

INTERNATIONAL STANDARD



**Printed electronics –
Part 302-3: Equipment – Inkjet – Imaging-based measurement of drop direction**

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

PRINTED ELECTRONICS –

**Part 302-3: Equipment – Inkjet –
Imaging-based measurement of drop direction**

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
119/332/FDIS	119/344/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62899 series, published under the general title *Printed electronics*, can be found on the IEC website.

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INTRODUCTION

Establishing the jetted drop direction under specific operating conditions of inks and inkjet print-heads is significant for accurate drop placement during the manufacture of printed electronics. Manufacturers that include such print-heads in their equipment should know the angular spread of ink drop directions because this influences the achievable spatial resolution of the printed material, and in particular whether any neighbouring conducting tracks could be connected by stray materials, which would affect the printed electronics' product performance. This document defines the methods for in-flight imaging measurement of jetted drop direction from drop-on-demand type inkjet print-heads to be used in printed electronics equipment.

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PRINTED ELECTRONICS –

Part 302-3: Equipment – Inkjet – Imaging-based measurement of drop direction

1 Scope

This part of IEC 62899 specifies in-flight imaging methods for the measurement of the direction of ink drops jetted from inkjet print-heads using drop watchers. It does not apply to holographic or other interference techniques, or to any method assessing deposited ink drops. It is specific to drop-on-demand type inkjet print-heads (used in printed electronics equipment).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62899-302-1, *Printed electronics – Equipment – Inkjet – Imaging based measurement of jetting speed*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62899-302-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

inkjet nozzle plane

flat outer surface of the inkjet print-head nozzle plate

Note 1 to entry: The inkjet nozzle plane is defined for a drop-on-demand multi-nozzle print-head, or as otherwise specified by the print-head manufacturer or inkjet equipment integrator and stated in the measurement results.

3.2

nozzle row direction

line in the inkjet nozzle plane passing through a row of nozzle exit centres

Note 1 to entry: Typically along the length of the inkjet nozzle plane, or as otherwise specified by the print-head manufacturer or inkjet equipment integrator and stated in the measurement results.

3.3

reference direction

normal angle (90°) to the inkjet nozzle plate

Note 1 to entry: Or as otherwise specified by the print-head manufacturer or inkjet equipment integrator and stated in the measurement results.

3.4 measurement region

3-D space closest to the inkjet nozzle plane used for imaging of the jetted drops

3.5 drop trajectory

direction of drop travel in 3-D in the measurement region

Note 1 to entry: It can be measured with two drop watchers mounted with a wide angle between them simultaneously imaging jetted drops.

3.6 trajectory angles, pl.

two orthogonal angles necessary to define the drop trajectory

Note 1 to entry: The polar angle is relative to the reference direction; the azimuthal angle is relative to a specific direction within the nozzle plane, often assumed to be the nozzle row direction.

3.7 projected angle

angle of the drop trajectory in the 2-D image plane of a single drop watcher

Note 1 to entry: The projected angle does not correspond to the polar angle of the drop trajectory unless the azimuthal angle is 0° or 180°.

3.8 reference speed

speed of the drop along the reference direction

3.9 projected speed

speed of the drop along the projected angle

3.10 absolute speed

speed of the drop along the drop trajectory

4 Measurement methods

4.1 General

The jetted drop direction shall be determined by using one of the following methods, unless there is an agreement between the user and the supplier. In that case the method is fully reported with the measurement results.

All equipment engaged in the trajectory measurement shall have a carefully calibrated geometry.

The image plane shall be aligned in a precisely orthogonal direction to the inkjet nozzle plane before the start of the measurement.

4.2 Process for projected angle using one double flash drop watcher (method 1)

- 1) Establish reliable jetting from the nozzle under study in the image measurement region.
- 2) Record the images and analyse the drop image position changes for the chosen double flash delay.
- 3) Report the projected angle, using the formula provided in A.2.1.
- 4) Report the conditions as indicated in Clause A.3.

4.3 Process for projected angle using one single flash drop watcher (method 2)

- 1) Establish reliable jetting from the nozzle under study in the image measurement region.
- 2) Record a single flash image of a jetted drop and of the nozzle under study and analyse the drop and nozzle exit image positions. Alternatively, record two single flash images of two separate drops jetted at different times from the nozzle under study, and analyse the single flash drop image positions.
- 3) Report the projected angle, using the appropriate formula specified in A.2.2.
- 4) Report the conditions as indicated in Clause A.3.

4.4 Process for projected angle using one strobe flash drop watcher (method 3)

- 1) Establish reliable jetting from the nozzle under study in the image measurement region.
- 2) Record a strobe flash image, at a chosen flash delay time, of the nozzle under study and the superposed drops, and analyse the image positions of the nozzle exit centre and the superposed drops. Alternatively, record two strobe flash images, at two different delay times, of two separate drops from the same nozzle, and analyse the change of the single flash image positions.
- 3) Report the projected angle, using the appropriate formula specified in A.2.3.
- 4) Report the conditions as indicated in Clause A.3.

