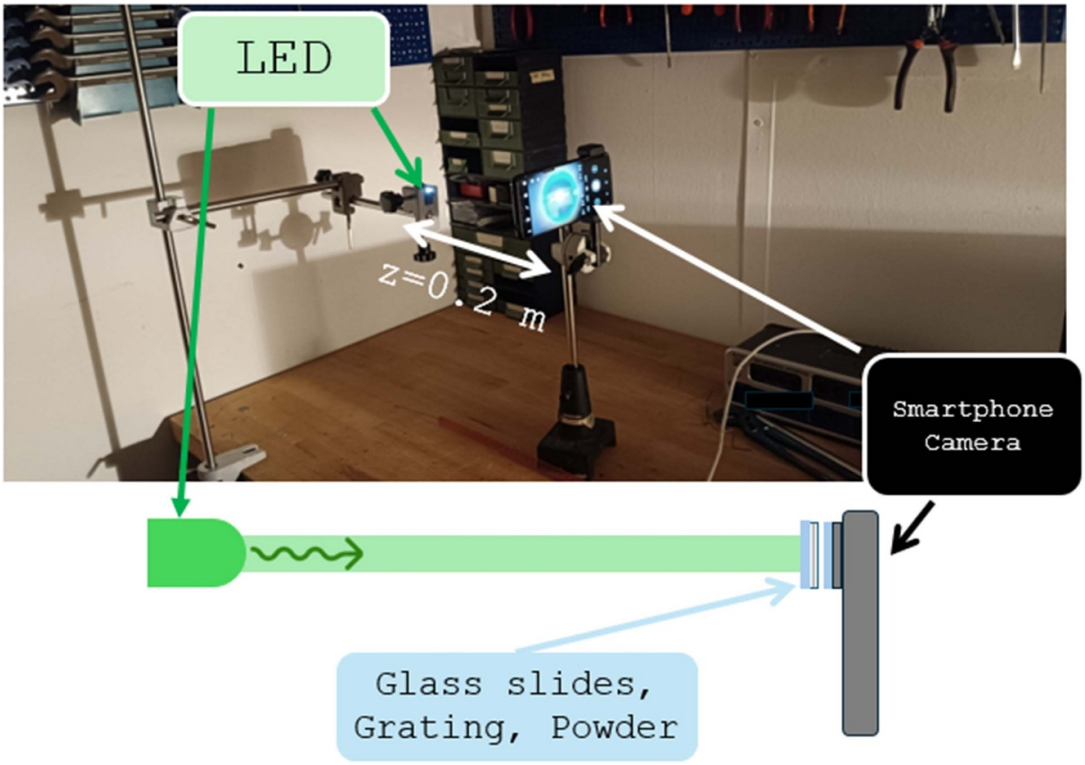


Figure 5. The experimental setup.

