Aerial wetting contact angle measurement using confocal microscopy

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Abstract
A method is presented in which the wetting contact angle of a sessile drop is acquired aerially using confocal techniques to measure the radius and the height of a droplet deposited on a planar surface. The repeatability of this method is typically less than 0.25\textdegree, and often less than 0.1\textdegree, for droplet diameters less than 1 mm. To evaluate accuracy of this method, an instrument uncertainty budget is developed, which predicts a combined uncertainty of 0.91\textdegree for a 1 mm diameter water droplet with a contact angle of 110\textdegree. For droplets having diameters less than 1 mm and contact angles between 15\textdegree and 160\textdegree, these droplets approach spherical shape and their contact angles can be computed analytically with less than 1\% error. For larger droplets, gravitational deformation needs to be considered.

Keywords: wettability, contact angle, confocal microscopy

(Some figures may appear in colour only in the online journal)

1. Introduction

The sessile drop method is a measurement technique that is used to investigate interfacial systems [1–4]. The key concept of the sessile drop method is to evaluate the angle of intersection made by the liquid surface of a sessile drop and the substrate on which the drop rests. The angle of intersection is more commonly known as the wetting contact angle and, in a simplistic sense, is a relative measure of the ratio between the cohesion forces within the liquid bulk and the adhesion forces between the liquid and the substrate. While the mechanics of droplet deposition and geometric measurement involve the control and influence of many interdependent experimental conditions, the interpretation of contact angles is well documented and, therefore, not discussed herein (see [5–8] for background).

Sessile drops have historically been measured using contact angle goniometers. A contact angle goniometer is comprised of a stage where the substrate, including the sessile drop is placed, and a camera. To optically measure the wetting contact angle, the camera is positioned so that its focal plane is approximately perpendicular to the substrate plane and coincident with the axis of symmetry on the drop. For illustration, an image used to determine the wetting contact angle of a 2.5 \(\mu\)l glycerin drop on a silica substrate using the sessile drop method with a goniometer is shown in figure 1.

From figure 1, the limitations of contact angle goniometry are apparent. First, and most importantly, contact angle goniometry requires a clear line of sight to the triple phase contact line (i.e. the locus of points where solid, liquid and air are coincident). Second, edge detection is difficult because the boundary between blocked and unblocked light is defined by a highly reflective and tangential surface. Finally, if the camera angle is too low to view the reflection, or the contact angle approaches 90\textdegree, the location of the triple phase contact line on the substrate becomes difficult to distinguish.
Another significant limitation arises with *in situ* testing of a component where the line of sight to the droplet may be obscured, either by features on the component itself, or by other components in an assembly. One example of a challenging application occurs in the semiconductor manufacturing industry, where flip-chip dies are mounted on organic substrates such that the die bumps made with arrays of solder bumps. This packaging technique includes the deposition of epoxy underfill near the edge of the die, which is then drawn beneath the die into the interstitial spaces between connections by capillary action, which is driven by the surface energy of the surfaces and the surface tension of the underfill. Measuring how well the substrate solder resist surface wets is critical to the development of materials and assembly processes. One challenge, however, is that *in situ* testing is difficult as it is typical to have other components, such as capacitors and dies, mounted to the substrate that restrict the clear line of sight. In addition, the traditional sessile drop method requires a drop size on the order of a microlitre, which necessitates the droplet to be placed far away from the solder bump field. What is needed is a method that can use much smaller droplets to be placed as close to the bump field as possible, and does not depend upon a clear line of sight horizontally across the substrate.

To overcome the limitations outlined above, an aerial contact angle measurement method has been developed [8]. This technique uses a scanning confocal microscope to image the sessile drop from above and uses a geometric model to calculate the wetting contact angle.

2. Measurement principle

For small sessile drops, it is plausible to assume that the liquid/air interface is spherical in form, which is referred to as the spherical approximation herein. Additionally, in most metrological applications it can be assumed that the substrate is planar and that the optical axis of the imaging system is aligned perpendicularly to the substrate. With these assumptions, the contact angle $\theta_c$ of a sessile drop can be calculated from the measured droplet radius $r_m$ and the height $h_m$ relative to the substrate using

$$\theta_c = \cos^{-1}\left(1 - \frac{h_m}{r_m}\right).$$

In this work we measure the radius and the height of the droplets using a laser scanning confocal microscope [9, 10]. The conventional output from an Olympus LEXT laser scanning confocal microscope (Model OLS 4000) is shown in figure 2, along with illustrations of the radius (via a least-squares fit to a sphere) and the height (distance from apex of the fitted sphere to a planar fit of the substrate) of the droplet. More specifically, this microscope outputs a 2D matrix of surface heights, herein referred to as a surface map. Using this surface map and algorithms that fit the sphere and plane, the calculation of the wetting contact angle then becomes straightforward using equation (1.1).