4.5 Process for trajectory angles using two double flash drop watchers (method 4)

- 1) Establish reliable jetting from the nozzle under study in the image measurement region, with the image planes of the two double flash drop watchers having a wide angle between them aligned with a common axis along the reference direction.
- 2) Record double flash images of the same drop in each drop watcher for the chosen double flash delay times and analyse the drop image positions in each double flash drop watcher.
- 3) Report the trajectory angles, using the appropriate formula specified in A.2.4.
- 4) Report the conditions as indicated in Clause A.3.

4.6 Process for trajectory angles using two single flash drop watchers (method 5)

- 1) Establish reliable jetting from the nozzle under study in the image measurement region, with the image planes of the two single flash drop watchers having a wide angle between them aligned with a common axis along the reference direction.
- 2) Record single flash images of the same drop and nozzle exit at a chosen delay time in each drop watcher and analyse the image positions of the drop and nozzle exit centre in each single flash drop watcher. Alternatively, record images, at chosen delay times in each single flash drop watcher, of separate drops jetted from the nozzle under study, and analyse the single flash drop image positions in each drop watcher.
- 3) Report the trajectory angles, using the appropriate formula specified in A.2.5.
- 4) Report the conditions as indicated in Clause A.3.

4.7 Process for trajectory angles using two strobe flash drop watchers (method 6)

- 1) Establish reliable jetting from the nozzle under study in the image measurement region, with the image planes of the two strobe flash drop watchers having a wide angle between them aligned with a common axis along the reference direction.
- 2) Record strobe flash images of the superposed drops and nozzle under study at a chosen strobe flash delay time and analyse the image positions of the nozzle exit centre and superposed drops in each strobe flash drop watcher. Alternatively, record strobe flash images, at two different delay times, of separate drops jetted from the nozzle under study, and analyse the superposed drop image positions in each strobe flash drop watcher.
- 3) Report the trajectory angles, using the appropriate formula specified in A.2.6.
- 4) Report the conditions as indicated in Clause A.3.

Annexe A **(informative)**

Determination of jetted drop direction

A.1 Imaging-based measurements of jetted drop direction

The jetted drop direction should be determined from drop image position measurements for at least two different points in three-dimensional space. While IEC 62899-302-1 determines 2-D components of drop velocity it does not explicitly consider imaging-based measurement of the spatial components necessary to specify the jetted drop direction (or velocity) in 3-D space.

This document also uses just two different points to define the jetted drop direction, by assuming a straight-line motion and the absence of electrical and gravitational effects on jetted drops. All the drop watcher types are assumed to provide a flat 2-D image plane in this document, with the camera image plane aligned orthogonally to the inkjet nozzle plane. This alignment can be checked using reliably jetted drops with different delays spanning the region of interest in the camera image plane. Drop trajectories for drop-on-demand printed ink drops studied using multiple flashes, high-speed photography and orthogonally mounted drop watchers showed straight line motion holds in the absence of sideways aerodynamic and significant electric field effects. The effects of gravity as compared with air drag forces acting on near-vertically jetted drop-on-demand inkjet drops are usually negligible.

In-flight imaging measurement methods are not based on the final printed drop position or any other print quality (PQ) assessment methods applied to inkjet-printed electronics products. By contrast, the measurement of printed drop positions on a fixed substrate defines final 3-D locations at the expense of accurate knowledge of in-flight drop directions, and importantly does not accurately determine the drop trajectory close to the nozzles, i.e. where jetted drops are fully formed and furthest from their final printed positions.

Drop watchers provide the direct means of observing the region of interest for free-flying jetted drops, although practical considerations can prevent the imaging of the nozzle exit. The extent of the region of interest will depend upon these practical limits and the flash delay times chosen, together with drop speed and the drop formation process, which in turn depend on the ink properties and the particular inkjet print-head technology. Drop travel (throw) distances from the jetting nozzle to the printed substrates are typically less than 1 mm; completion of the drop formation process to give near-spherical droplets can require 100 μm travel from the nozzle. The region of interest for the measurement of jetted drop direction would be around 100 μm to 300 μm from the nozzle, but not near a substrate.

In-flight determination of the jetted drop direction relies on double flash drop watchers or single flash drop watchers or strobe flash drop watchers taking one or more images of a single drop or of different drops (and possibly the nozzle exit). Only methods such as that using two double flash drop watchers can provide a direct measurement of the drop trajectory for a single drop. Single flash drop watchers provide a projected angle based on image positions for different drops (or possibly one and the nozzle exit), at two different single flash delays. Strobe flash drop watchers provide an inherently representative average measured image position for a number of superposed drops and a projected angle based on inherently representative average measured image positions for two sets of superposed drops (or possibly one set and the nozzle exit) at different strobe flash delays. This hierarchy of methods should be associated with increasing uncertainties in the quoted projected angle and in the quoted trajectory angles. The method used should always be reported, whether based on this document or under an alternative user-supplier agreement.