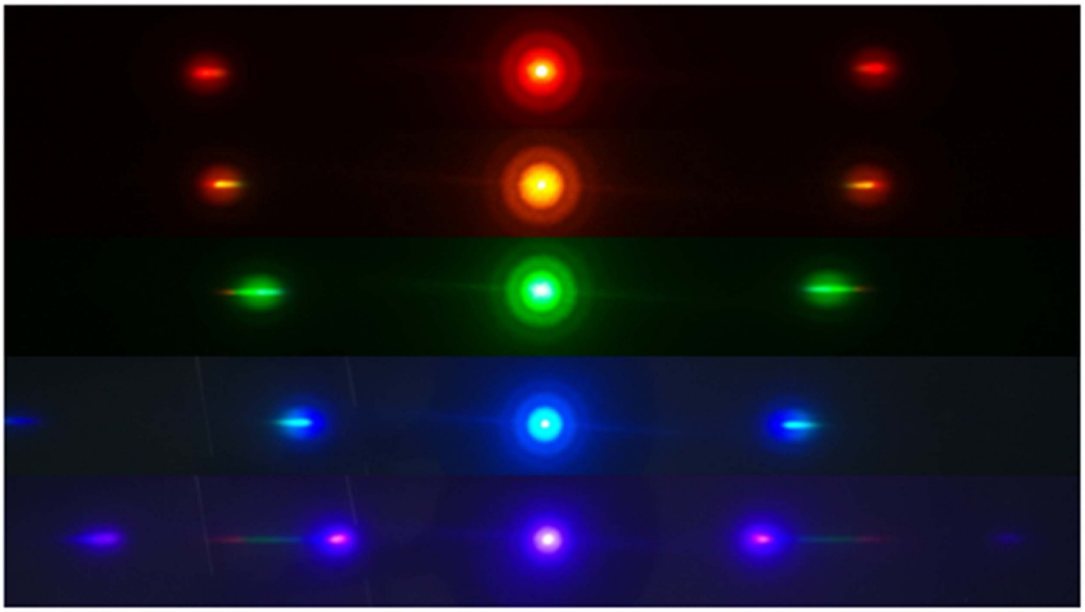


Figure 6. Diffraction patterns for the Lycopodium for red, orange, green, blue and violet LEDs.

Table 1. Slope of the linear interpolation calculated for the Lycopodium and the resulting diameter for different LED colours.

LED colour	Slope (unit $y_1 \cdot 10^3$)	Diameter of Lycopodium (μm)
Red	61	33 ± 2
Orange	60	33 ± 1
Green	60	33 ± 1
Blue	64	31 ± 1
Violet	64	31 ± 1

Table 2. Slope of the linear interpolation calculated for the 6 μm powder and the resulting diameter for different LED colours.

LED colour	Slope	Diameter of Lycopodium (μm)
Red	0.31 ± 0.01	6.4 ± 0.2
Orange	0.31 ± 0.01	6.4 ± 0.2
Green	0.30 ± 0.01	6.7 ± 0.2
Blue	0.30 ± 0.01	6.7 ± 0.2
Violet	0.32 ± 0.01	6.2 ± 0.2

yields 32 ± 1 μm, substantially compatible with the known dimensions of the Lycopodium microparticles, whose specific values is often cited around 30–35 μm [28].

4.2. 6 μm powder

For the particles with diameters of 6 μm the procedure used for image analysis is analogous to the one described previously, with the difference that in this case, the diffraction maxima were used for interpolation, as they were more evident and defined. Results are reported in table 2, while an excerpt of the images taken by the smartphone is reported in figure 7.

The weighted average of the measurements yields a value of 6.5 ± 0.2 μm. The obtained result shows an overestimation compared to the nominal value of the powder diameter; with a discrepancy of 0.2 μm, also considering the uncertainties.

4.3. 2 μm powder

For the 2 μm particles, the interpolation method was also used, even though, due to the large angular size of the diffraction pattern, only the first two maxima are visible in the images (see figure 8). Results are reported in table 3.

The weighted average of the diameters obtained yields a value of 2.3 ± 0.2 μm. The measured value is not compatible with the nominal value, showing a slight overestimation (with a discrepancy of 0.1 μm).

4.4. 1 μm powder

As the size of the resulting diffraction pattern and the angular aperture of the smartphone camera lens only allow for the recognition of the first diffraction maximum (see figure 9), we proceeded by measuring the radius of the ring and subsequently calculating the particle diameter using equation (8). The measured radius of the first Airy ring and the resulting particle diameter measurement are shown in table 4. The unit length is again given by $y_1 \equiv 1$. Thanks to Tracker we acquire the radius by employing the tool 'find circle' and tracking the circle in different points of the ring. To calculate the uncertainty in the radius measurement, we considered the thickness of the luminous ring. This thickness was determined using the 'line profile' tool in Tracker and was defined as the full width at half maximum of the profile, determined using the Tracker tool 'line profile' (figure 10). The image obtained using the violet LED is an exception: in this case, one proceeds