In practice, only an upper portion of the surface map is accurate because of the slope limitations of the technique.
There are two reasons for this slope limitation. The first is the loss of signal from specular surfaces with increasing slope. As a result of this, the measurement uncertainty associated with fitting a sphere to a partial dataset increases non-linearly as the measurement area (or the included angle of the measured patch) is reduced [11]. Secondly, there are additional slope dependent errors in the surface map inherent to the transfer function of the instrument [12–14]. As an example, a perfect sphere will be measured as a paraboloid with its original at the apex. This will produce an additional term to the uncertainty budget.

When the surface map proves to be inaccurate, the measurement of wetting contact angle can be improved by using an advanced confocal technique to measure the radius directly. The basic principle behind the advanced confocal technique uses the difference in the relative locations of the cats-eye condition (when the focal point is coincident with the apex of surface) and the confocal condition (when the focal point is coincident with the centre of curvature) as a measure of the radius of curvature [15–18]. A schema is shown in figure 3. A complete theoretical discussion of the optical response for a scanning confocal microscope, when measuring small spheres, is outlined elsewhere [18, 19].

2.1. Radial measurement using commercial confocal instruments

Typically commercial confocal microscopes provide only two forms of data output; a planar preview (horizontal slice) and the surface map. An illustration of slice orientation is shown as figure 4. To provide data for subsequent analysis, code was implemented on a Keyence Violet Color 3D laser scanning microscope (Model VK-9701K) that automated the collection of the vertical confocal planes for analysis. Also, the surface topography information embedded in the measurement file of the Olympus LEXT was extracted with both data sets being analyzed using MATLAB.

To be able to use the cat’s eye/confocal measurement technique, a vertical confocal slice, including the axis of symmetry of the sessile drop, must be obtained. For reference, let
The wetting contact angle of a set of 5 µl glycerin drops resting within 3 h of each other. In accordance with the sessile drop measurement trials. The result shown in table 1 is the result of a mean taken over five confocal microscope and an AST Products Video Goniometric on a silica substrate was measured using both the Keyence instrument response of the Keyence scanning confocal microscope was repeatedly symmetric, the maximum of a Gaussian fit was used to identify the location of the features. Note that, depending on the contact angle being above or below 90°, the center of the spherical fit could be higher than or below the measured location of the substrate (see figure 3). After the relative locations have been identified, equation (1.1) can be used to calculate the wetting contact angle.

### 3. Experimental results

#### 3.1. Measurements on sessile drops

The wetting contact angle of a set of 5 µl glycerin drops resting on a silica substrate was measured using both the Keyence confocal microscope and an AST Products Video Goniometric Contact Angle System (Model 2540XE). Each measurement result shown in table 1 is the result of a mean taken over five measurement trials.

| Artifact/machine | Confocal | Goniometer | Difference |
|------------------|----------|------------|------------|
| Drop #1          | 60.14°   | 61.8°      | 1.7°       |
| Drop #2          | 57.38°   | 60.5°      | 3.1°       |
| Drop #3          | 59.14°   | 59.6°      | 0.5°       |

With the confocal slice acquired, the irradiance values along a path of evaluation can be analysed for the computation of the location of the features, see figure 5. An example showing the irradiance, or more generally the intensity, as a function of distance along the path of evaluation is shown in figure 6.

Once the irradiance values along the path of evaluation have been extracted, the relative location of each feature can be obtained using least-squares fitting to a Gaussian function. Because the instrument response of the Keyence scanning confocal microscope was repeatedly symmetric, the maximum of a Gaussian fit was used to identify the location of the features. Note that, depending on the contact angle being above or below 90°, the center of the spherical fit could be higher than or below the measured location of the substrate (see figure 3). After the relative locations have been identified, equation (1.1) can be used to calculate the wetting contact angle.