Figure A.1 depicts the positions (1 and 2) of a jetted drop at two different locations (hence the flash delay times) in the region of interest near the inkjet nozzle 0 for the double flash measurement method; positions (1 and 2') of different jetted drops at two different locations (and flash delay times) in the region of interest near the inkjet nozzle 0 for the single flash measurement method; and the image of superposed nozzle position 0'' and of the centroids of the superposed jetted drop images 1'' and 2'' at two different locations (and flash delay times) for the strobe measurement methods. Figure A.1 can represent 2-D (x, y) projections or 3-D locations in space for drop images.

The direction of jetting is either defined using the change in the image position between the centre of the nozzle exit (0 or 0'') compared to the centroid position (1 or 1'') of a drop at later times or, as more usual for regions of interest without the nozzle visible, by using the change in the centroid positions (i.e. 1 and 2, or 1 and 2', or 1'' and 2''). Some drop image positions (1'' and 2'') have exaggerated extent compared with the other positions, representing the multiple drops superposed in strobe flash images; likewise nozzle exit image position (0'') can shift during strobe flash imaging. Lines between the nozzle image positions 0 (or 0'') and drop positions 2' (or 2'') are shown to emphasize the additional inherent inaccuracies of single flash measurement methods. The lowest inaccuracies in the measurement of the trajectory angles are expected when using the double flash measurement method for single drops based on centroid positions 1 and 2, provided their separation is sufficient.

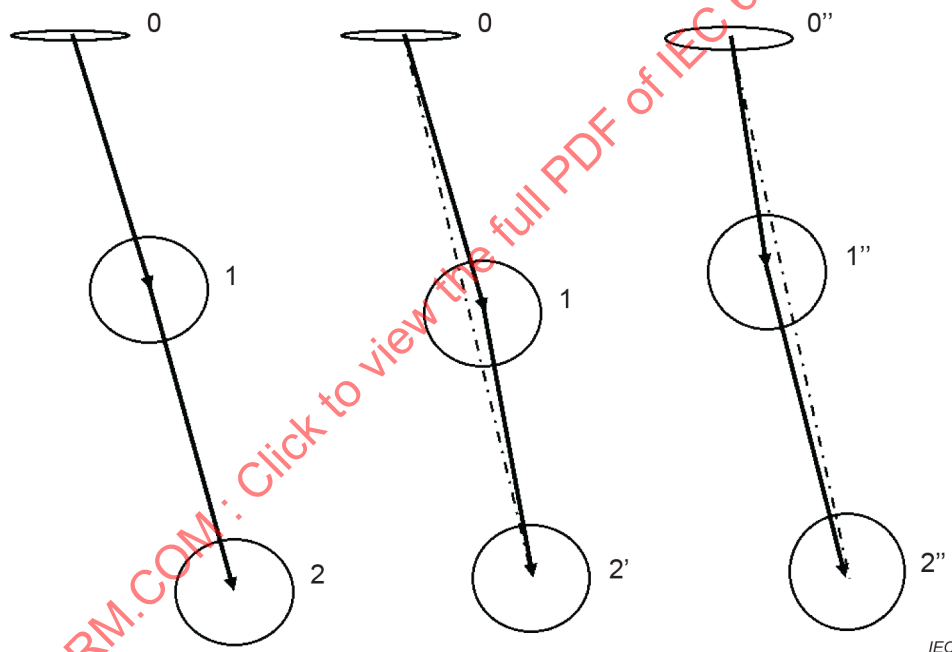


Figure A.1 – Schematic representation of jetted drop positions below a jetting nozzle (0) for double flash (1-2), single flash (1-2') and strobe flash (1''-2'') at different delays

With two drop watchers aligned with a common x -axis and a wide angle χ (typically 90°) between the image planes, the trajectory angles (and the absolute speed) for a jetted drop can be determined. When there is only one drop watcher, only the projected angle (and the projected speed) for a jetted drop can be obtained.

Polar angle θ is measured relative to the reference direction (x -axis); azimuthal angle ψ is measured relative to a specific direction within the nozzle plane, often assumed to be along the nozzle row direction. A representation of these jetted drop angles in Figure A.2 shows: a), the projected angle δ in 2-D corresponding to a double flash drop watcher (1 and 2), the nozzle exit and other drop images at different delays for a single flash (0, 1 and 2') or a strobe flash (0'', 1'' and 2'') drop watcher; b), the trajectory angles θ and ψ in 3-D as measured by two orthogonal (wide angle $\chi = \psi_A + \psi_B = 90^\circ$) or non-orthogonal drop watcher systems A and B for the double flash scenario. Equivalent schematic representations for trajectory angles θ and ψ found with orthogonal or non-orthogonal single flash or strobe flash drop watcher systems A

and B are not given here. They can be obtained from Figure A.2b) after appropriate substitutions for the coordinate labels (' or '), respectively, following the notation already shown in Figure A.1.