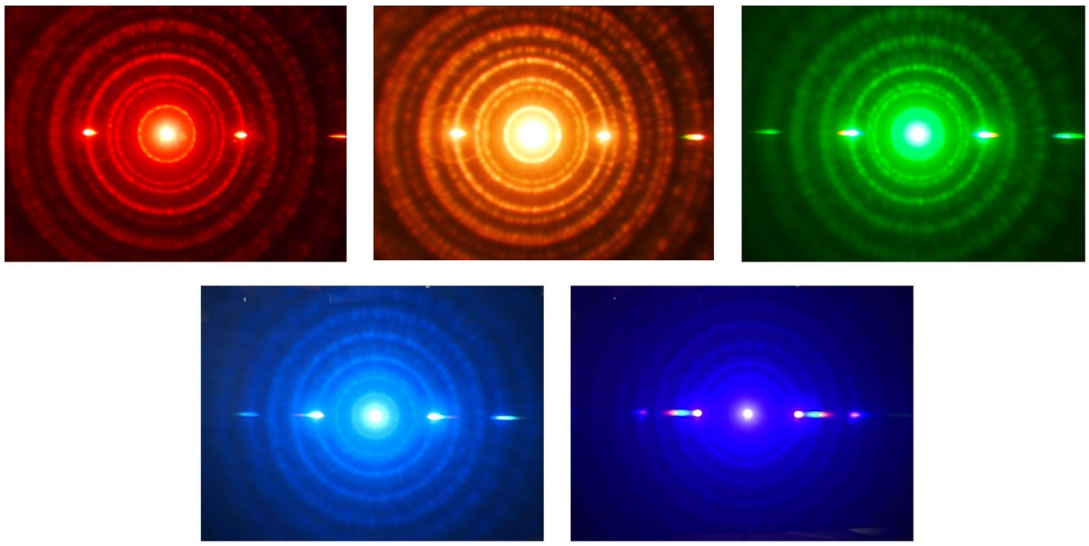


Figure 7. Diffraction patterns for the 6 μm powder for red, orange, green, blue and violet LEDs. It should be noted that, in order to make the maximum number of peaks visible, the exposure used to take the photograph resulted in saturation at the centre of the image, making it impossible to distinguish the first two bright rings. In this case, the interpolation starts from the third order.

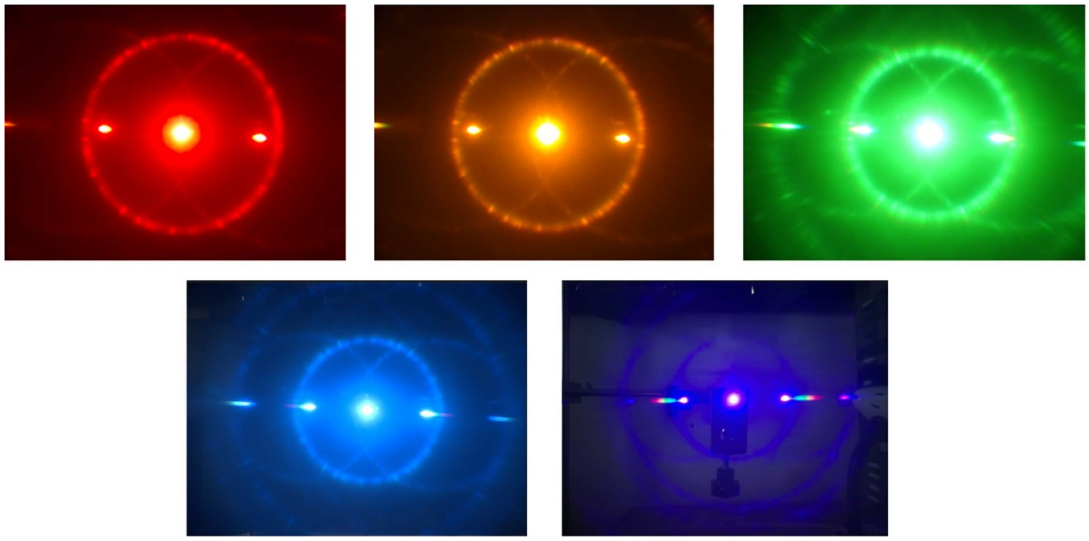


Figure 8. Diffraction patterns for the 2 μm powder for red, orange, green, blue and violet LEDs.

similarly to the 2 μm powder by considering the first two bright rings and performing linear interpolation, as this method yields a more reliable result.