### 3.2. Comparison between measurement techniques

Three measurement types were employed for a baseline comparison between techniques, including goniometry, confocal and contact (described below). To enable the comparison with contact measurement, and to significantly improve the temporal stability of the specimens to be measured, a set of representative measurement artifacts were used. These artifacts (International Precision Engineering Artifact Set Model 55SS-2013) consist of three gauge blocks (numbers 1–3) each with a single row of five stainless steel spheres with diameters of 0.5 mm, 1 mm and 1.5 mm respectively, set into conical recesses to provide apparent contact angles of 55° ± 15°, 90° ± 5°, and 110° ± 5° respectively. A similar artifact from the set is shown in figure 7 and comprises a 5 by 5 array of 0.5 mm diameter spheres at a pitch of 0.8 mm.

In addition to the two instruments mentioned in section 3.1, a Mitutoyo dial gauge (Model—ID-C112CEB 12.7-0.001 mm) referencing from a Mitutoyo precision granite stand (Model 527-896 Grade A) was used to measure the height of the spheres relative to the gauge block surface. All three measurement sets were conducted in temperature controlled environments, and all (except one) using equation (1.1) to calculate the measured contact angle. The exception was the case of contact measurement, where the measured radius, \( r_{\text{true}} \), was taken as half the measured diameter of the spheres.

The results from the three techniques are shown in figure 7. For reference, the nominal results shown are calculated from an average of five measurement trials. An estimated measurement uncertainty is provided and was calculated as either: the standard deviation across the five measurements in the
Notes: Measurements are carried out on a set of artifacts that were designed to simulate sessile drops.

Table 3. Comparison of the proposed confocal, traditional goniometric, and direct contact methods.

| Artifact/setting | Confocal | Goniometer | Contact | Maximum deviation |
|------------------|----------|------------|---------|-------------------|
| ⌀0.5 mm #1a      | 45.34° ± 0.22° | 42.8° ± 2.3° | 44.80° ± 0.36° | 2.5° |
| ⌀0.5 mm #1b      | 57.46° ± 0.22° | 54.0° ± 7.6° | 56.86° ± 0.35° | 3.5° |
| ⌀0.5 mm #1c      | 61.69° ± 0.22° | 60.5° ± 7.5° | 61.10° ± 0.33° | 1.2° |
| ⌀1.0 mm #2a      | 90.68° ± 0.12° | 93.9° ± 4.9° | 91.07° ± 0.16° | 3.2° |
| ⌀1.0 mm #2b      | 85.39° ± 0.12° | 92.9° ± 6.5° | 85.01° ± 0.16° | 7.9° |
| ⌀1.0 mm #2c      | 90.68° ± 0.12° | 92.5° ± 4.0° | 90.07° ± 0.16° | 2.5° |
| ⌀1.5 mm #3a      | 107.00° ± 0.10° | 107.5° ± 3.2° | 106.28° ± 0.13° | 1.2° |
| ⌀1.5 mm #3b      | 112.52° ± 0.10° | 115.8° ± 2.0° | 111.65° ± 0.13° | 4.1° |
| ⌀1.5 mm #3c      | 113.50° ± 0.10° | 116.5° ± 1.7° | 112.90° ± 0.13° | 3.6° |

The maximum deviation between all measurements was 7.9°. This comparison should be reviewed with the note that the scales of the artifacts are smaller than that for which the AST goniometer was designed to measure. However, this was used because it is the only commercial instrument capable of measuring these parameters. If only the confocal and contact measurement techniques are compared (those with the highest degree of confidence in measurement), the maximum deviation is 0.87° when measuring the 1.5 mm #3c artifact.

3.3. Repeatability of radial measurement using surface map

To determine the contribution of radius uncertainty, \( u_{rm} \), to the combined measurement uncertainty, a single sphere of the Number 1 International Precision Engineering gauge block was repeatedly measured using the Olympus confocal microscope. For reference, the microscope was configured with a 20x objective having a numerical aperture (NA) of 0.6. A best fit radius was determined using a 4° of freedom least-squares algorithm (radius and the Cartesian location of the centre of curvature) and the surface map of each measurement. To ensure consistent results, the surface map was filtered using a circular mask with a radius of 160 \( \mu m \), determined by an acceptance angle of 40°, which is typical for 0.6 NA. The best fit radii and each corresponding standard deviation are shown in table 3. For reference, each data set encompassed approximately 200000 data points, and the average measured radii was found to be 255.6 \( \mu m \), with a standard deviation of 1.98 \( \mu m \) across the seven measurements.