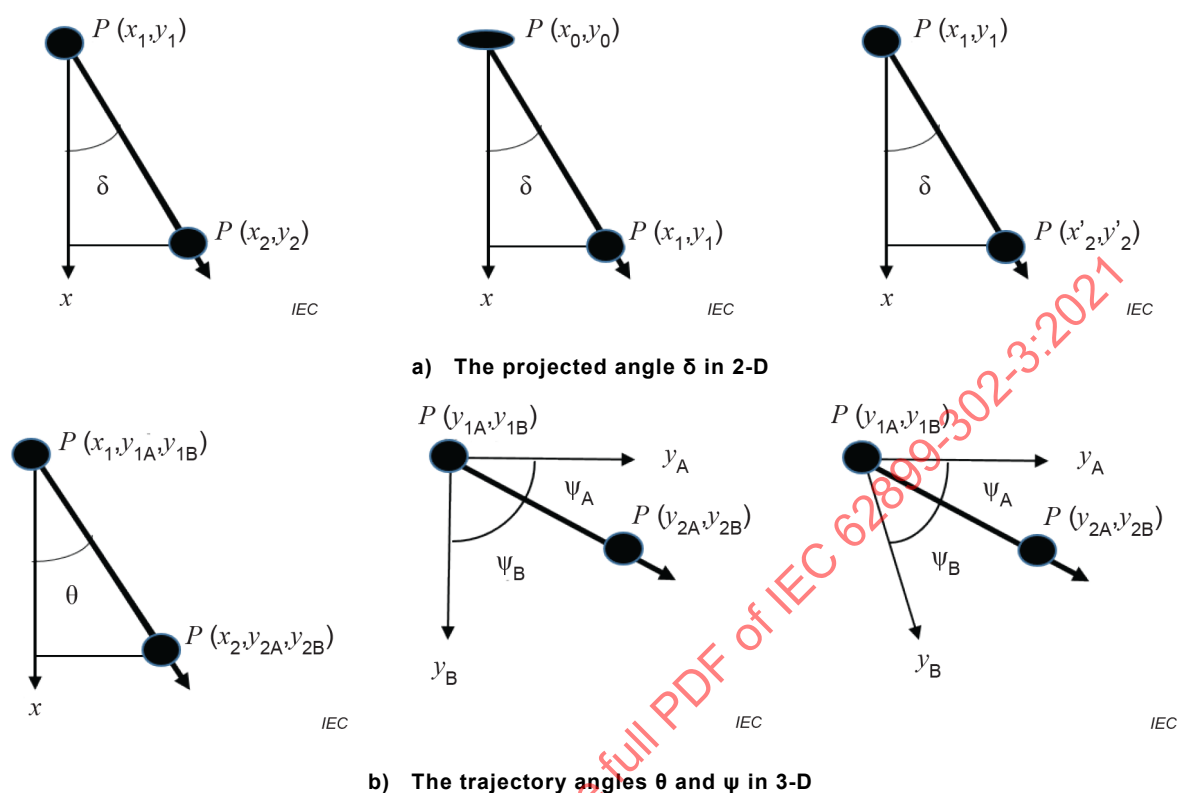
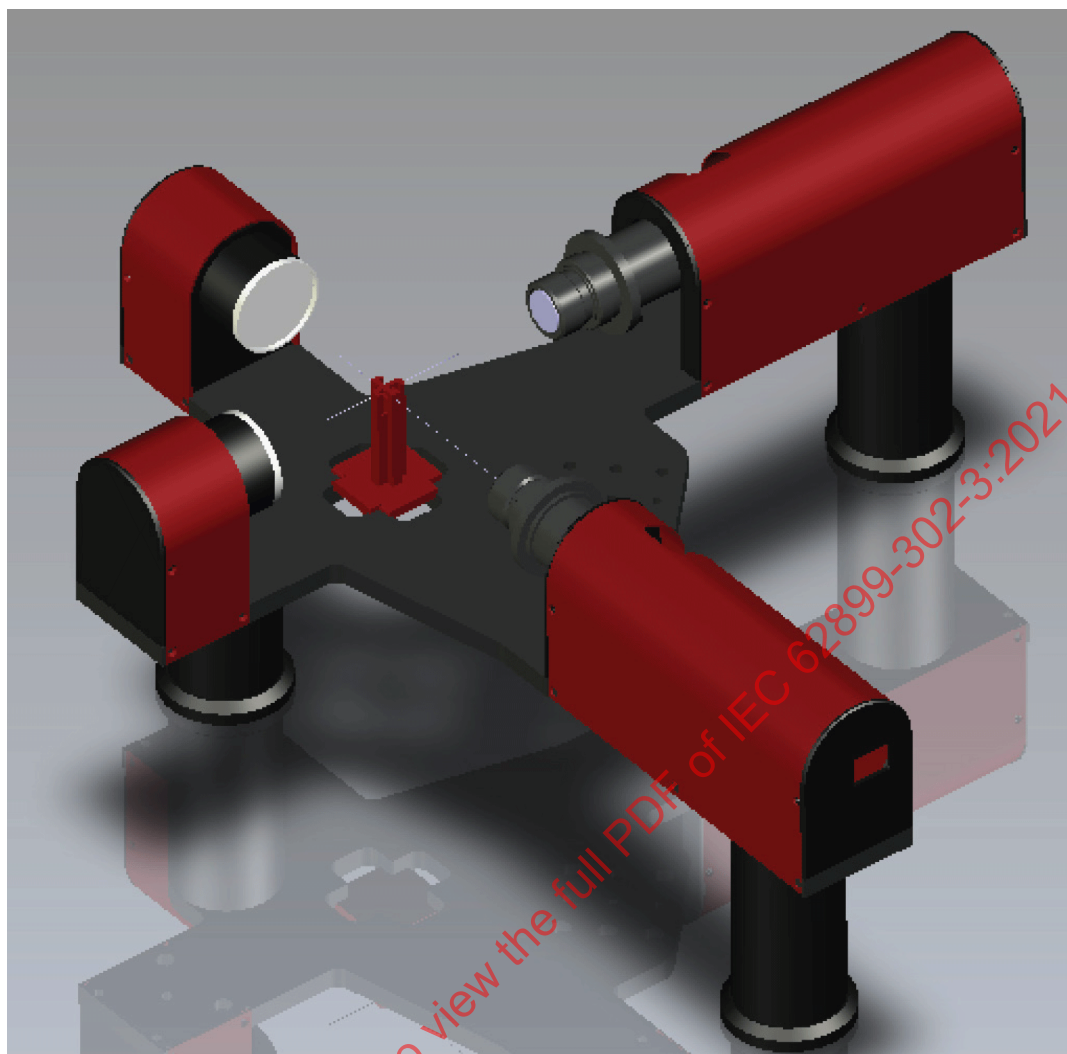