The weighted average of the measurements yields a value of 1.3 ± 0.2 μm. As in the previous case, there is a slight overestimation compared to the nominal value (a discrepancy of 0.1 μm).

Table 3. Slope of the linear interpolation calculated for the 2 μm powder and the resulting diameter for different LED colours.

LED colour	Slope (unit y_1)	Diameter (μm)
Red	0.92 ± 0.07	2.2 ± 0.2
Orange	0.90 ± 0.06	2.2 ± 0.2
Green	0.87 ± 0.06	2.3 ± 0.2
Blue	0.84 ± 0.05	2.4 ± 0.1
Violet	0.85 ± 0.05	2.4 ± 0.1

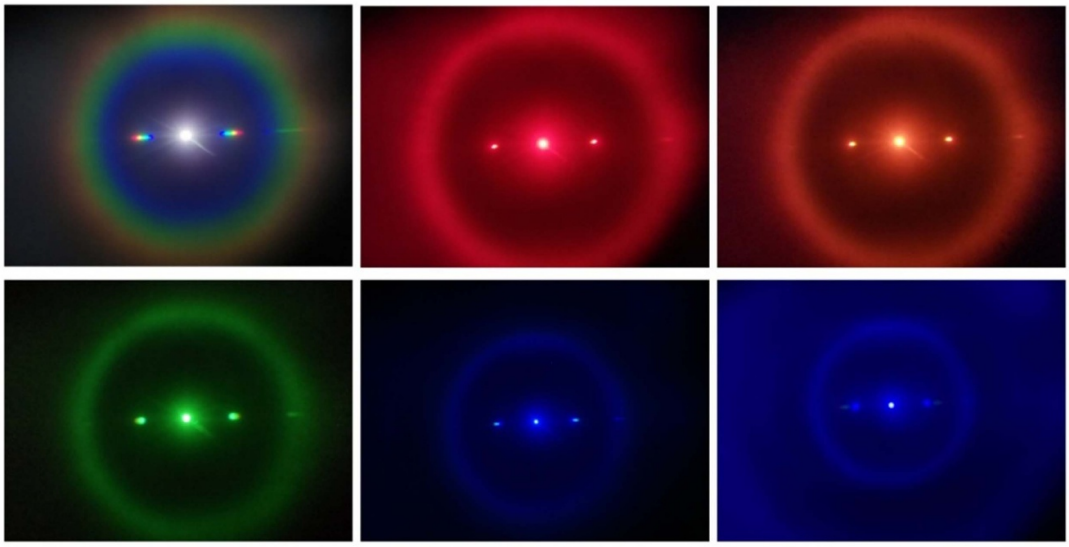


Figure 9. Diffraction patterns for the 1 μm powder for white, red, orange, green, blue and violet LEDs.

Table 4. Radius of the first luminous ring of the diffraction pattern produced by the 1 μm powder and the resulting diameter. For violet light, it was possible to photograph the first two maxima, so it was decided to use the interpolation method for calculating the diameter, as it is more accurate.

LED colour	Radius (unit y_1)	Diameter (μm)
Red	2.5 ± 0.4	1.3 ± 0.2
Orange	2.5 ± 0.4	1.3 ± 0.2
Green	2.4 ± 0.4	1.4 ± 0.2
Blue	2.2 ± 0.3	1.5 ± 0.2
	Slope (unit y_1)	
Violet	2.1 ± 0.2	1.2 ± 0.2