3.4. Measurement of translucent objects

To validate this technique for translucent droplets, a 50 \( \mu m \) diameter silica sphere resting on a silica substrate (standard laboratory microscope slide) was measured using the Olympus confocal microscope. The microscope was configured to return irradiance readings at a vertical scan interval of 100 nm. The measured irradiance is plotted against height in figure 8.

The measured height, \( h_{me} \), determined from the single peak values was found to be 50 \( \mu m \) and the measured radius, \( r_{me} \), was 25 \( \mu m \). This result, that the measured radius was equal to half the measured diameter, indicates consistency at 0.1 \( \mu m \).
The results of this experiment demonstrate the plausibility of using a confocal microscope to measure wetting contact angle on translucent objects resting on translucent surfaces. To improve the confidence of height and radii measurements on translucent spheres, it will be necessary to obtain spheres with substantially lower geometric uncertainties. To our knowledge, such spheres do not currently exist.

A more theoretically based evaluation of sphere measurement using confocal microscopes, along with the associated influences of interference, is outlined in [18]. With the support of both the measurements reported here and the theory outlined in [18], it is concluded that the interference caused by the recombination of light, at the scales investigated here, has a negligible impact on the calculated location of the features of interest in this work. As drop sizes approach the micrometre regime, the impact on feature location measurements on translucent objects must be revisited as it is clear that measurement anomalies exist from the recombination of light [18].

4. Uncertainty analysis

At the time of writing, ISO specification standards to link the measured output of scanning confocal microscopes to a traceable measurement standard are still at draft stage [12], although some good practice guidance is available [13]. Such a specification standard would necessarily address slope dependent measurement errors [14] and a standardised approach to evaluate, and possibly compensate for, the optical transfer function [20]. Currently there are ongoing efforts to develop characterisation techniques for the use of an instrument's optical transfer function in traceable measurements [21, 22].

4.1. Instrument bias estimate

One source of error in dimensional measurements is due to instrument bias, \( u_b \), which is difficult to determine. For our purposes we are comparing measurements of the steel sphere artifacts with contact measurements that are established and accepted to have low uncertainties. To gain a sense of the magnitude of this bias, the results in section 3.3 are compared with section 3.2. For reference, using the contact method the diameter was 509.6 µm with a standard deviation of 0.63 µm over fourteen measurements (assumed radius of 254.8 µm). Using the confocal method the radius was 255.6 µm with a standard deviation of 1.98 µm across seven measurements. This difference of 0.8 µm is taken as an instrument bias.

4.2. Confocal characterisation

To measure the response characteristics of the Keyence confocal microscope, a single setting, 0.5 mm diameter #1b, in the stainless steel artifact set was measured repeatedly. The microscope was configured to use a 20× objective having an NA of 0.46. To characterise the instrument response to each feature, a high resolution scan was acquired. More specifically, the fine scan consisted of 350 confocal planes, 254 through the centre peak, 50 through the substrate surface, and 50 through the apex of the sphere, and with a minimum axial spacing between planes of 300 nm. As previously discussed, the laser intensity was adjusted between the scan of each feature (rather than each measurement) such that the maximum measured intensity of each feature was just below the detector saturation. The results of the scan are shown in figure 6 as a plot of the intensity values along the measurement path. It can be noted that the sampling spacing was not evenly distributed; rather there is a concentration of measured points around the regions of highest intensity and the regions with the highest changes in intensity per change in position. As shown in figure 6, the apex, substrate and centre are clearly visible. Further, the detection of each feature, including the centre peak, are all indicative of a typical confocal microscope response which represents the instrument’s point spread function at a singular measurement feature [23]. The Gaussian fit used a least-squares technique with 4° of freedom, including amplitude, lateral and vertical offsets.
and width. To decrease processing times, the amplitude was set as the maximum measured intensity value on each feature; the vertical offset was set to a value equal to the mean of the measurement noise. Additionally, to avoid measurement anomalies, each feature was measured using a filter to offset noise. More specifically, in these measurements the intensity data in each plane was averaged over a 5 by 5 pixel area.