Figure A.2 – Schematic representation of a) the projected angle δ in 2-D and b) the trajectory angles θ and ψ in 3-D



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Figure A.3 – Example of two orthogonally-mounted in-flight imaging drop watchers

When determining the trajectory angles of the jetted drop direction for a specific inkjet nozzle, it is preferable that the very same drop is measured by the drop watcher(s) involved, to avoid the additional direction uncertainties which will arise from any jetted drop-to-drop variations, as depicted in Figure A.1.

An example of two orthogonally mounted in-flight imaging drop watchers is shown in Figure A.3. Orthogonally-mounted drop watchers provide image planes at 90° and have the downwards reference direction in common with each other; alternatively, these two drop watchers should have their image planes at a wide non-zero angle with respect to the common downwards direction.

The use of two drop watchers simultaneously imaging drops, jetted from a specific nozzle, in two different 2-D planes allows a more accurate measurement of jetted drop speed than possible with a single drop watcher, although for a small polar trajectory angle the difference between the speeds is very small: the absolute speed exceeds the projected speed, which exceeds the reference speed.

A.2 Formulae used for imaging results from the measurements

A.2.1 Formulae for projected angle using one double flash drop watcher (method 1)

Two image centroids of an individual drop, at different locations corresponding to the drop motion between the double flashes in the drop watcher image, are denoted by (Px_1, Py_1) and (Px_2, Py_2) , where the x -axis lies in the nominal jetting direction and where the y -axis is in the drop watcher image plane at right angles to the x -axis. The projected angle δ in the drop watcher image plane is given by

$$\tan \delta = \left(\frac{Py_2 - Py_1}{Px_2 - Px_1} \right) \text{ hence } \delta = \tan^{-1} \left(\frac{Py_2 - Py_1}{Px_2 - Px_1} \right)$$

The projected angle δ is normally quoted in units of 10^{-3} radians (mrad) or in degrees. Note that unless the actual drop direction lies within the x - y plane, the polar angle θ of the actual drop trajectory always exceeds the projected angle δ , as does the (undetermined) absolute speed, which exceeds the projected speed of the jetted drop.

A.2.2 Formulae for projected angle using one single flash drop watcher (method 2)

The centre coordinates of a nozzle and the image centroid of a drop jetted from this nozzle in the same single flash drop watcher image are denoted by (Px_0, Py_0) and (Px_1, Py_1) , where the x -axis lies in the nominal jetting direction and where the y -axis is in the drop watcher image plane at right angles to the x -axis. The projected angle δ in the drop watcher image plane is given by

$$\tan \delta = \left(\frac{Py_1 - Py_0}{Px_1 - Px_0} \right) \text{ hence } \delta = \tan^{-1} \left(\frac{Py_1 - Py_0}{Px_1 - Px_0} \right)$$