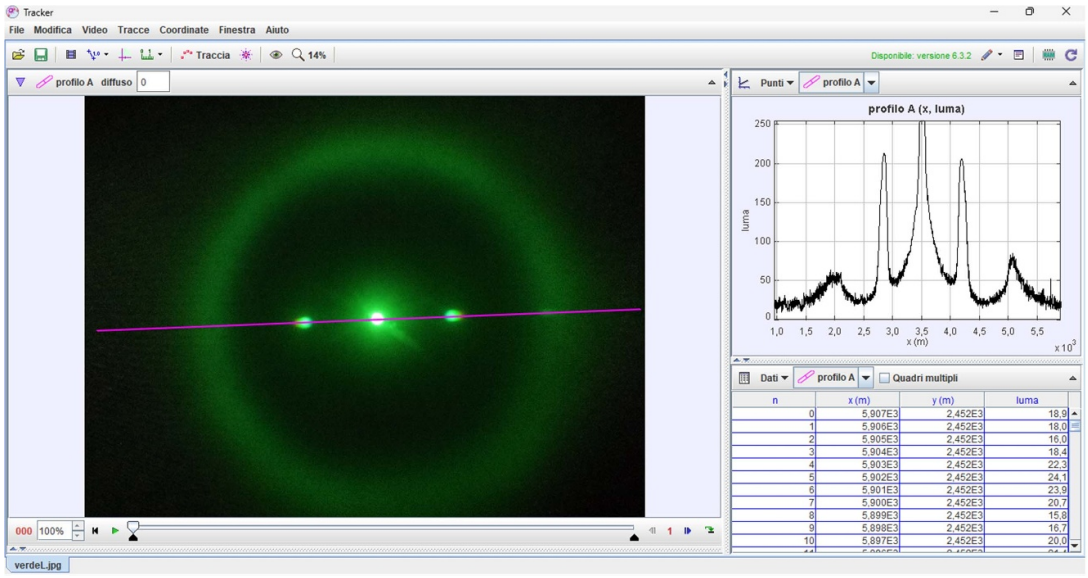


Figure 10. Use of the 'line profile' tool in Tracker. The image shows the diffraction produced by the 1 μm powder with a green LED: the central peak, the two small peaks of the grating diffraction pattern, and the width of the powder's first diffraction ring are evident.

5. Conclusions

We presented a simple, low-cost, and safe experimental setup for quantitatively measuring the diameter of microparticles, making it highly suitable for distance learning applications. The method utilizes readily available materials: a smartphone camera, a low-cost diffraction grating, and commercial LEDs as light sources, thereby circumventing the high cost and potential hazards associated with traditional laser-based techniques. By relying on Babinet's principle, which approximates a particle's diffraction pattern to that of a circular aperture, we introduced students to key concepts of wave optics and particle size measurement. We also demonstrated different simple analysis methods using the open-source software Tracker. A summary scheme of the measurements obtained for the different powders is reported in table 5.

In summary, as the particle size increases, from 1 μm to 6 μm, the uncertainty of the measurement drastically decreases, but a potential systematic error persists which tends to measure diameters that deviate from the nominal value (either in excess or in defect, depending on the data taken into consideration). It is thus interesting to derive a range of validity for the proposed method, which highlights how, as the particle diameter decreases, it yields values affected by an ever-increasing uncertainty (from 3% to 15%), even though a result close to the nominal value can still be obtained. It is interesting to note that the most precise measurements are obtained the more rings are considered; the ring corresponding to the first diffraction maximum always yields a roughly overestimated value compared to the nominal one. The gap, however, narrows the higher the orders considered. The systematic uncertainty can be attributed to the validity limit of the Fraunhofer approximation, as the size of the particles might be too close to the wavelength of the light emitted by the LEDs, so the Mie theory should be adopted,

Table 5. Overview of the results obtained for the different microparticle powders.

Nominal diameter (μm)	Measured diameter (μm)
30–35	32 ± 1
6.00 ± 0.08	6.5 ± 0.2
2.00 ± 0.05	2.3 ± 0.2
1.00 ± 0.03	1.3 ± 0.2

and consequently the spherical Bessel functions [25]. Another factor to consider is the effect of angular distortion: to derive the diameter, the small-angle approximation was used. However, when the particle size is very small, the diffraction pattern broadens significantly, thus moving towards the limit of the compatibility range of this approximation.

The experiment was pilot tested using Lycopodium powder samples during postgraduate courses and training workshops for high school teachers. It was highly appreciated for its minimal equipment requirements and ease of data collection, as well as for the clarity in the interpretation of the results. Furthermore, the diffraction pattern stimulated surprise and curiosity among the students due to its distinct visual characteristics.