The steel sphere artifact was measured seven times. After analysing the confocal data, the mean radius of the sphere was measured to be 257.61 $\mu$m with a standard deviation of 0.67 $\mu$m, and the mean height was measured to be 199.07 $\mu$m with a standard deviation of 0.76 $\mu$m. In practice, the uncertainty of measurement will include errors of the instrument itself, operator error and random variations in contact locations and forces (associated with operator errors). Because estimates for the first two sources are not known, both standard deviation values were then taken as the uncertainty of differences as a simple means of estimating the uncertainty due to hydrostatic deflection, a MATLAB programme was used to generate a matrix of differences; one for each radius, in the range from 1 $\mu$m to 1 mm, and for each contact angle in the range from 15° to 165°. An illustration of the programme set up is shown in figure 9. The programme generated a theoretical profile for each radius in the matrix (labeled Theoretical profile), and then, for every theoretical contact angle, an artificial horizon was established coincident to the point on the theoretical profile where the slope was equal to the theoretical contact angle ($\theta_f$). Using the horizon as a boundary condition, a circular profile was fitted using a least-squares technique, from which the slope of the circle at the intersection of the horizon is determined ($\theta_i$). The slope found on the best-fit circle at the intersection of the horizon was compared to the theoretical contact angle ($\theta_f$). Using water under standard gravity conditions is shown in figure 10.

To assess the magnitude of the difference in contact angle due to hydrostatic deflection, a MATLAB programme was used to generate a matrix of differences; one for each radius, in the range from 1 $\mu$m to 1 mm, and for each contact angle in the range from 15° to 165°. An illustration of the programme set up is shown in figure 9. The programme generated a theoretical profile for each radius in the matrix (labeled Theoretical profile), and then, for every theoretical contact angle, an artificial horizon was established coincident to the point on the theoretical profile where the slope was equal to the theoretical contact angle ($\theta_f$). Using the horizon as a boundary condition, a circular profile was fitted using a least-squares technique, from which the slope of the circle at the intersection of the horizon is determined ($\theta_i$). The slope found on the best-fit circle at the intersection of the horizon was compared to the theoretical contact angle ($\theta_f$). Using water under standard gravity conditions is shown in figure 10.

For simplicity, a bi-cubic surface was fitted to the matrix of differences as a simple means of estimating the uncertainty due to the spherical approximation, $u_f$. The equation for the bi-cubic surface is

\[
\frac{d\Delta \theta}{d\phi} = \frac{\gamma r \cos \phi}{\rho \rho \rho r^2 - \gamma \sin \phi}
\]

\[
\frac{d\Delta \theta}{d\psi} = \frac{\gamma r \sin \psi}{\rho \rho \rho r^2 - \gamma \sin \psi}
\]

where $r$ and $\psi$ are the lateral and vertical coordinates in a cylindrical coordinate system, $\phi$ is the slope at the point of interest, $\gamma$ is the surface tension of the fluid at the air interface, $\rho$ is the density of the liquid, $g$ is the acceleration due to gravity, and $R$ is the radius at the apex of the drop (see figure 9 for illustrations of these parameters).

4.3. Validity of spherical approximation

The measurement technique discussed here is largely based on the assumption that the drop is spherical. In practice, the profile of a sessile drop in the presence of a gravity field is governed by [7]:

and width. To decrease processing times, the amplitude was set as the maximum measured intensity value on each feature; the vertical offset was set to a value equal to the mean of the measurement noise. Additionally, to avoid measurement anomalies, each feature was measured using a filter to offset noise. More specifically, in these measurements the intensity data in each plane was averaged over a 5 by 5 pixel area.

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\]
where the coefficients of the bi-cubic are tabulated in tables 4–6, each corresponding to an analysis using parameters for water, glycerin and mercury respectively and with units of radius, $R$, in metres, and the units of the contact angle, $\theta$, in radians. Note that the calculated standard deviation of the difference in the resulting matrix from analysis on a water droplet and the bi-cubic fit was calculated to be 0.21° using a matrix of 1350 differences. Calculations for mercury and glycerin droplets exhibited similar quality of fit.

4.4. Combined measurement uncertainty estimation

Assuming the uncertainty distribution is Gaussian and that the standard uncertainties are uncorrelated, the combined uncertainty, in radians, can be estimated as the root sum of squares given by

$$u_{\theta} = \sqrt{u_{r_{m}}^2 + u_{h_{m}}^2 + \frac{h_{m}^2}{2r_{m}h_{m} - r_{m}^2h_{m}} + u_{b}^2 + u_{f}^2},$$

(1.4)

To better illustrate the effective boundaries when using the proposed technique, a 2D study was conducted using equation (1.4) and the various parameters given throughout this paper. Figure 11 shows the estimated measurement uncertainty as a function of contact angle and droplet radius. The grey scale region of the scale bar in this figure is limited to the area of interest (1.5° and below) so that any part of the uncertainty surface exhibiting a pure white coloration indicates a region for which there will unacceptable measurement uncertainties by this criteria.