Where the centre coordinates (x_0, y_0) of a nozzle are outside the field of view, a frequently used alternative is to use the image centroid (Px'_2, Py'_2) of one other drop (') jetted from the same nozzle, but this substitution should be noted in the reporting of results because it introduces additional errors. The projected angle δ in the drop watcher image plane is given by

$$\tan \delta = \left(\frac{Py'_2 - Py_1}{Px'_2 - Px_1} \right) \text{ hence } \delta = \tan^{-1} \left(\frac{Py'_2 - Py_1}{Px'_2 - Px_1} \right)$$

The angle δ is normally quoted in units of 10^{-3} radians (mrad) or in degrees. Note that unless the actual drop direction lies exactly within the x - y plane, the polar angle θ of the actual drop trajectory always exceeds the projected angle δ , as does the (undetermined) absolute speed, which exceeds the projected speed of the jetted drop.

A.2.3 Formulae for projected angle using one strobe drop watcher (method 3)

The centre coordinates of a nozzle and the centroid of multiple drops jetted from this nozzle, all imaged with the same strobe delay time by the drop watcher, are denoted by (Px''_0, Py''_0) and (Px''_1, Py''_1) , where the x -axis lies in the nominal jetting direction and where the y -axis is in the drop watcher image plane at right angles to the x -axis. The multiple drop average projected angle $\langle \delta \rangle$ in the drop watcher image plane is given by

$$\tan < \delta > = \left(\frac{Py_1'' - Py_0''}{Px_1'' - Px_0''} \right) \text{ hence } < \delta > = \arctan \left(\frac{Py_1'' - Py_0''}{Px_1'' - Px_0''} \right)$$

Where the centre coordinates (Px_0'', Py_0'') of a nozzle are outside the field of view, the frequently used alternative is to find the image centroid (Px_2'', Py_2'') of other multiple drops (") jetted from the same nozzle; this substitution should be noted in the reporting of results because it introduces additional uncertainties themselves dependent on whether the drops (") correspond to other drops jetted by this nozzle and visible within the measurement region or strobe imaged for a longer flash delay. The multiple drop average projected angle $< \delta >$ in the drop watcher image plane is given by

$$\tan < \delta > = \left(\frac{Py_2'' - Py_1''}{Px_2'' - Px_1''} \right) \text{ hence } < \delta > = \arctan \left(\frac{Py_2'' - Py_1''}{Px_2'' - Px_1''} \right)$$

The multiple drop average projected angle $< \delta >$ is normally quoted in units of 10^{-3} radians (mrad) or in degrees. Note that unless the multiple drop average 3-D trajectory lies exactly within the x - y plane, the polar angle $< \theta >$ of the multiple drop average trajectory always exceeds the multiple drop average projected angle $< \delta >$, as does the (undetermined) absolute multiple drop average speed exceed the multiple drop average projected speed.

A.2.4 Formulae for trajectory angles using two double flash drop watchers (method 4)

Two double flash drop watchers A and B with the same nominal in-plane magnification view the very same drop from wide-angle, often orthogonal, directions having a common x -axis. The double flash delays Δ_A and Δ_B used for imaging by the drop watchers A and B have values that should be recorded in the reporting of results because of the possible additional uncertainties introduced. The formula for one double flash drop watcher, given in A.2.1, applied to images in the two double flash drop watchers A and B, gives the two projected angles δ_A and δ_B in the image planes respectively as

$$\delta_A = \tan^{-1} \left(\frac{Py_2 - Py_1}{Px_2 - Px_1} \right)_A \text{ and } \delta_B = \tan^{-1} \left(\frac{Py_2 - Py_1}{Px_2 - Px_1} \right)_B$$

Note that for straight trajectories the δ_A and δ_B values hold even for differing flash delays Δ_A and Δ_B because the projected angle δ is determined by the ratio of coordinate changes in the same drop watcher (A or B) alone. However, for differing flash delays Δ_A and Δ_B the ratio of lateral coordinate changes between drop watcher A and drop watcher B scales linearly with Δ_A/Δ_B , or equivalently with the ratio of changes in the common x -axis direction, further complicating the determination of azimuthal angle ψ .

The drop trajectory in the measurement region and the trajectory angles (θ, ψ) can be found using these projected angles δ_A and δ_B with the measured (x, y) coordinates in the drop watchers A and B together with the wide-angle χ between the two image planes. The trajectory polar angle θ is solely determined by a combination of the individual projected angles δ_A and δ_B from the drop watchers A and B, suitably modified for the wide-angle χ , which is usually set at 90° .