In conclusion, this robust and reproducible approach offers a valuable educational tool for exploring diffraction phenomena that can be easily replicated in a home environment, with inexpensive and safe tools (a cheap, single LED diode and easily commercially available Lycopodium powder[1]).

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

[1] We recommend the use of larger powders, such as Lycopodium powder, since particles smaller than 10 micrometers—typically found in liquid suspensions—require greater caution when handled, as they can penetrate more deeply into the respiratory system.

Appendix

We present the analysis procedure using Tracker software (for image analysis) and a spreadsheet (for data analysis).

As an example, we present the image obtained from the diffraction of Lycopodium using a blue LED. To calibrate the distances within the image, the 'calibration stick' tool is used, where the distance between the two first-order maxima produced by the diffraction grating (to the left and right of the central maximum) is set equal to 2, so that y_1 (as defined in equation (6) becomes the unit of measurement for distances in the image. Once the orthogonal reference system has been inserted, with the centre at the central maximum and the x-axis directed along the line joining the first-order maxima of the grating, the distance from the centre of the dark fringes produced by the Lycopodium diffraction pattern (figure A1) is measured.

To pinpoint the locations with greater precision, the 'plot profile' tool in Tracker is used, which allows for viewing the light intensity along a line (see figure 10). Once the data concerning the position of the dark fringes of the diffraction pattern were acquired (figure A2), we determined the diameter of the Lycopodium using a spreadsheet. Firstly, we plot in a graph the order m of the dark fringe (as defined in equation (2) on the x-axis and the corresponding position of the minima on the y-axis (figure A3). By interpolating the data we obtain a line, as described by equation (7). As the uncertainty in the position r_{m} of the dark fringes, we consider the fringe width. The resulting angular coefficient (slope) corresponds to the fraction d/D, thus allowing the diameter of the Lycopodium particle to be derived. In this case, uncertainty is the standard uncertainty from the linear regression. The data analysis leads $D = 31 \pm 1\ \mu$m.

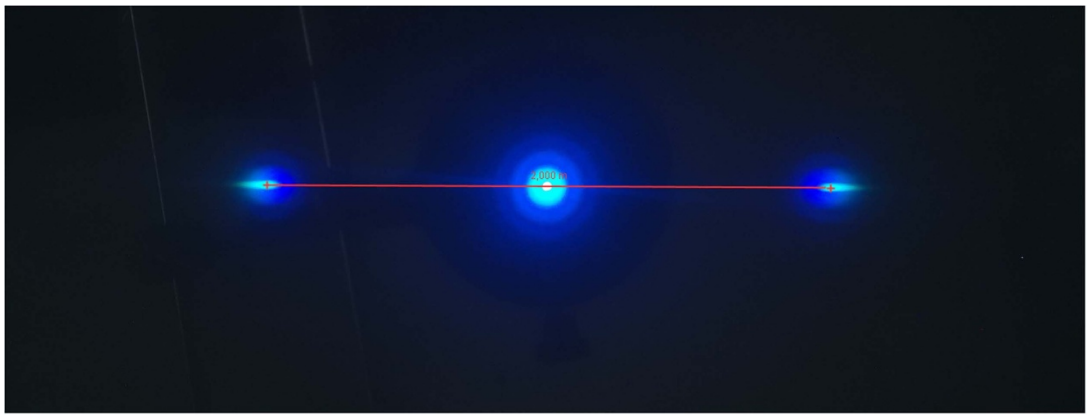


Figure A1. Positioning of the ‘calibration stick’ tool.