4.5. Uncertainty example

To illustrate the use of these bi-cubic coefficients and other uncertainty components for derivation of combined uncertainties, consider the measurement of a water drop with a diameter of 1 mm resting on a PTFE substrate in a normal air environment (contact angle assumed to be 110°) using the Keyence laser scanning confocal microscope and the measurement process outlined above. From the given geometric parameters, it is possible to calculate the values shown in table 7 from which a combined measurement uncertainty of 0.9° is estimated.

5. Conclusions

This paper has demonstrated a novel confocal measurement method to determine the geometry of sessile droplets. For spherical droplets on a flat surface, such a measurement can be used to determine the contact angle for wettability studies. The major advantage of this technique over traditional goniometry is that the droplet can be measured from above, thereby eliminating the complexities in identifying the triple phase contact line when viewing from an oblique angle. This aerial measurement is often more convenient for industrial quality control, particularly if viewing at an oblique angle is
observed. A further advantage of this method is that it can be used to determine the volumetric and other geometric features of the droplet with only calibration of displacement in a vertical axis being necessary, for which there are mature technologies providing nanometre uncertainty over ranges extending to tens of millimetres.

For droplets having diameters less than 1 mm and contact angles between 15° and 160°, these droplets approach spherical shape and their contact angles can be computed analytically with less than 1% error. For larger droplets, gravitational deformation needs to be considered.

Four experimental studies have been carried out to assess the performance of this technique:

1. A direct comparison is presented of contact angle measurement on 5 µl glycerin droplets using both traditional goniometry, and the confocal technique, which resulted in a measured difference of 3.1° in the worst case.

2. A three technique comparison (goniometric, confocal and contact measurement), using stainless steel reference artifacts having nominal radius of 254 µm and apparent contact angles ranging from 45° to 113°, showed results differing by 7.9° across all three measurement techniques, and 0.87° between the confocal and contact methods.

3. A radius measurement repeatability experiment conducted on 254 µm radius spheres using a laser scanning confocal microscope yielded a mean radius of 255.6 µm with a standard deviation of 1.98 µm across the seven measurements.

4. Finally, a proof-of-concept study demonstrating the capability to confocally measure a 25.0 µm radius using the cat’s eye method on a 50.0 µm diameter transparent glass sphere. The diameter of the sphere was measured as the height from the top surface to a plane fitted to the substrate on which it was placed. The height resolution in this experiment was 0.1 µm.

Generally, it has been found that contact angles can be repeatedly measured using this technique with deviations typically being less than 0.25° and often less than 0.1°. This level of repeatability is an improvement over the repeatability of droplet measurements using goniometric methods available in our laboratory that show deviations of 7° or more.

One issue that is currently unresolved is a lack of sub-millimetre reference spheres with known uncertainties that are traceable to standards. For larger spheres, this is being addressed by determination of mass using the crystal density methods for which uncertainties of a few nanometres have been achieved [24]. The radius of the steel spheres was measured using three methods, fitting from the surface map, the cats-eye and confocal distance, and using a surface plate and dial gauge. While these had a nominal radius of 0.254 mm, the three measured values were 0.2556 mm (number of measurements $n = 7$), 0.2576 mm ($n = 7$), and 0.2548 mm ($n = 14$) with deviations of 1.98 µm, 0.67 µm, and 0.63 µm respectively. Contact deformations cannot be ruled out for the smaller radius measured using the dial gauge. A student’s $t$ test comparing mean values between the cats-eye method and contact produces a value of $t = 9.4$, indicating a significant difference between these two measurements. A $t$ value of 2.5 for the two optical measurements is inconclusive indicating a difference at the 5% significance level and no difference at 2%. While these deviations do not significantly impact the results in this paper, the absolute measurement of small spheres remains a metrology challenge.

While this study has measured droplets having diameters between 25 µm and 1 mm, in principle our method can be extended to other sizes. At lower bound, it is expected that this method is limited by the point-spread function of the confocal instruments, which is on the order of a few wavelengths. On the other hand, larger droplet size can also be measured by this method, provided that gravitational deformation can be accounted for. The simplicity of this method makes fast measurements practical, which could be applied to study droplet deposition processes, for example, contact angle hysteresis and contact angle variation over time.

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