For two orthogonally mounted drop watchers, $\chi = 90^\circ$ and the polar angle θ is given by the formula

$$(\tan \theta)^2 = (\tan \delta_A)^2 + (\tan \delta_B)^2 \text{ hence } \theta = \tan^{-1} \sqrt{(\tan \delta_A)^2 + (\tan \delta_B)^2}$$

In general, the polar angle $\theta(\chi)$ measured with respect to the common x -axis direction of drop watchers A and B mounted at the mutual angle χ can be computed from the formula

$$\begin{aligned} (\tan \theta(\chi))^2 &= ((\tan \theta)^2 - 2 \tan \delta_A \tan \delta_B \cos \chi) / (\sin \chi)^2 \text{ hence} \\ \theta(\chi) &= \tan^{-1} \sqrt{((\tan \theta)^2 - 2 \tan \delta_A \tan \delta_B \cos \chi) / (\sin \chi)^2} \end{aligned}$$

The computed value of $\theta(\chi)$ can be used in the computation of the trajectory's azimuthal angle ψ_A (or ψ_B) with respect to the image plane of drop watcher A (or B) according to the formula

$$\psi_A = \cos^{-1} \left(\frac{\tan \delta_A}{\tan \theta(\chi)} \right) \text{ or } \psi_B = \cos^{-1} \left(\frac{\tan \delta_B}{\tan \theta(\chi)} \right)$$

For straight trajectories, these ψ_A and ψ_B values hold even for differing flash delays Δ_A and Δ_B . They add up to the included angle χ between image planes A and B for all points between them, as shown in Figure A.2b).

$$\psi_A + \psi_B = \chi$$

When both $(Py_2 - Py_1)_A = 0$ and $(Py_2 - Py_1)_B = 0$, the trajectory angles (θ, ψ) are $(0, 0)$. This holds for any wide-angle value for the included angle χ between image planes A and B, as the measured successive positions (1 and 2) are parallel to the direction of the reference (x -) axis.

The trajectory angles θ and ψ are normally quoted in units of 10^{-3} radians (mrad) or in degrees: the polar angle $\theta(\chi)$ is quoted with respect to the reference direction and, if appropriate, the azimuthal angle ψ can be quoted with respect to the nozzle row direction.

The absolute speed exceeds the projected speed, which also exceeds the reference speed, for non-zero trajectory angles.

A.2.5 Formulae for measured trajectory angles using two single flash drop watchers (method 5)

Two single flash drop watchers A and B with the same magnification view the very same drop from orthogonal directions having a common x -axis. The single flash delays Δ_A and Δ_B used for imaging by the drop watchers A and B have values that, especially if they differ, should be recorded in the reporting of results because of the possible additional uncertainties introduced. Following the description for one single flash drop watcher, given in A.2.2, but now with two measured drop directions δ_A and δ_B from the two single flash drop watchers A and B respectively, the drop trajectory in the measurement region and the trajectory angles can be found.

$$\delta_A = \tan^{-1} \left(\frac{Py_1 - Py_0}{Px_1 - Px_0} \right)_A \text{ and } \delta_B = \tan^{-1} \left(\frac{Py_1 - Py_0}{Px_1 - Px_0} \right)_B$$

Where the centre coordinates (x_0, y_0) of a nozzle are outside the field of view, a frequently used alternative is to use the image centroid (Px'_2, Py'_2) of one other drop (') jetted from the same nozzle, but this substitution should be noted in the reporting of results because it introduces additional errors. The projected angles δ_A and δ_B in the image planes of drop watchers A and B are given by

$$\delta_A = \tan^{-1} \left(\frac{Py'_2 - Py_1}{Px'_2 - Px_1} \right)_A \quad \text{and} \quad \delta_B = \tan^{-1} \left(\frac{Py'_2 - Py_1}{Px'_2 - Px_1} \right)_B$$

Note that for straight trajectories the δ_A and δ_B values hold even for differing flash delays Δ_A and Δ_B because the projected angle δ is determined by the ratio of coordinate changes in the same drop watcher (A or B) alone. However, for differing flash delays Δ_A and Δ_B the ratio of the lateral coordinate changes between the drop watcher A and B scales linearly with Δ_A/Δ_B , or equivalently with the ratio of changes in the common x -axis direction, further complicating the determination of azimuthal angle ψ .

The drop trajectory in the measurement region and the trajectory angles (θ, ψ) can be found using these projected angles δ_A and δ_B with the measured (x, y) coordinates in the drop watchers A and B, together with the wide-angle χ between the two image planes. It should be noted that the trajectory polar angle θ is determined by a combination of the individual projected angles δ_A and δ_B from the two orthogonal drop watchers A and B, suitably modified for the wide-angle χ , which is usually set at 90° .