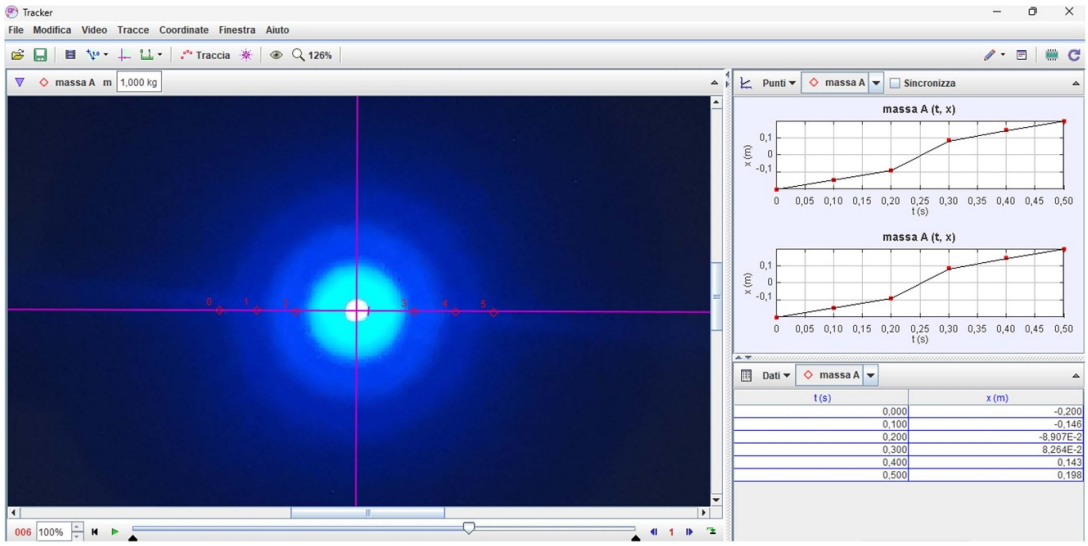


Figure A2. Determination of the position of the diffraction minima using ‘point mass’ tool.

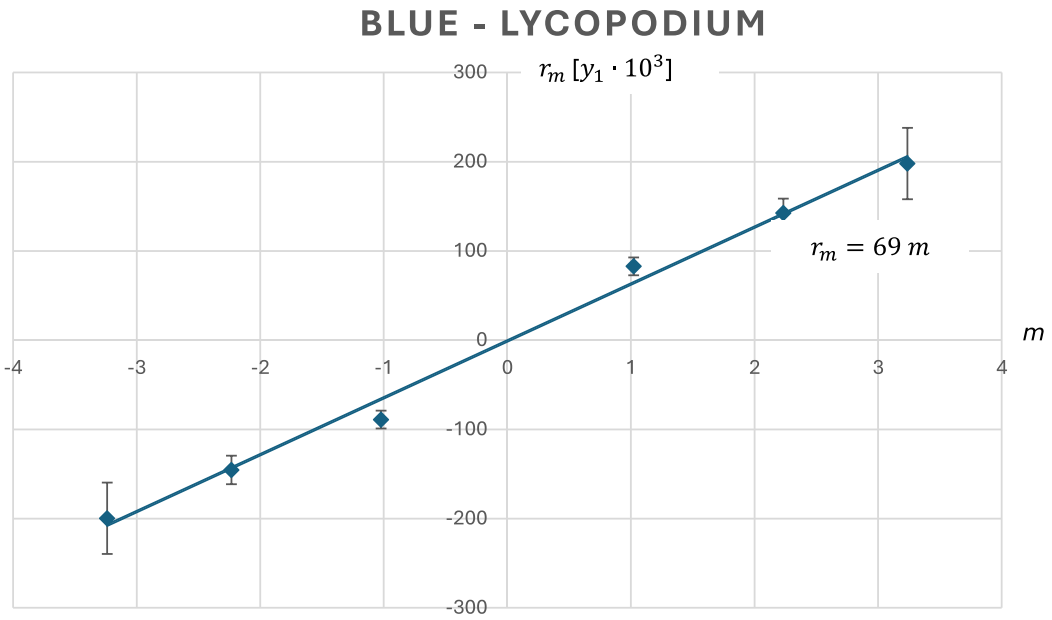


Figure A3. Graph and interpolation of the positions of the minima (y-axis) with respect to the diffraction order (x-axis).

ORCID iDs

Andrea Zamboni 0009-0006-4085-1178
Alessandro Salmoiraghi 0009-0006-8116-5078
Pasquale Onorato 0000-0002-2110-7582

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