For two orthogonally mounted drop watchers, the polar angle θ is given by the formula

$$(\tan \theta)^2 = (\tan \delta_A)^2 + (\tan \delta_B)^2 \quad \text{hence} \quad \theta = \tan^{-1} \sqrt{(\tan \delta_A)^2 + (\tan \delta_B)^2}$$

In general, the polar angle $\theta(\chi)$ measured with respect to the common x -axis direction of drop watchers A and B mounted at the mutual angle χ can be computed from the formula

$$\begin{aligned} (\tan \theta(\chi))^2 &= ((\tan \theta)^2 - 2 \tan \delta_A \tan \delta_B \cos \chi) / (\sin \chi)^2 \quad \text{hence} \\ \theta(\chi) &= \tan^{-1} \sqrt{((\tan \theta)^2 - 2 \tan \delta_A \tan \delta_B \cos \chi) / (\sin \chi)^2} \end{aligned}$$

The computed value of $\theta(\chi)$ can be used in the computation of the trajectory azimuthal angle ψ_A (or ψ_B) with respect to the image plane of drop watcher A (or B) according to the formula

$$\psi_A = \cos^{-1} \left(\frac{\tan \delta_A}{\tan \theta(\chi)} \right) \quad \text{or} \quad \psi_B = \cos^{-1} \left(\frac{\tan \delta_B}{\tan \theta(\chi)} \right)$$

For straight trajectories, these ψ_A and ψ_B values hold even for differing flash delays Δ_A and Δ_B . They add up to the included angle χ between image planes A and B for all points between them, as shown in Figure A.2b).

$$\psi_A + \psi_B = \chi$$

When both $(Py'_2 - Py_1)_A = 0$ and $(Py'_2 - Py_1)_B = 0$, the trajectory angles (θ, ψ) are (0, 0). This holds for any wide-angle value for the included angle χ between image planes A and B, as the measured successive positions (1 and 2') are parallel to the direction of the reference (x -) axis.

The trajectory angles θ and ψ are normally quoted in units of 10^{-3} radians (mrad) or in degrees: polar angle $\theta(\chi)$ is usually quoted with respect to the reference direction and, if appropriate, the azimuthal angle ψ can be quoted with respect to the nozzle row direction.

The absolute speed exceeds the projected speed, which also exceeds the reference speed, for non-zero trajectory angles.

A.2.6 Formulae for measured trajectory angles using two strobe flash drop watchers (method 6)

Two strobe flash drop watchers A and B, with the same magnification, view the same image drops jetted from the nozzle under study from wide angle, often orthogonal, directions having a common x -axis. The single flash delays Δ_A and Δ_B used for imaging by the strobe flash drop watchers A and B have values that, especially if they differ, should be recorded in the reporting of results because of the possible additional uncertainties introduced. Following the description for one strobe flash drop watcher, given in A.2.3, but now with two (multiple drop average) projected angles δ_A and δ_B (with $\langle \rangle$ omitted) from the two strobe flash drop watchers A and B respectively, the drop trajectory in the measurement region and the trajectory angles can be found.

$$\delta_A = \tan^{-1} \left(\frac{Py''_1 - Py''_0}{Px''_1 - Px''_0} \right)_A \quad \text{and} \quad \delta_B = \tan^{-1} \left(\frac{Py''_1 - Py''_0}{Px''_1 - Px''_0} \right)_B$$

Where the centre coordinates (x''_0, y''_0) of a nozzle are outside the field of view, a frequently used alternative is to use the image centroid (Px''_2, Py''_2) of other drops (") jetted from the same nozzle, but this substitution should be noted in the reporting of results because it introduces additional errors. The multiple average projected angles in the two strobe flash drop watchers are given by

$$\delta_A = \tan^{-1} \left(\frac{Py''_2 - Py''_1}{Px''_2 - Px''_1} \right)_A \quad \text{and} \quad \delta_B = \tan^{-1} \left(\frac{Py''_2 - Py''_1}{Px''_2 - Px''_1} \right)_B$$

Note that for straight trajectories the δ_A and δ_B values hold even for differing flash delays Δ_A and Δ_B because the multiple drop average projected angles δ_A and δ_B are determined by the ratio of the coordinate changes in the same drop watcher (A or B) alone. However, for differing flash delays Δ_A and Δ_B the ratio of the lateral coordinate changes between the drop watcher A and B scales linearly with Δ_A/Δ_B , or equivalently with the ratio of changes in the common x -axis direction, further complicating the determination of azimuthal angle ψ .

The multiple drop average trajectory in the measurement region and the multiple drop average trajectory angles (θ, ψ) can be found using these multiple drop average projected angles δ_A and δ_B with the measured (x, y) coordinates in the strobe flash drop watchers A and B, together with the wide-angle χ between the two image planes. It should be noted that the multiple drop average trajectory polar angle θ is determined by a combination of the multiple drop average projected angles δ_A and δ_B from the two strobe flash drop watchers A and B, suitably modified for the wide-angle χ , which is usually set at 90° .

For two orthogonally mounted strobe flash drop watchers, the multiple drop average polar angle θ is given by the formula

$$(\tan \theta)^2 = (\tan \delta_A)^2 + (\tan \delta_B)^2 \quad \text{hence} \quad \theta = \tan^{-1} \sqrt{(\tan \delta_A)^2 + (\tan \delta_B)^2}$$

In general, the multiple drop average polar angle $\theta(\chi)$ measured with respect to the common x -axis direction of strobe flash drop watchers A and B mounted at the mutual angle χ can be computed from the formula